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The physical properties of major aquifers in England and Wales

Hydrogeology Group
Technical Report WD/97/34
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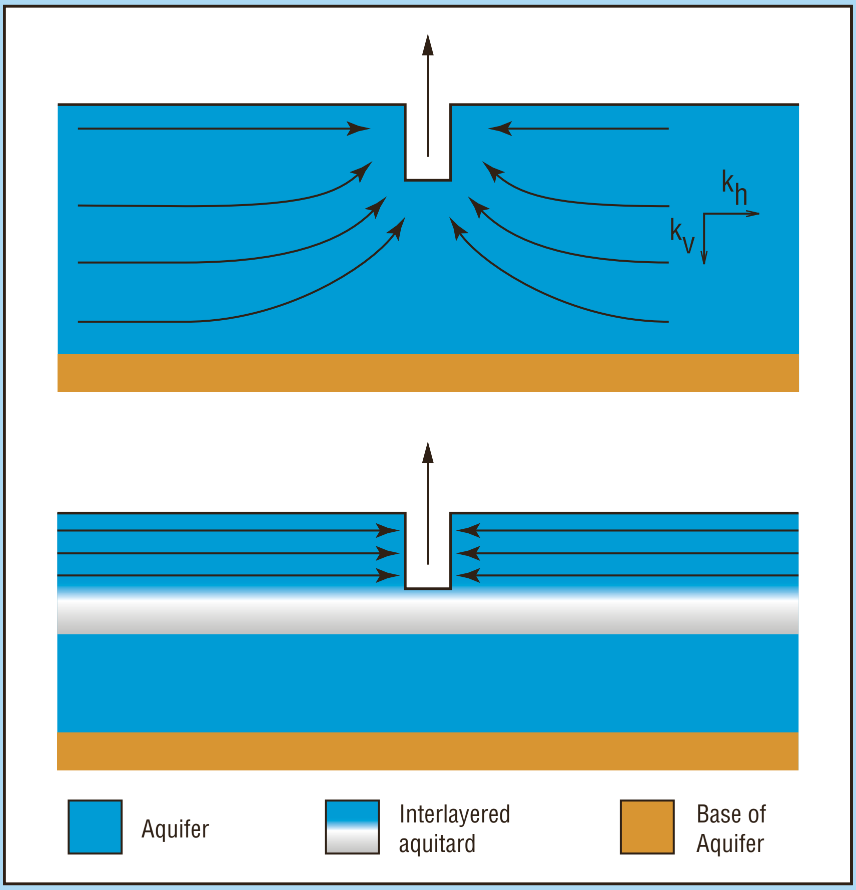

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The physical properties of major aquifers in England and Wales

D J Allen, L J Brewerton, L M Coleby, B R Gibbs, M A Lewis, A M MacDonald, S J Wagstaff and A T Williams

Contributing authors: J A Barker, M J Bird, J P Bloomfield, C S Cheney and J C Talbot

Editors: D J Allen[1], J P Bloomfield[1] and V K Robinson[2]

1 British Geological Survey
2 Environment Agency

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BRITISH GEOLOGICAL SURVEY

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Keyworth, Nottingham NG12 5GG

☎ 0115–936 3100 Telex 378173 BGSKEY G
Fax 0115–936 3200

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131–667 1000 Telex 727343 SEISED G
Fax 0131–668 2683

London Information Office at the Natural History Museum, Cromwell Road, London SW7 2BD

☎ 0171–589 4090 Fax 0171–584 8270
☎ 0171–938 9056/57

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS

☎ 01232–666595 Fax 01232–662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491–838800 Telex 849365 HYDROL G
Fax 01491–692345

Parent Body

Natural Environment Research Council

Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793–411500 Telex 444293 ENVRE G
Fax 01793–411501

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Foreword

This report is the main product of a three-year collaborative study between the British Geological Survey (BGS) and the Environment Agency, formerly the National Rivers Authority (NRA). Both the Environment Agency, or the Agency, and BGS are national organizations with interests in a broad survey of aquifer properties data. For the Agency the incentive for the project was the need to provide a sound scientific basis for the understanding of fundamental inputs to the Groundwater Protection Zones Project, and to assist with the understanding of groundwater resources. For BGS, the study was seen as helping to satisfy its Charter, in which the dissemination of information is seen as an important role for the Survey.

The project has been undertaken by BGS staff, with the assistance of many members of the Agency staff in such matters as the provision of data, contributing expert opinion and editing the reviews of aquifer properties.

Project staff have attempted to ensure that information contained in this report is as accurate as possible. However neither BGS nor the Environment Agency can be held liable for any inaccuracies or omissions in the report or its appendices.

Numerous authors have contributed to the report. The authors principally responsible for each of the chapters are listed below.

Introduction	—	D J Allen
Information collection and use	—	D J Allen
Use of the Aquifer Properties Database in groundwater modelling	—	A T Williams, J A Barker
The Chalk	—	A M MacDonald, L M Coleby
The Lower Greensand	—	A M MacDonald
The Jurassic Limestones	—	M A Lewis, L M Coleby, C S Cheney
The Permo-Triassic Sandstones	—	S J Wagstaff, B R Gibbs
The Magnesian Limestone	—	L J Brewerton
The Carboniferous Limestone	—	D J Allen

Dr R J Pentreath
Chief Scientist and Director of Environmental Strategy
Environment Agency

Professor S S Foster
Assistant Director
British Geological Survey

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In addition to the principal authors, the following BGS Hydrogeology Group staff contributed to the report: M J Bird, J P Bloomfield and J C Talbot.

A large number of individuals and a range of organizations have contributed to the project. This assistance has been received at all stages of the study; several organizations have offered data, many individuals have freely given their advice, and many have helped to review draft chapters of the Manual.

In particular, the authors would like to thank the staff of the former NRA, for their assistance during the laborious task of searching NRA files for pumping test data, for their advice during the process of reviewing regional aquifer properties, and for their editorial assistance. Of the many individuals in the former NRA who have contributed to the project we would particularly like to thank the following:

Anglian Region	— G Bryan, P McConvey, A Moss, B McSorley, J Pacey, D Seccombe, P Soames, C Taylor
North West Region	— A Peacock
Northumbria and Yorkshire Region	— J Aldrick, P Butler, D Chadha, M Kershaw, K Owen
Severn Trent Region	— P Armstrong, A Dacey, S Fletcher, E Parry, P Stewart
Southern Region	— H Ballington, J Ellis, R Murchie, S Peedell, B Thorn, G Warren
South Western Region	— S Hartley, P Johnstone, W Stanton, C Tubb
Thames Region	— V Robinson, A Attwood, M Forshaw, N Bailey
Welsh Region	— W Davis, S Neale

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Many other individuals and organizations provided useful advice and/or data, including: M Cook and S Eyre (Anglian Water), S Hobbs and A Marsland (Aspinwall and Company), D Downing (independent consultant), J Campbell and S Walthall (North West Water Engineering), S Kirk and N Mackenzie (South West Water), R Brassington (Southern Science), K Baxter and R Sage (Thames Water Utilities), P Meanley (Three Valleys Water), J Lloyd and J Tellam (University of Birmingham), W Burgess and J Dottridge (University College London), T Cosgrove and P Stansfield (Wessex Water). Other individuals, particularly those who provided source material in the form of academic theses are referenced in the text.

M D Eggboro (Environment Agency, Water Resources Topic Leader), and S S D Foster (BGS, Assistant Director) oversaw the project and provided much helpful assistance.

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Contents

LIST OF TABLES

LIST OF FIGURES

Glossary

Bulk hydraulic conductivity This term is used in the report to represent the average *hydraulic conductivity* of a section of aquifer, and is made up of matrix and fracture components.

Fracture The term fracture is used in the report to refer to a parting in a rock. The term does not imply any particular orientation or origin, except that of brittle failure. Thus joints and faults are fractures, but a fracture is only referred to as a joint or fault if the relevant mode of formation is known. The term fissure is commonly used by hydrogeologists but its meaning is imprecise and is not used in the report. Where fractures are thought to have been enlarged by solution they are described as such.

Hydraulic conductivity The hydraulic conductivity, K [LT^{-1}] of a material is the constant of proportionality in Darcy's Law, which relates the flowrate of a liquid through a material to the hydraulic gradient (see Appendix 1 for further discussion).

Karst Used to refer to a limestone region characterised by a dry and barren surface and underground drainage via channels; with swallow holes, caves, large springs and other features found in the Karst region of the Dinaric Alps, near to the Adriatic coast of former Yugoslavia (discussed more fully in Chapter 9).

Locality As used in the database, the term refers to an area encompassing sites within 100 m of each other.

Permeability The term permeability, used in a general sense, refers to the capacity of a rock to transmit water (see Appendix 1 for further discussion).

Porosity Porosity Φ [dimensionless] is commonly defined as the ratio of the pore volume to the bulk volume of a material. Several types of porosity may be defined within this general definition (see Appendix 1 for further discussion).

Site As used in the database, the term refers to a geographical point from which data are available.

Specific storage S_s [L^{-1}] of a saturated aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head (see Appendix 1 for further discussion).

Specific yield S_y [dimensionless] is taken broadly to represent the storage coefficient of an unconfined aquifer (see Appendix 1 for further discussion).

Storage coefficient S [dimensionless] is the volume of water which an aquifer releases or takes into storage per unit surface area of aquifer per unit change in head. It is sometimes referred to as storativity (see Appendix 1 for further discussion).

Talik An unfrozen zone in permafrost.

Transmissivity Transmissivity T [L^2/T] can be defined as the product of hydraulic conductivity and aquifer thickness, with values usually quoted as m^2/d (see Appendix 1 for further discussion).

Notation

A	cross-sectional area of rock perpendicular to flow
bgl	below ground level
brt	below rotary table
d	day
g	acceleration due to gravity
i	hydraulic gradient
k	intrinsic permeability
K	hydraulic conductivity
K_h	horizontal component of hydraulic conductivity
K_v	vertical component of hydraulic conductivity
m	metre
m^3/d	cubic metres per day
OD	Ordnance Datum
Q	flow rate
S	storage coefficient
S_s	specific storage
S_y	specific yield
T	transmissivity
V	rock volume
Vp_I	interconnected pore volume in rock of volume V
Vp_T	total pore volume in a rock of volume V
α	aquifer compressibility
β	water compressibility
μ	dynamic viscosity
ρ_w	water density
ρ_b	dry bulk density
Φ	porosity
Φ_I	total interconnected porosity
Φ_K	kinematic porosity
Φ_T	total porosity

Summary

This report is the result of a three-year collaborative project between the British Geological Survey and the National Rivers Authority (now the Environment Agency). The aim of the project has been to collect, collate and present information concerning the physical hydraulic properties of the major aquifers in England and Wales. The properties addressed are those which are substantially invariant with time; permeability and porosity, transmissivity and storage coefficient. These properties have been investigated for the six main aquifers; the Chalk, the Lower Greensand, the Jurassic limestones, the Permo-Triassic sandstones, the Magnesian Limestone and the Carboniferous Limestone.

Although the parameters studied were limited in number, the study has proven to be both broad and complex for several reasons. Firstly the aquifers themselves are hydraulically complicated. They are in the main heterogeneous, fractured bodies of rock, sometimes with indeterminate boundaries. This presents a double problem; hydraulic tests on such materials often violate the classic assumptions used in the test analysis, and the complexity of the aquifers makes interpolation between data points difficult. Secondly the physical properties of the aquifers are often scale dependent, so that the value of a parameter at one scale may not be appropriate for use at a larger or smaller scale. Thirdly there are problems of data quality and quantity. The quality of the pumping tests is variable and many results are from pumping tests of short duration which are designed more to assess the yields of boreholes than to examine the properties of the aquifer. Also, data obtained from boreholes tend to be clustered in high yielding areas, making an assessment of the true variation of hydraulic properties across an aquifer difficult.

As a result of these difficulties the approach to the project has been to collect both data and knowledge about the aquifers, in order that the report can address not only the magnitudes and variability of the aquifer parameters, but also to provide some insight into factors controlling the properties. To this end project resources were used in two distinct ways. Initially the main effort of the project was put into data collection. This involved a detailed search principally through the records of the former NRA, with additional information from BGS, industry and published and unpublished literature. Most of the data obtained were from pumping tests, and these were digitised and stored in a database designed for the project. The database was linked with the BGS Core Analysis Database to form a large set of basic data for the aquifers under consideration.

The second main strand of the project was the collection of knowledge about the aquifers. This took the form both of collecting reports of hydrogeological studies carried out on the aquifers and of canvassing expert opinion (a vital source of information which is not often published).

The results of these two approaches are synthesised in this report. After the introductory sections each chapter takes the form of a detailed review of the physical properties of one aquifer (subdivided as necessary). The purpose of the review is to present the magnitudes and variability of the data (mainly from the database, but with other examples) in the context of current understanding of the controls on the data. To that end the review encompasses appropriate aspects of the geological, geographical and physical hydrogeological nature of the aquifers. Summaries of data from the database are also presented in the form of appendices on an accompanying CD-ROM.

The intention of the report is therefore not only to acquaint the reader with the aquifer properties data values which characterise the aquifers, but also to show the perceived complexity of their hydraulic structure and the physical controls on the data — there is therefore an overt intention to dissuade the reader from taking raw values out of context. A further purpose of the report is to provide a comprehensive set of references by which the reader can obtain more detailed information about particular areas of interest in an aquifer.

As a result of the collection and review of information about the physical properties of the aquifers it is apparent that there are many areas in which knowledge is inadequate. For example the scale dependence of aquifer properties in the Permo-Triassic sandstones, and in particular the effects of fractures, are perceived to be important but are poorly understood. In the Chalk the extent to which the aquifer may be considered to be karstic, in the sense of allowing rapid flow to occur in discrete zones of high permeability, is an often debated issue on which there has been little research. Many other areas of uncertainty are apparent in the information presented in this report; however this is an important function of the study, for by summarising the extent of available knowledge its inadequacies will be more readily seen.

KEY WORDS

UK Aquifers, Chalk, Jurassic limestones, Lower Greensand, Magnesian Limestone, Permo-Triassic sandstones, Carboniferous Limestone, hydraulic conductivity, transmissivity, porosity, storage coefficient.

1 Introduction

1.1 PROJECT DESCRIPTION AND SCOPE OF THE REPORT

1.1.1 Introduction

The Aquifer Properties Project, of which this report is the principal product, was a three-year study carried out between 1993 and 1996. The study was funded on an equal basis by the Environment Agency's predecessor body, the National Rivers Authority (NRA) and by BGS and was undertaken by BGS staff, with significant input from NRA staff.

For the Agency the production of this report forms part of the continuing commitment to protecting the groundwater sources of the United Kingdom. With the publishing of the *Policy and Practice for the Protection of Groundwater* by the NRA (NRA, 1992), a commitment was made to the creation of source protection zones around all potable groundwater abstractions. These are currently being produced by each Agency region using a number of internationally accepted computer modelling packages. All require the input of aquifer parameters, often in complex hydrogeological situations. It is hoped that this report will encourage a consistency in approach to setting up models and underpin the long term objective of producing defensible protection zones around groundwater sources which are respected by all.

For BGS this report forms an important product of its basic scientific survey work. The collection, collation, interpretation and dissemination of hydrogeological information is an important part of the Survey's role, and the Aquifer Properties Project was perceived as falling entirely within this remit.

The specific objective of this report is to provide a source of information on the magnitude and variability of basic physical hydraulic parameters for the main aquifers in England and Wales. This is the first time that such a comprehensive document has been produced; previous studies involved fewer data (e.g. Monkhouse and Richards, 1982), or were confined to a single aquifer (e.g. Lovelock, 1977), or had a broader hydrogeological scope (e.g. Rhodda, Downing and Law, 1976). It is therefore hoped that this report will be used as the major reference work on the current state of knowledge and known data availability for the physical properties of the six major aquifers of England and Wales.

1.1.2 Parameters and aquifers covered by the report

The aquifer properties addressed by the report are:

permeability (as hydraulic conductivity)
transmissivity
porosity
storage (as storage coefficient)

These parameters (which are defined in Appendix 1) were chosen because they represent the fundamental physical properties (in a hydrogeological sense) of an aquifer, and which are in general time invariant (although it is recognised that a term such transmissivity depends on the saturated thickness of the aquifer, which can vary with time). The report does not cover physical aspects of aquifers such as water levels, hydraulic gradients, hydraulic boundaries or recharge (except to comment on their importance to the basic aquifer properties) because these tend to vary with time, are complex, and their inclusion would have been beyond the resources of the project.

The aquifers covered are:

Chalk (including the Upper Greensand)
Lower Greensand
Jurassic limestones
Permo-Triassic sandstones
Magnesian Limestone
Carboniferous Limestone

The choice of these aquifers was based on their classification as major aquifers by the Agency.

1.2 PROJECT APPROACH

Given the objectives of the project report (to provide information on the magnitude and variability of aquifer properties) it was important to consider the extent to which parameter values might be ascribed to particular areas of aquifer — in other words, how prescriptive the document could be. For the aquifer properties to be addressed there are three factors to be considered; aquifer complexity, available data quality and quantity and issues of scale.

1.2.1 Aquifer complexity

Aquifers in England and Wales do not in general approximate to the ideal aquifers on which most groundwater analysis is based. They are hydraulically complex, heterogeneous bodies of rock, often without clearly defined boundaries, in which the magnitudes and variability of aquifer properties are imperfectly known.

The Chalk is the principal aquifer of the UK, providing around 55% of total licensed groundwater abstractions (1977 figures from Monkhouse and Richards, 1982) with boreholes commonly yielding several thousands of cubic metres per day, and sometimes exceeding ten thousand cubic metres per day. The Chalk has an insignificant matrix permeability and is only an aquifer by virtue of open water-bearing fractures (which are often enlarged by solution). These fractures are not uniformly distributed throughout the Chalk, either with depth or geographically. Open fractures tend to be restricted to the upper few tens of metres, and therefore, although the Chalk may be several hundreds of metres thick in places, the productive thickness of the aquifer may only be of the order of 50 m. There is also considerable areal variation in transmissivity, with values varying over a few kilometres by an order of magnitude or more. These variations are thought to be associated with topography, but the form of the relationship is poorly known, and the lack of data has meant that even an empirical connection has only been established in one area. Storage in the Chalk also tends to be controlled by fractures, because although the porosity of the material is high, the pore sizes are small.

The Permo-Triassic sandstones form the second most important aquifer in the UK, forming around 25% of total licensed groundwater abstractions (1977 figures from Monkhouse and Richards, 1982). Borehole yields are variable, but range up to ten thousand cubic metres per day. The aquifer properties of the Permo-Triassic sandstones are controlled by a combination of factors involving lithology (mineralogy, grain size, sorting) the degree of cementation and the type and extent of fracturing. These factors — and therefore the properties of the aquifer — are often both complex and difficult to predict, both laterally and with depth. Unconfined storage coefficients (where seen) tend to be larger than those of the Chalk, because the larger pores in the sandstone are able to drain.

In the Jurassic limestones groundwater is mainly confined to discrete fractures, and the concept of transmissivity has to be used with care, since large volumes of aquifer may be required to approximate an equivalent porous medium. This difficulty is increased for the Magnesian Limestone, and is most acute in the Carboniferous Limestone. In the latter aquifer the concept of aquifer properties in a traditional hydrogeological sense tends to break down particularly in the more karstic regions of the aquifer, where substantial flows may occur through large conduits.

As the foregoing indicates, the hydraulic complexity of aquifers in England and Wales is to a large extent determined by the degree to which they are fractured. For most aquifers in most areas of the United Kingdom knowledge of fracture location, fracture geometry and the hydraulic behaviour of the fractures is very poor. Where fractures are interconnected, fracture aperture is the fundamental control on rock permeability. In general, the more fractured the aquifer the less predictable are its hydraulic properties, and those aquifers in which flow occurs through fewer, larger fractures tend to have the least predictable properties.

Figure 1.2.1 illustrates this concept for various British aquifers. Thus the Lower Greensand is considered to have minor fracturing and essentially intergranular flow, whereas the Carboniferous Limestone is characterised by flow in large conduits and virtually no matrix permeability. The sequence in the carbonate aquifers from Chalk to Carboniferous Limestone is characterised by limited intergranular flow and increasing fracture size, and is also proportional to the age of the aquifer (this carbonate series was first pointed out by Atkinson and Smart [1981]).

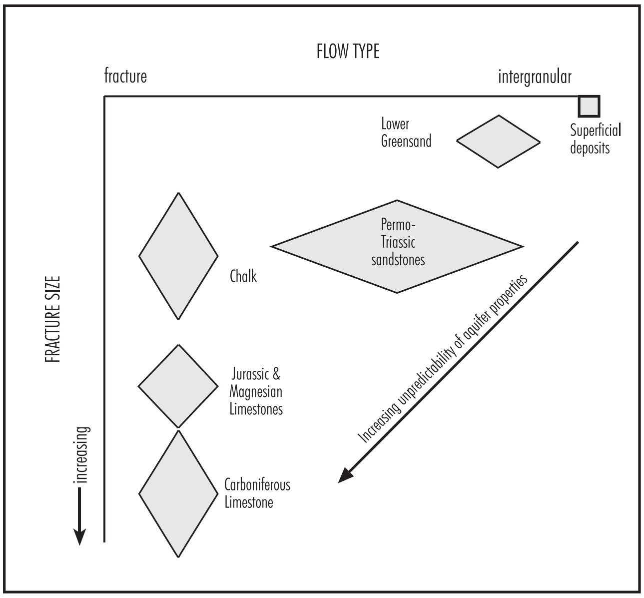

Figure 1.2.1 Flow types in British aquifers (after Grey et al., 1995).

1.2.2 Data quantity and quality

Despite the inherent variability of the aquifers, both as a result of lithological complexity and fracturing, it might be conjectured that if sufficient data were available, spread throughout the aquifers, then interpolations could be made between data points to provide parameter value estimates at any location. Whether this is true or not in principle, in practice the complexity of the aquifers is such that data requirements to achieve this result would be very large, and far in excess of the present data availability. The quantity and quality of data collected during the project are discussed in more detail in Chapter 2, but in summary the available aquifer properties data are generally too sparse, or too poor in quality to allow enable simple interpolations between data points to be made. Also the available data tend to be biased towards sites with higher yields.

1.2.3 Scale problem

As a result of the significant heterogeneity of aquifers in England and Wales, values of a parameter obtained at one scale may not necessarily be appropriate for use at a different scale. Values of hydraulic conductivity obtained at the core scale may be significantly different from those found from pumping tests, which may, for example, be affected by the existence of fractures. In turn pumping test values may be different from values appropriate for regional models (depending for example on the degree of regional interconnection of fractures). Thus the scale at which the data were obtained should be taken into account when considering their use. Further, while a single averaged value of hydraulic conductivity may be appropriate for resources modelling, the significant vertical heterogeneity of most aquifers in England and Wales may render this simplification inappropriate for transport modelling, where actual flow paths need to be considered.

1.2.4 Conclusions

In view of the above factors it is clearly not possible to attempt to produce a prescriptive document which provides an estimate of an physical properties parameter for every point in an aquifer, and even if it were feasible it would not necessarily be appropriate for all uses. The philosophy of the project, therefore, has been to attempt to obtain both data from, and knowledge about, each aquifer, and also to assess the limits of understanding of the aquifer properties.

This report therefore consists of a synthesis of knowledge about the magnitude, variability and controls on the properties of the main aquifers. It contains information gleaned from tests on aquifer material at varying scales, from published and unpublished literature and from expert opinion (the latter becoming very significant in regions where data are few). Data are provided, both in the text, and in the form of an appendices and diagrams, but they are presented with the injunction that they are used only in the context of knowledge about the likely heterogeneity, scaling effects and lithological, structural and other controls present in the aquifers, and also in the light of uncertainties about these effects. Users of the project report may then derive the most appropriate values of parameters (as far as they are known) for their purpose, with an understanding of their context, and therefore of their likely validity.

1.3 AUDIENCE

The report is designed to be used by hydrogeologists, or by those familiar with standard hydrogeological concepts and techniques. Thus the reader is assumed to be familiar with standard pumping test procedures and analysis (although not with core analysis techniques for which a brief discussion is provided in Appendix 3).

It is intended that the data contained within the report are only used in the context of knowledge about the aquifer. The report is therefore intended as a document for use by hydrogeologists, who will have the skills necessary to understand the validity of the data when set in the appropriate hydrogeological context. Given this, the report assumes little prior knowledge of the aquifer properties of the aquifers covered. Thus it is likely to be useful both as a source of data for hydrogeologists already familiar with an aquifer and as an introductory guide for those working in a new area.

Users of the report will probably include those involved in groundwater protection zone work, water resource studies, and other physical hydrogeological investigations requiring knowledge of aquifer properties.

1.4 STRUCTURE AND USE OF THE REPORT

1.4.1 Introduction

The report is designed to be used in several ways; as a source of data, as a source of information, placing the data in context, and as a guide to more detailed material. The report and its associated data may be considered as a hierarchy with the following form:

i) the report text and associated diagrams provide a detailed discussion of the magnitudes, variation and controls on the aquifers properties of the main aquifers.

ii) underpinning the text are the summary pumping test and core analysis data results, given in the appendices.

iii) the results in (ii) are a summary of the much larger volume of information held on the Aquifer Properties Database. This database is held by the BGS Hydrogeology Group Inquiry Service (to which application should be made for access to information).

In general terms therefore it is intended that the user of this report should obtain information at a scale and level of detail appropriate for their purpose (while recognizing that the more that information is summarised the less detail can be presented).

1.4.2 Report structure

The report is designed to allow the user to focus on particular areas of aquifers easily. To this end each aquifer is allocated a separate chapter, and within each chapter there is a hierarchical structure, beginning with a general discussion, and followed by a review of the aquifer properties of the aquifer on a regional and sub-regional basis. It is intended that each regional section is self-contained, so that the reader who is interested in a particular area only has to read the relevant aquifer introduction and the appropriate regional section to obtain all relevant information (however it is appreciated that this does mean that there is occasional repetition between regional sections).

Chapter 2 addresses aspects of data collection, storage and manipulation which were common to all the aquifers.

It is likely that an important use of the report will be to help those involved in modelling groundwater systems. Chapter 3 considers various issues relevant to such work.

Chapters 4 to 9 comprise the main body of the report, in which the physical properties of the individual aquifers are reviewed. Each chapter provides such general information concerning the geology and hydrogeology of the aquifer as is pertinent to the aquifer properties, followed by a more detailed discussion of those properties, on a regional basis where appropriate.

Appendix 1 gives definitions of the parameters addressed by the report, with common ranges of values. Data summaries on a locality basis are provided as Appendices 2 and 3. Appendix 2 gives values for transmissivity and storage coefficient (derived from pumping test results) from over 2300 localities over the major aquifers. The method of selection of the values is also described in the appendix. Appendix 3 presents average matrix (horizontal) permeability and porosity values (from core analysis data) for sites with more than ten samples and includes a description of the techniques used to obtain the data, with which many hydrogeologists may not be familiar. The aquifer properties data given in Appendix 2 are presented as part of a GIS on the accompanying CD-ROM, in order to illustrate their areal variability. It should be stressed that these data should be used only in conjunction with the information provided in Chapter 2 and the appropriate regional chapters, where the data may be set in context.

1.4.3 Report use

In broad terms the aquifer properties are presented in the report in a form which does not presuppose any particular use, but an attempt is made to indicate the conditions for which the information is appropriate. Thus, for example a semi-confined storage coefficient is often obtained for pumping tests in the Permo-Triassic sandstones; however for long periods of pumping (for example in de-watering operations) an unconfined value for storage should be used.

It is intended that hydrogeologists should use information which is appropriate for their particular needs. Two main uses of the information in the report are envisaged however, requiring aquifer properties information to be employed in somewhat different ways.

Groundwater resources

In general terms the bulk properties of an aquifer are required in order to estimate groundwater resources. The main aquifer properties of interest are the aquifer's storage coefficient and its transmissivity (though naturally factors such as recharge and hydraulic boundaries which are not covered by the report would also have to be assessed in order to evaluate resources). The report considers these factors in the light of current data, and opinion, and where appropriate considers the effect of the measurement methodology on the data values, and the likely controls on the parameter values (for example the effect of topography on transmissivities in the Chalk).

The report is relevant to water resource modellers for three reasons: (i) as an aid to forming a conceptual model of the aquifer; (ii) as a source of data; and (iii) as a guide to more detailed sources of information.

An important step in the process of creating a groundwater model is the development of a conceptual model of the system. It is hoped that a significant function of the report will be to help those faced with modelling a new area to decide which features of the aquifer in the study area are significant controls on the aquifer properties, and how well they are known.

The report also acts as a source of data, both in the text and in the data appendices, and by using the two together it is hoped that modellers will be provided with both the measured magnitudes of the aquifer properties, and an idea of the uncertainty in the values at the scales of measurement.

The contents of the report include the results of a large number of existing studies, and it is hoped that the references will be of use to modellers wishing to obtain more detailed information about particular areas.

Groundwater transport

It is hoped that the report will be useful to those studying groundwater transport for essentially the same reasons as it may be used for resource studies. However it is recognised that the study of the movement of pollutants in groundwater is significantly more complex than that of predicting borehole behaviour or estimating resources. Generally, in resource investigations it is not necessary to know the flow paths of groundwater, except in broad terms. However knowledge of flow paths is fundamental to understanding groundwater pollutant movement, or to defining source protection zones.

The complex hydraulic nature of many British aquifers, caused principally by fracturing, or by layering, or both, presents a significant challenge to the prediction of subsurface pollutant transport, and it is the express intention of the report to recognize and where possible, elucidate, these complexities in order to promote realistic modelling of pollutant transport and source protection zones.

1.5 UPDATING THE REPORT

This report was written using information which was available up until 1995; however the database information given includes data added in early 1996. In order that the report may maintain its relevance as a source of information it is hoped that it should be updated every few years. This will also provide an opportunity to include information which the present study has omitted because the authors were unaware of its existence, and to correct any factual inaccuracies. The authors would therefore be very pleased to hear of any information (including data) which could be used to improve the accuracy of future editions of this report.

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2 Information collection and use

2.1 TYPES OF INFORMATION COLLECTED

2.1.1 Introduction

A significant proportion of the resources of the study were spent on obtaining information. This involved the collection of a range of basic data — mainly core analysis and pumping test results — and the collection and review of knowledge from the literature and from expert opinion (usually local to the aquifer being reviewed).

The basic aquifer properties data were digitised and stored in a database to enable them to be easily sorted and retrieved, and a synthesis of this information was used with information obtained from the literature and from expert opinion to provide the source material for the aquifer review chapters of this report.

2.1.2 Core analysis data

Core analysis data are taken to represent point estimates of permeability, bulk porosity, and pore-size distribution within an aquifer. As the size of core samples is relatively small, laboratory results provide information on the aquifer properties at the matrix scale. The results of core analysis studies may be used, in combination with the results of field tests, to assess the relative contribution of matrix and fractures to the overall hydraulic response of an aquifer.

Most of the core data used in the report originate from the BGS database of core analysis data, although other published and unpublished records have been used. Over the last 25 years staff from the Aquifer Properties Laboratory of the BGS have performed core analysis studies on material from most of the major and minor British aquifers. A relational database has been established which contains information concerning the location, depth and stratigraphy of the samples, and includes the results of porosity, bulk density and permeability tests from over thirteen thousand samples from the major aquifers in England and Wales. The samples were mainly obtained from cored boreholes, although there are a limited number of samples from surface exposures. The other core analysis data were obtained from published and unpublished studies, including PhD projects. These core analysis data are generally in the form of averages, with little detail concerning the test procedure. This information, though referred to in the text, is not held on the database.

2.1.3 Pumping test data

Much pumping test information was obtained during the project. Such information is important as it provides the only direct source of transmissivity and storage coefficient estimates for the aquifers on a local scale.

Pumping test information was obtained mainly from the regional offices of the Agency. Project staff visited all appropriate regional and area offices and recorded the results of pumping test analyses. At the outset the numbers of records of tests were unknown, but were believed to be of the order of 2000 (in the event, data from a total of around 3500 tests in major aquifers at over 2600 sites were obtained). The amount of data to be collected from each test needed to strike a balance between obtaining sufficient information to be useful in understanding the test result, but not so much as to exhaust project resources. Given the anticipated numbers of tests it was unreasonable to expect that tests could be re-analysed within the project, but it was considered necessary to obtain more than simply the transmissivity and storage coefficient values assigned to the test by the analyst.

Given the expected numbers of tests a data collection form, or data sheet, was devised which would allow the salient features of the test (and the pumped borehole) to be recorded. This also enabled data presented in many differing formats to be collected in one standard manner. In addition to recording aquifer and borehole details, test configuration and the results of test analyses, the data sheet allowed for an assessment of the quality of the test results. This is a subjective judgement, made by the data collector and is based on an overall impression of whether the test was carried out and analysed well or not. Each data sheet was given a unique number, and the source of the data (e.g. pumping test report) was recorded in a separate data collection diary.

The data collected had many different origins. The most common by far was as a result of applications to abstract groundwater under Acts of Parliament. Prior to 1963, no formal permission was required to take water out of the ground. The Water Resources Act of 1963 required all new abstractions from that time onwards to be licensed (the Act was not retrospective). One purpose of this Act was to be able to monitor and thus regulate the amount of water abstracted from any one source with particular regard to the management of the resource and the effect of abstraction on other sources.

Small amounts of abstraction, defined as domestic, were not subject to this process but larger amounts (non-domestic) were subject to licensing. This included such diverse applications as water supplies to farms, factories, breweries, quarries and many other sorts of industry. Latterly the large growth in the leisure industry has resulted in applications becoming common for large hotels, holiday complexes and golf courses. Above all, applications for groundwater abstraction for public supply provide many good pumping tests.

In order to be able to assess the effect of abstraction for licensing purposes, relevant data had to be made available for the assessors to make their decisions. Knowledge of local aquifer parameters such as transmissivity and storage coefficient is as important as the yield of a borehole. It was in order to provide this information that pumping tests were performed on a more routine basis; indeed the latest revision of the Act in 1991 gives statutory powers to make a pumping test compulsory on any licence application to the Agency at their discretion.

The standard of pumping test data from licence applications varied greatly. Tests ranged from a few hours with no data being collected from other than the abstraction well, to tests of several days (usually seven or 14) with one or more observation wells. This criterion was a factor in the awarding of a suitable test quality rating (see above). In general it is true to say that the more recent the test and the larger the amount of water to be abstracted, the higher the quality of the test. This is a direct reflection of the realisation of the importance of this knowledge and the ability of, for example, well drillers to be able to carry out a successful test.

Whilst licence applications were the source of most of the data, especially historically, the growth of hydrogeology as a specialist scientific subject led to other data sources becoming available. Much of the more recent and usually better quality data was available in reports of scientifically based studies. The old River Boards, River Authorities and other similar public bodies carried out much hydrogeological research for their own purposes. Most of the pre-Agency bodies did research into many topics. Artificial recharge schemes, river regulation schemes, river augmentation schemes, basin studies and many other forms of work necessitated pumping tests to provide information. The subsequent reports on this type of project were a rich source of information and data.

Since the privatization of the water industry in 1989 with the setting up of the NRA and the private water companies, the potential for acquiring pumping test data has increased. The Agency carries out a limited amount of its own research (albeit often via contractors) while the water companies also conduct research projects and other forms of data gathering of their own. The water companies need to know the amount and extent of their water resources to be able to supply their customers. They have an obligation to supply the Agency with details of tests if they wish to obtain a licence for abstraction, but under some circumstances they can do research work including test pumping and keep their results, which may or may not be confidential.

The final sources of data were, by comparison, fairly minor. These included published proceedings from meetings and symposia, PhD theses deposited with the Agency, engineering reports (eg. roads, tunnels), saline intrusion studies and inputs to computer model studies. These are just a few of many other, often small studies from which aquifer parameters were gathered.

In addition to data obtained from the Agency, pumping test analyses were obtained from BGS records, from literature (published and unpublished) and from industry. All the water companies in England and Wales with groundwater sources were approached, and most were willing to supply data, or to assist with other information. However most relevant water company data was obtained from Agency records, as a result of licence applications. Several consultants were approached to ascertain whether they held appropriate data. While the response from these companies was often favourable, problems of data confidentiality, and the perception that the extra information would not add substantially to the data already held, led to a decision not to pursue this information. An exception was a database of hydrogeological information held by Aspinwall and Company, created as part of the Agency Source Protection Study, part of which was incorporated into the Aquifer Properties Project Database.

2.1.4 Model calibration data

Model calibration aquifer properties data were collected as part of the general review of information. Such data were obtained for important regional aquifer model studies held by the Agency. This information is important as a comparison with data obtained at other scales.

2.1.5 Literature

Much information concerning the magnitude of, variation in, and particularly the controls on, aquifer properties, was obtained from literature. A substantial review of the literature regarding UK aquifer properties was carried out which included published literature, unpublished reports held by the Agency and BGS, and theses held by Universities. Much guidance on the source of relevant literature was obtained from hydrogeologists in the former NRA and colleagues in BGS.

Information collected included the results of packer tests, geophysical logging results and geological, hydrogeological, hydrological and hydrochemical information pertinent to the physical properties of the aquifers.

2.1.6 Expert opinion

This was a very important component of the study. Much aquifer properties information is held in the form of unpublished ideas or work held by acknowledged authorities on aquifers in different areas. As far as possible these have been consulted — in particular the Agency regional hydrogeologists — and their opinions incorporated into the report.

2.2 PROJECT DATABASE

2.2.1 Introduction

A large quantity of pumping test data was collected during the life of the project, and much of the information was digitised and stored along with the existing digitised core analysis data. The database software chosen was Microsoft ACCESS™. This was considered to be sufficiently powerful and flexible to handle the anticipated types of data manipulation, and could be run on a standard PC.

A relational database structure was developed to hold the pumping test and core analysis information, comprising 16 interlinked tables. All information contained in the database is connected by means of a site identifier, which is allocated to each site from which information has been obtained (usually a borehole or core analysis site). The database tables hold information such as site location and geology, borehole geometry, pumping test data, pumping test analysis types and results, core sample location and core analysis results. The structure of the database enables queries to be readily designed to sub-select information using a variety of criteria, such as location, geology, type of test or type of analysis. A conservative philosophy has been adopted for data entry, in that data in different tables are only connected if there are clear reasons for doing so. Therefore, for example, a new set of data is allocated a new site number unless it clearly comes from an existing site.

2.2.2 Database contents — pumping test data

Data distribution

A subset of the pumping test data collected during the course of the project was transferred to the digital database, for ease of manipulation. In total, in December 1995 the database held pumping test information from 2616 sites in the major aquifers (the database is not static and information is added as resources allow). In addition the database held some data on minor aquifers as well as information unattributed to a particular aquifer. It should be borne in mind that this dataset is likely to be biased towards sites with high transmissivities; boreholes tend to be drilled where a reasonable yield is expected, and boreholes with low yields are less likely to be tested.

The distribution of sites over the major aquifers is shown in Table 2.2.1. The table also shows the average density of sites as numbers of sites per 100 km^2 of the aquifer outcrops (these figures are in reality too high, because not all the boreholes are at the aquifer outcrop, but they show the general distribution).

The figures given in Table 2.2.1 indicate the general densities of sites for which pumping test data are available for each aquifer. However they conceal the fact that the data tend to be clustered in higher yielding areas and commonly pumping test densities are likely to be much lower; for example around 25% of the sites in the database are within 1 km of other sites.

Each borehole for which aquifer properties data are held in the database has been tested by pumping at least once, and that test has produced at least one transmissivity estimate, and possibly a value of storage coefficient. Some boreholes have been tested several times, and many tests have multiple results due to multiple analyses. Table 2.2.2 shows the number of tests, by aquifer, and the total numbers of transmissivity and storage coefficient estimates obtained from the tests. It is evident from the table that the Chalk has the greatest number of tested boreholes, followed by the Permo-Triassic sandstones, which is as expected given the relative importance of these aquifers.

Data quality

As discussed in Section 2.1.2 a general assessment of the quality of pumping test data was made during data collection. However this was only done where sufficient raw test information could be seen to enable an assessment of quality to be made. Also, while a quantitative assessment of quality was used (on a scale of one [highest quality] to five [poor quality]) the fact that the data were collected by several different people meant that the assessment was inevitably subjective. Thus the ratings should be considered merely to distinguish good (or very good) data (ratings 1 and 2) from poor data (rating 5), with an intermediate area of average to moderate data (ratings 3 and 4).

Quality ratings were obtained for a total of 1994 tests and are shown in Figure 2.2.1. These were approximately normally distributed over the quality range, with a total of 470 tests meriting a high quality rating of 1 or 2. Over 1400 tests were not allocated a rating because insufficient raw data were seen, but if the quality of these test was also normally distributed in the same way as the rated data then around 800 tests, or about a quarter of the total, would be rated as high quality. In reality this figure is likely to be an under-estimate because in general test results obtained from the literature are likely to be good, but they are unrated because the raw data were not seen. Nevertheless it seems unlikely that more than around 1000 tests in total would merit a good or better rating, leaving a minimum of around 2500 tests to be regarded as average or worse.

It should be pointed out however that tests with average or poor quality ratings were not necessarily poorly carried out; on the contrary the test procedure may have been exemplary, but if the data analysis techniques did not match the data well then the test would be marked down. These problems of non-conformance to standard test analysis techniques were quite common. In many cases pumping tests were analysed by a variety of techniques, producing a range of estimated aquifer properties, often with no preferred value (the handling of this information is discussed in Section 2.3.1).

Another measure of data quality might be the availability of observation borehole information; the database holds such information for around 30% of the tests.

The database holds test length information for 2118 tests, or about 60% of the total. The distribution of test length for tests up to 14 days is shown in Figure 2.2.2 (the database holds information for 231 tests longer than 14 days). This information should not necessarily be a measure of data quality, but rather of the volume of aquifer

Table 2.2.1 Distribution of pumping test sites for which data are held in the Aquifer Properties Database.

Aquifer	Number of sites	Approximate aquifer outcrop area(km^2)	Site density (sites/100 km^2)
Chalk	1474	21 000	7
Lower Greensand	77	1500	5.1
Jurassic lst	171	3600	4.8
Permo-Triassic sst	764	9000	8.5
Magnesian Lst	93	1600	5.8
Carboniferous Lst	37	3500	1.1
SUMMARY	Tot. 2616	Tot. 40 200	Ave. 6.5

Table 2.2.2 Distribution of pumping test data held in the Aquifer Properties Database.

Aquifer	Number of tests	Number of transmissivity values	Number of storage coefficient values
Chalk	2083	5201	2881
Lower Greensand	96	168	86
Jurassic lst	213	674	364
Permo-Triassic sst	955	2276	566
Magnesian Lst	105	245	77
Carboniferous Lst	39	81	7
TOTALS	3491	8645	3981

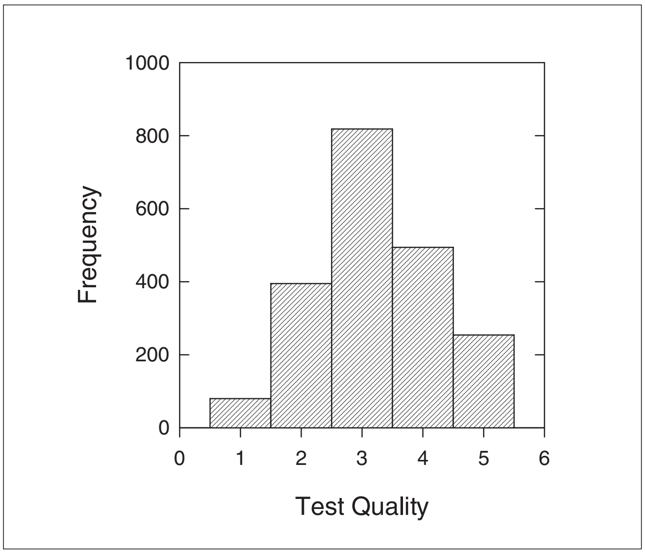

Figure 2.2.1 Distribution of quality ratings for pumping test data (1 = high, 5 = low).

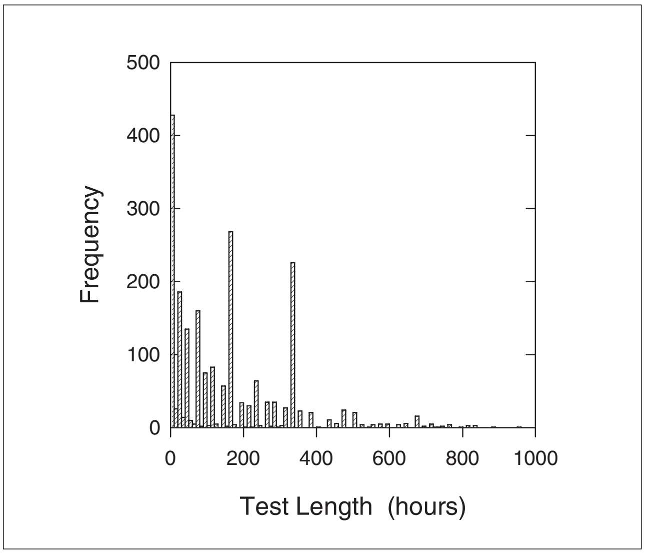

Figure 2.2.2 Distribution of test lengths for pumping test data (for tests of up to 14 days).

which the test sampled. However in practical terms longer tests provide more information for the analyst to assign appropriate aquifer properties parameter values. Figure 2.2.2 indicates that a significant number of tests were undertaken for less than a day — and are therefore likely to be more prone to analysis difficulties than longer tests.

In general terms therefore, while data for a significant number of pumping tests are available for the major aquifers the quality of the data is variable and care needs to be exercised in using the results.

2.2.3 Database contents — core analysis data

Data distribution

Table 2.2.3 summarises the total number of sites and number of samples tested from the aquifers covered by the project. Details of sample numbers as a function of geographical distribution across each aquifer, and numbers of specific tests performed on samples for each aquifer are given in the appropriate chapters of the report.

Table 2.2.3 Distribution of core analysis data held in the Aquifer Properties Database (figures in bold are totals for the aquifer).

Aquifer	Number of sites	Number of samples
Permo-Triassic sst	**523**	**8933**
Sherwood Sandstone		5205
Permian sandstones		3342
Permo-Triassic sst (undifferentiated)		386
Chalk	**97**	**2270**
Upper Chalk		722
Middle Chalk		513
Lower Chalk		241
Undifferentiated		794
Jurassic (lst and sst)	**50**	**931**
Lower Greensand	**43**	**340**
Magnesian Limestone	**14**	**140**
TOTALS	**727**	**12 614**

Usually each sample taken from a core was tested for porosity and permeability, and often two samples were taken from a given depth in a borehole, to provide a horizontal and a vertical estimate of permeability.

2.2.4 Database contents — further parameters

The future development of the database is likely to include the addition of other parameters. There follows a brief discussion of the types of physical parameter which could be added.

Anisotropy

Anisotropy relates to scale. Although sedimentary rocks exhibit anisotropy on a small scale due to the deposition process, permeability anisotropy mostly relates to larger scale heterogeneity with spatial correlation, almost exclusively due to bedding. This will normally give a vertical anisotropy which will not, in general, be homogeneous; that is, the permeability ratio should vary with depth. Occasional low permeability horizons will have a dominant effect on the vertical permeability, averaged over some depth interval.

Therefore, if anisotropy ratios are recorded in the database, it would be necessary to make it clear that they cannot be used sensibly below a certain scale.

For fractured rocks anisotropy is observed both vertically and horizontally. However, it is not until a certain scale is reached that it may be appropriate to apply 'porous medium' concepts to such systems, and only then is it sensible to refer to or quantify anisotropy. Horizontal anisotropy can be determined from long-term pumping tests with distant observation wells.

When a constant-rate pumping test in a horizontally anisotropic aquifer is analysed by a Jacob plot, the transmissivity value obtained will be the geometric mean of the principal components of transmissivity. The value of storage coefficient obtained will depend on the position of measurement of drawdown in relation to the principal directions of transmissivity and on the ratio of maximum and minimum transmissivity values.

Strictly speaking, permeability is a tensor field — it varies in space and in direction. Either the full tensor or the principal components and the principal directions are required.

Diffusivity

It is interesting to note that for most purposes, the storage parameters of an aquifer are never used other than in combination with permeability parameters in the form of a hydraulic diffusivity. The obvious exception being in the estimation of aquifer storage. Indeed, this argument can be taken further and it can be said that many determinations of storage parameters are based on a determination of the diffusivity and a permeability. It therefore appears that diffusivity is, sometimes, a more fundamental parameter than the storage parameters.

Diffusion coefficient

Molecular diffusion is the most important dispersive mechanism for pollutants in fractured aquifers such as the Chalk. For example, protection zones in the Chalk aquifer should relate strongly to the diffusion coefficient (as well as the fracture parameters). Diffusion coefficients are normally measured under carefully controlled laboratory conditions.

Dispersion

The term dispersion refers to the process of spreading during transportation: solutes, particles and heat are all dispersed in groundwater. The processes of matrix diffusion and adsorption both have dispersive effects, however the term hydrodynamic dispersion refers more specifically to spreading due to spatial variations in the flow velocity, mainly caused by branching of the flow paths. (Unfortunately, some writers use the term hydrodynamic dispersion to represent both advective and diffusive mechanisms of spreading.) The process takes effect at many scales, from the pore-scale upwards.

Hydrodynamic dispersion presents two major problems: (a) there is no generally accepted physical and mathematical description for heterogeneous media, and (b) it is very difficult to perform experiments (e.g. tracer tests) to quantify the dispersive characteristics of rocks.

If advective transport could be fully characterized throughout the system, there would be no additional dispersion phenomenon to consider. So, strictly speaking, dispersion is not a process in its own right, it is rather an expression of the fine (often random) detail of the advection process. Dispersion must therefore be related to the advective model (conceptual or mathematical) in use, particularly to its scale of averaging. This point is particularly relevant to this project.

Engineering geology parameters

Engineering geology is a subject that has significant overlap with hydrogeology. Indeed, topics such as subsidence could equally well be studied in either discipline. The main point of overlap considered here is that where parameters used in the two field are related. The importance of this, for the hydrogeologist, is the possibility of deriving hydrogeological parameters from engineering geology databases.

Even when an engineering geology parameter cannot be exactly converted into a hydrogeological parameter, if there is some correlation between two or more parameters then this can aid the extrapolation of hydrogeological parameters into regions where there is little information.

Unsaturated flow parameters

The essential differences between water movement in saturated and unsaturated rocks are due to capillary forces which cause a pressure difference between the water and air phases. As a rock drains the residual water becomes progressively isolated in the smaller pores which result in greater curvatures of the water/air interface and consequently greater pressure or head differences. The saturation of the rock is clearly related to head and it is normal to try to characterize the rock by a soil water retention curve.

Darcy's law is normally assumed to apply to unsaturated flow, but the hydraulic conductivity is no longer considered constant but a function of the saturation or head.

The soil water retention is not a unique function; the water content depends on the prior history of water movement. This hysteretic behaviour is due to: (i) the presence of different contact angles during wetting and drying, (ii) geometric restrictions (the, so called, 'ink-bottle' effect), (iii) entrapped air, (iv) shrinking and swelling phenomena, and (v) rates of wetting and drying.

When these functions are assumed to be of a particular form — represented by a particular functional form — the parameters characterizing those two equations can be regarded as aquifer parameters. Unfortunately, no single functional form will work well for various rock types, so the functional form becomes itself a type of parameter.

This situation is further complicated by the fact that the storage and conductivity functions must vary vertically as well as with saturation.

For databasing purposes, it is probably necessary to summarize the hydraulic conductivity and retention characteristics in terms of parameters within empirical formulae. Possibly the most appropriate formula would become itself a datum associated with each point.

2.3 USE OF INFORMATION COLLECTED DURING THE STUDY

2.3.1 Use of pumping test information

General

Although pumping tests often provide the only direct estimates of transmissivity and storage coefficient in aquifers there are inherent problems with the use of pumping test data.

The interpretation of pumping test data (for example drawdown versus time) may be ambiguous unless other — possibly circumstantial — information is taken into account. Totally objective analysis of pumping tests is not possible, and subjective elements in analysis include: the choice of the model used to analyse the test (a particular problem in fractured British aquifers), type-curve fitting (when used), and the choice of data points for analysis. An additional difficulty encountered in the present study is that tests have often been analysed by several different methods without an indication by the analyst as to which analysis is considered to be the most appropriate.

Pumping test information collected by the project has been used in three main ways:

i) data from the database have been used to provide the information given in Appendices 2 and 4

ii) data from the database have been used in the aquifer review chapters

iii) pumping test information derived from reports and expert opinion has been incorporated in the aquifer review chapters.

Construction of data appendices

Details of the methodology used to produce the data shown in Appendix 2 are given there, but it is appropriate to consider the general approach here. The aim of Appendices 2 and 3 is to provide summary aquifer properties data for different localities, and therefore a methodology had to be developed which would enable an appropriate value to be distilled from the range of information which may be available at a given locality. It should be noted here that the term 'locality' as used in the report has a specific meaning, being defined as an area encompassing sites lying within 100 m of each other — the reasons for this are given below.

The methodology used to obtain locality values of transmissivity and storage coefficient had to take into account the fact that pumping test results held in the database ranged from single values for a test, to a range of results with no indication as to which if any was the most appropriate. Also, at each site there might be several tests, and there could be several sites at a given locality. Given these considerations, it was decided that the choice of locality values for transmissivity and storage coefficient should be made by applying a simple set of criteria (in the form of database queries) to all the pumping test data held in the database. This had three advantages: (i) it would avoid unnecessary extra subjectivity in the handling of data, since all the pumping test information would be approached in the same way; (ii) the method of selection of the values would be overt and clear to users; and (iii) the method could be readily revised subsequently if necessary.

The approach taken had two stages; firstly pumping test analyses were examined to produce an appropriate value for each pumping test, and secondly the pumping test values were examined to produce an appropriate site or locality value. The criteria used to obtain an appropriate value of transmissivity or storage coefficient for pumping test values are described in Appendix 2, but essentially they involved a simple set of criteria designed to select the most reliable analysis (or average of analyses) for a particular test.

Once an appropriate result for each pumping test had been obtained, a second set of criteria were used to select an appropriate site value (for sites with multiple tests). These criteria were designed to select the highest quality test results — or those least affected by near-borehole effects — to characterise the site. Where there were several sites in very close proximity (less than 100 m from each other) the sites were treated as one locality, and an appropriate locality value of transmissivity and storage coefficient was determined. Appendix 2 and the plotted data on the CD-ROM give the locality values of transmissivity and storage coefficient (which in most cases are the same as the site values) because this reduces the problems of plotting closely spaced data points, and removes potential cases of data duplication (where two sets of data with different site identifiers but similar grid references may actually refer to the same borehole, but where the available evidence was inadequate to merge them).

Use of locality data

It should be stressed that since the locality data shown in the appendix are a synthesis of the various test results obtained at the locality, the values should be used with care. Although the methodology used to choose the values is intended to give priority to high quality data and to emphasise aquifer rather than near-borehole characteristics most of the tests are relatively short, and the results invitably reflect conditions local to the borehole rather than in the aquifer generally. Also in condensing a variety of data to a single locality value, detail is inevitably lost. In addition the queries are relatively simple, and naturally cannot be expected to produce definitive values at complex sites where results cover a large range but where the analyst gave no preferred value. Therefore while the locality values provide a summary estimate for each locality, and illustrate in general terms the variability of parameters across an aquifer, they do not give a full representation of any particular site. Workers requiring details of pumping tests and results (for example types, lengths, water levels, analyses) for particular sites should seek access to the data contained in the database (either the digital subset or the parent data sheets). In particular it is recommended that for modelling purposes the database information is sought (and where appropriate the original test data consulted — these can be traced via the data collection sheets from which the digital database is constructed). Use of data directly from the database also has the advantage that a more up-to-date dataset can be used than that presented in this report.

Appendix 2 also provides the maximum and minimum values of transmissivity and storage coefficient estimates, and the numbers of estimates which are held in the database for each locality. These are given only to indicate the overall range and quantity of data held in the database for each locality — they emphatically do not imply suggested ranges of appropriate parameter values. Some of the ranges of locality data held are large. Reasons for this include variability of data quality, variability of values with test length, or between boreholes at the same locality.

Use of database pumping test data in aquifer review chapters

Pumping test data from the database have been used in a variety of ways in the individual aquifer chapters. Most commonly, pumping test results for different aquifers in different areas have been plotted to show the range of values obtained. Also, other information in the database has been used to investigate particular features of the data using techniques described in the relevant aquifer chapters (for example in the Triassic sandstones the layered nature of the aquifer enabled estimates of borehole hydraulic conductivity to be made from transmissivity data and information about aquifer saturated thickness penetrated by boreholes; these values could then be compared with core data). These types of analysis have necessarily been relatively simple, given the wide coverage of the project and the variable quality of the data, but the flexibility of the database provides significant future potential for investigating systematic variations in the data.

Pumping test results are commonly presented in the report in the form of histograms and cumulative frequency plots. Both are normally given, because while the cumulative frequency distribution provides the most statistical information, the histogram conveys the general form of the data more easily. Since both transmissivity and storage coefficient data tend to extend over several orders of magnitude they are plotted on a logarithmic scale. The statistics chosen to describe the data are the median, interquartile range and geometric mean. The first two are used because they do not depend on the form of the distribution, while the geometric mean is appropriate where the data may be assumed to be lognormally distributed.

Use of reported pumping test information

In addition to the basic results of test interpretations held in the database much useful information about pumping test results, aquifer heterogeneity and borehole behaviour was obtained from published and unpublished literature and from expert opinion. This has been of considerable use in the aquifer review chapters, where much reliance has been placed on the practical experience of hydrogeologists. In particular this information has been useful in providing a framework of knowledge in which to set the test results, and the locality estimates of transmissivity and storage coefficient derived from pumping tests given in the report.

2.3.2 Use of core analysis information

General

Core analysis provides direct values of matrix permeability and interconnected porosity, but, as with the pumping test information, there are significant problems of data bias and adequacy. Core analysis data are biased towards lithologies which are sufficiently consolidated to be sampled. Thus unconsolidated or poorly consolidated sands which might have relatively high permeabilities may not be sampled, and low permeability materials with low competence, such as clays or shales, may not be tested. In addition, insufficient samples may have been taken from a core to characterise adequately the variations in matrix properties; no studies seem to have been carried out to date in British aquifers to identify statistically robust sampling regimes. It must therefore be concluded that, while available core data may be used as a guide to the range of values likely to be encountered within an aquifer, there are few sites with enough information to justify a direct comparison with data from larger scale field measurements.

Construction of the data appendix

Core analysis data from the database were used to construct Appendix 3 in which average matrix values are provided for each site for which data are held. Such information is only intended as a guide, since at many sites only a few samples are available from the aquifer. Full details of the methodology used are given in the appendix.

Use of core analysis information in aquifer review chapters

Core analysis data from the database have been used to indicate matrix values of porosity and permeability in the aquifer review chapters. Generally the approach has been to show the distribution of data for an aquifer or aquifer subdivision in the area under discussion. Where appropriate and where sufficient data are available, horizontal and vertical hydraulic conductivities have been distinguished. The data are shown on similar types of plot to the pumping test data (see above), except that while hydraulic conductivities are shown on a logarithmic scale, porosity data are given on a linear scale.

Reported core analysis information has been used along with the database data as the basis for the assessment of the matrix properties of the aquifers. In addition a limited amount of interpreted geophysical information was available. The importance of the matrix information varied between aquifers and was treated accordingly. In the Chalk, for example, where the matrix properties are relatively uniform, and where the matrix permeability provides a small contribution to the aquifer's transmissivity, the matrix properties are discussed in the overview section of the chapter. Conversely the varied and significant contribution of the matrix to the aquifer properties of the Permo-Triassic sandstones merited detailed discussion in the regional sections of the chapter dealing with the aquifer. In particular the scale dependence of the aquifer properties of the Permo-Triassic sandstones, and specifically the role of fractures, can only be addressed by understanding the behaviour of the matrix as compared with that at larger scales.

2.3.3 Use of other information

Many other sources of information have been used in the project to provide insight into the aquifer properties of the major aquifers (see Sections 2.1.4 and 2.1.5). The discussion in the regional aquifer review chapters is mainly based on a combination of information from these sources and the analysis of the data from the database.

3 The use of the aquifer properties database in groundwater modelling

3.1 GROUNDWATER MODELS

3.1.1 Introduction

This chapter differs from the rest of the report in that it steps back in order to take a broader view of aquifer properties databasing. It examines issues pertinent to the use of data held in the Aquifer Properties Database and how the database may be developed further. The first part of the chapter gives a general overview of groundwater modelling. This section is intended as an introduction to those unfamiliar with the complexities of models and modelling and, as such, can be skipped by more experienced readers. This is followed by a discussion of the parameters which are required for model construction and calibration. The relationship between the data available and those required is then considered and the chapter concludes with a look at how the database might be used in the future.

As with any database, the value of the Aquifer Properties Database can only be assessed in terms of its use. Generally, parameters find their use in models. Sometimes those models may be no more than simple formulae, such as Darcy's law, but often they are numerical models run on computers. Therefore it is necessary to consider in particular the appropriate use of the parameters in numerical models and how that use might best be enhanced. The use of numerical models in hydrogeology has increased dramatically in the last twenty years with the advent of easily available computing power. Groundwater modelling packages are now widely available which enable any hydrogeologist to produce a numerical model of a hydrogeological situation. However, this ready availability of numerical models disguises the fact that successful hydrogeological modelling requires more than access to the modelling software.

The development of a useful groundwater model is a multi-stage process. Anderson and Woessner (1991) provide an excellent review of groundwater modelling techniques and in their introduction they give a concise guide to modelling protocol. The description represents the stages that would be carried out under ideal conditions. In reality the position is often quite different, and the resources are not available to allow the modelling process to be well designed.

3.1.2 Analytical models

The flow of groundwater in an aquifer is described by two basic equations. These are Darcy's law, and the continuity equation. The parameters used in these equations to describe groundwater flow are the storage parameters of the aquifer material and its permeability. To solve these equations boundary conditions must also be described, and for transient solutions it is necessary to specify the starting conditions. The solution to the equations are normally required in the form of the head in the aquifer at a specific place and time.

In general the equations can only be solved analytically if a number of assumptions are made about the aquifer. The most common assumptions are those of uniformity of aquifer properties and aquifer geometry. The boundary conditions also have to described in simple terms — generally the aquifer is assumed to be of infinite extent or is surrounded by no-flow boundaries. Whilst these assumptions may at first sight seem to make analytical solutions of little value in a practical sense, this is not the case. The most commonly used methods of analysing pumping tests — Theis-curve fitting and Jacob straight-line method, are in fact the result of the analytical solution of the governing equations. The assumptions made in deriving the Theis solution are very strict — and often unrealistic — but they apply sufficiently well for short times near to a pumped well that the solution to the model is acceptable.

The assumptions of a homogeneous, isotropic aquifer in which the transmissivity does not vary make the governing equations linear in terms of head. This means that the Principle of Superposition applies to the solution. This, in turn, means that the head pattern due to two or more abstraction wells, for instance, can be derived by combining the solutions for the individual abstractions. This feature of the solution to the governing equations has been incorporated in the modelling packages WHPA and QuickFlow. These packages are very useful for small-scale problems — especially where the lack of real data is a limiting factor.

3.1.3 Numerical models

The problem with analytical solutions is that the complexity of aquifer geometry, boundary conditions and aquifer properties cannot be properly represented. If these features are important parameters in the problem that is being considered then numerical solutions to the governing equations probably represent the correct approach.

Numerical solutions are based on the discretisation of space and time into 'blocks', within which the various parameters do not vary. There are various methods which are used to discretise the spatial dimensions of the aquifer. The most commonly used in groundwater models are the finite-difference method and the finite-element method.

The choice between a finite difference and a finite element model depends on the problem to be solved and on the preference of the user. Finite differences are easier to understand and program and in general, fewer input data are needed to construct a finite difference grid. Finite elements are better able to approximate irregularly shaped boundaries than are finite differences. Also, it is easier to adjust the size of individual elements as well as the location of boundaries with the finite element method, making it easier to test the effect of nodal spacing on the solution. Finite elements are also better able to handle internal boundaries and can simulate point sources and sinks, seepage faces and moving water tables better than finite differences.

3.1.4 Uses for models

Regional models

Numerical models on a regional scale (10s to 1000s of kilometres) are used to help with the management of an aquifer's resources. In general they are two-dimensional models with a fairly coarse grid spacing. Regional models usually overcome the problem of defining realistic boundaries by extending to the geographical extremities of the aquifer. The assumption of two-dimensional flow is a reasonable one at this scale as the vertical extent of the aquifer is orders of magnitude smaller than the horizontal extent. The aquifer properties that are required as input data for regional models are average values over large areas. Calibration is usually carried out by comparing model output with water level hydrographs and, where appropriate, river flow hydrographs.

Near well simulations

For the investigation of aquifer behaviour in the vicinity of pumping wells, radial flow models are generally employed. The assumption is that in the vicinity of the well the regional behaviour of the groundwater has little effect compared to the effect of the pumping. Boundary conditions for these models generally consist of constant head or constant flow boundaries. The constant flow option, where available, is preferable as this can be set at the pumping rate of the borehole under investigation.

The processes that can be investigated with these models are those associated with the effect of the borehole on the aquifer. Skin effects, gravel packs and changes in hydraulic conductivity due to, for example, acidisation can all be incorporated into a radial flow model. The model output is usually used to interpret pumping tests during which water level measurements have been made in the pumping well.

Predictive

Models are often used for predicting the effect of future changes on the aquifer system. This may be for management purposes or for protection of water resources. The models used for resource management will generally be regional, transient models. It is important that the effects of uncertainty are considered when predictions are made on the basis of model output. The uncertainties which should be considered exist in all the parameters, apart from geographical ones, which are required for the model. It is often helpful to perform a series of model runs using a variety of possible values for the most influential parameters. This is usually referred to as a Monte Carlo simulation.

Contaminant transport

Numerical models can be used in two ways in problems of pollutant transport. The first is to use the model to determine the value of dispersion coefficients for an aquifer where data for pollutant concentration are known. A second use is to predict possible pathways for pollutants should a spill or leak occur. Naturally, if a model is to be used for prediction, values for the dispersion coefficients must be specified. This sort of use of a model lends itself well to the use of Monte Carlo simulations.

Protection zone delineation

The delineation of protection zones can be accomplished using contaminant transport models. However, the necessary dispersion coefficients are generally not known and so the accepted practice is to use a basic flow model with 'particle tracking' to define the boundaries of protection zones. This method involves calculating the path that a particle would follow through the gridded head values calculated by the flow model. The particles can be tracked up or down gradient to delineate the source of water abstracted at a borehole or the possible area that could be polluted in case of a spill. These models do not include any dispersion of the particles and so the results must be treated cautiously.

3.2 DATA REQUIREMENTS

3.2.1 Introduction

Setting up and running a model requires a large amount of data. The advantages that numerical models have over analytical models are that they allow for spatial and temporal variations in many parameters. The disadvantage is that values for these parameters must be specified by the modeller. Most of the parameters listed below must be defined for every element of a numerical model. This leads to a massive data requirement as even a small model of 20 km $\times$ 20 km will contain 400 elements if the grid spacing is 1 km. Generally the area modelled will be divided into smaller regions which are allocated the same values, but this in itself leads to a loss of the flexibility which one of a model's advantages.

The construction of a model is often an iterative procedure. It is unusual for all the parameters required for a model to be well quantified at the start of the procedure and for a model to reproduce reality at the first attempt. The development of a useful and usable model involves a fair amount of fine-tuning of the data in order to achieve the desired results.

In this section the different parameters required to construct a model will be discussed and an indication given of the possible sources of these data, and the complexity of acquiring the data. The Aquifer Properties Database includes values for only a few of the parameters required for modelling. The relationship between the available data and the model requirements for these parameters is discussed in more detail in Section 3.3.

3.2.2 Boundaries

All models require boundaries. Without these the equations describing flow in porous media cannot be solved. For resources modelling it is sufficient to ensure that the boundaries are far enough removed from the area of interest in the model that they do not significantly affect the solution. This is not true for protection zone modelling. Particle tracking routines track the water back to a no-flow boundary, or to the edge of the modelled area. Thus the position chosen for the boundaries is important. In particular, if many no-flow boundaries are used, a small change in head distribution near the boundaries can dramatically affect the shape of the resultant protection zone.

The area to be modelled must be completely surrounded by boundaries. The positioning and type of these boundaries will generally depend on the size and use proposed for the model. There are three types of boundaries that can be used in models, although some models only allow two types. The options are specified head boundaries (also known as Dirichlet conditions), specified flow boundaries (or Neumann conditions) and head dependant flow boundaries (Cauchy or mixed boundary conditions).

Often a groundwater divide is regarded as a boundary for modelling purposes. This does not represent a physical property of the aquifer and is non-permanent (being subject to changes in recharge and abstraction). Another type of no-flow boundary is encountered where a (probably thin) aquifer is faulted. This is a permanent feature. However, it may not even represent a significant change in permeability in the aquifer, just a change in level (stratigraphy).

Models normally allow upper and lower boundaries on aquifers to be one of: no-flow, fixed flux (recharge), phreatic, or leaky. Only in the case of a leaky aquifer are there any relevant aquifer parameters: the other cases relate to relative positions of the base and top of the aquifer and of the potentiometric surface.

The boundaries used for a model will usually be derived after consideration of regional conditions including geology and hydrogeology. A hydrogeological map (where available) is a good starting point.

3.2.3 Recharge

Recharge rates are not covered in this report, but are important parameters in numerical models. A recharge rate must be specified for every node. Some models allow a rainfall figure and an evaporation rate to be specified, from which a recharge rate is calculated. The value chosen for recharge rate is very significant in a model. It is important that the uncertainties inherent in recharge estimations are understood and that the factors which can affect the spatial variation in recharge rates are known. These include changes in cover, soil types, vegetation and the existence of rain shadows caused by hills.

Use of MORECS data, and a consideration of superficial deposits provide a basis for the definition of recharge for most modelling considerations.

3.2.4 Hydraulic conductivity

Values of hydraulic conductivity, or in some cases transmissivity, must be defined for every node of a model. Transmissivity data is available in the Aquifer Properties Database and is discussed further in Section 3.3.

3.2.5 Storage parameters

Storage parameters are required for transient models, and for particle tracking routines. The range of values expected for S is smaller than that possible for K. This means that the possible range of values for a formation is smaller, and often one value is chosen for each formation. Values for storage coefficient are stored in the Aquifer Properties database and are discussed in detail in Section 3.3.

3.2.6 Transport parameters

For contaminant transport models, as opposed to particle tracking models, it is necessary to define the various parameters which affect transport. These parameters include dispersion coefficients, adsorption isotherms and decay coefficients. Dispersion coefficients are properties of the aquifer. The other parameters describe the reaction between the solute and the aquifer material, and are thus dependant on the solute of interest. These parameters, which are not covered in this report, must be defined for all nodes in a model. Values are difficult to obtain, which is why models which use these parameters are rarely used. Laboratory and field experiments can be used to give values, but often model calibrations are used to derive values for these parameters.

3.2.7 River/aquifer interactions

The interaction between rivers and aquifers is of great importance in regional hydrogeological models. In may cases, rivers are the main, natural, outflow from the aquifer. Measurements of baseflow are often compared with model estimates of river flows to calibrate the model and so it is important that the rivers are correctly represented. In most cases two parameters are required to model a river. One is related to the permeability of the river bed, and the other is the elevation of the river. Elevation data are well defined and can be easily ascertained for all nodes. The permeability parameter however is usually not well known. This parameter must be defined at all nodes which represent the river, thus increasing further the number of variables which can be changed during model calibration in order to obtain a model which adequately represents the behaviour of the aquifer.

Most models characterize the connection between groundwater and surface water as either ‘in hydraulic continuity’ or ‘leaky’. In the first case the aquifer adopts the surface water head at the points of contact. In the second, leaky, case the interaction is characterized by a ‘leakance’ parameter. Such parameters can be determined by careful head measurements but are more usually obtained by model calibration, and so can be a source of error. That parameter may vary significantly along a river.

3.2.8 Model calibration

The discussion above emphasises the number and complexity of parameter values that must be defined for a numerical model. Once these data sets are acquired and the model run it is necessary to assess whether or not the parameter set and the conceptualisation of the system can reproduce the actual performance of the aquifer.

To do this the output of the model is compared with measured data. Generally water levels from boreholes and flow in rivers are used as calibration data. The parameters in the model are varied until a good correspondence between modelled and measured data is achieved. However it must be realised that there is no unique solution to the flow equations. Very similar head patterns can be achieved with quite different combinations of input parameters. This is especially true for regional models where there are a large number of parameters which can be varied. For instance, a steady-state model with recharge as input and a water table map as calibration data, can achieve a similar output if the transmissivity is halved and the recharge rate halved.

Storage coefficient values are only required for transient models. This makes it possible to calibrate a model for the correct hydraulic conductivity using a steady-state model and a long-term average recharge value, and then use the transient response to calibrate the storage coefficients.

A model can only be said to be calibrated for the range of conditions covered by the calibration data. Thus it is important that the period modelled for calibration contains a variety of wet and dry years, with and without abstraction. The more comprehensive the calibration data available the better the confidence which can be placed in the final model.

More sophisticated calibration aims to produce reasonable parameter values as well as fitting model predictions to observations. In crude terms this is done by introducing a *penalty* into the analysis which grows as a parameter deviates further from the expected value and this penalty offsets the improvement in fit to data. The extent to which any particular parameter value is honoured in such analysis depends on the certainty of the value. In the Aquifer Properties Database, the parameters are given an index of quality, where possible, and that, in principle at least, can be turned into a weighting factor. Currently, such penalty-function analysis remains a research effort but will no doubt become built into automatic calibration options on widely used models over the next decade.

3.3 PROBLEMS TO BE CONSIDERED WHEN USING THE DATABASE

3.3.1 Transmissivity data

Quality

As described in the previous chapter the present database consists of a number of related tables which contain a variety of information about sites which have been tested. The transmissivity data has been obtained from pumping tests which have been analysed by a variety of different methods, and which have lasted for differing lengths of time (see Section 2.2.2). Because of this, where feasible, the data have been allocated ratings which refer to the quality of the final result. When deciding the values to be used during a modelling exercise, the source of the data should be examined critically, as the length of the test and the existence of observation wells will give a good indication of whether the value quoted is likely to representative of a reasonable volume of aquifer.

Bias

Generally, transmissivity values are measured by the use of pumping tests. A pumping test requires the existence of a borehole and at present there is no programme of borehole drilling specifically designed to provide a good spatial network of transmissivity values. In most areas of the country, values for transmissivity available from pre-existing pumping tests are concentrated in those areas which are expected to provide usable amounts of water, i.e the most transmissive parts. Thus, it is difficult to get a good picture of the true range and variation of transmissivity values as required by a model, from measured values.

At present, there is no strategy for measuring transmissivities on a regional scale so that a sensible distribution (spatial and over the range of possible Ts) can be obtained. Model calibration would be more ‘convincing’ if the parameters used could be associated more closely with measured parameters. The reliability of models depends on the robustness of the methods of parameter estimation. Without an adequate coverage of the full range of transmissivities present in the aquifers, and without a good spatial coverage of data it is not possible to adequately describe the statistical distributions of relevance to the averaging processes. Thus it would be very useful for modellers if a programme of well drilling and testing could be developed to fill in the gaps in the existing data network.

Scaling

UPSCALING

Suppose we know (accurately) the permeability values on a grid, and we want to find appropriate permeability values on a larger (coarser) grid — this is an upscaling problem. There is a large body of mathematical work on this problem, and some results of practical importance have been obtained. For example upscaling of transmissivities should be carried out on the basis of geometric means in the absence of other information. Some caution is required however in applying these results since they are based on a series of assumptions that must be questionable for some formations. Current research emphasizes data collection and simulations to validate the results.

Numerical experimentation might help us to decide what methods are most effective (in a sense that would need to be carefully defined) for the UK aquifers. Several methods could be compared in some form of Monte Carlo study.

In general we should be seeking appropriate values of the permeability tensor (4 values in the horizontal) and not just two: this is probably impractical except at a few experimental sites. Any method of upscaling should be possible to apply in a self-consistent way. For example, if applied to 4 neighbouring nodes to obtain an average and then again to 4 of those nodes then the result should be the same as if the method were applied to the original 16 nodes involved (assuming the method has that flexibility).

DOWNSCALING

In performing the opposite process from the above — moving to a finer grid — given that no further information is available than the values on the coarser grid, there are several approaches. The fine grid values could be set equal to those of the coarser grid at the same location. They could also be found by geometric interpolation, using methods such as those used in contouring packages. They could be found by geostatistical methods (preferably based on original data), provided enough data were available to establish the correlation structure.

It should be recognised that parameter uncertainty should increase as grid size decreases.

Model compatibility

Suppose, for example, a transmissivity has been determined from a leaky-aquifer analysis. If that value is used in a model that does not include leakage, a question arises as to the applicability of the derived parameters. However, it may be that consistency is best achieved using a test analysis model that differs from the aquifer model. This arises because the time scales of pumping tests and aquifer simulation are likely to be significantly different. So the pumping test model must account for short-term effects which do not exhibit themselves during aquifer simulation.

Most models require values of hydraulic conductivity rather than transmissivity, although transmissivity is the more often measured parameter. This conversion from T to K involves the use of an aquifer thickness. This may be the full aquifer thickness, the thickness penetrated by the pumping well, the length of screened or open interval in a pumping well or some other depth thought to be supplying the water.

Averaging

A regional model may have a spatial mesh of the order of kilometres. Within a single ‘block’ of the model several pumping tests may have been performed and might have produced quite different results. What value — what average — should then be used in the numerical model?

The averaging of permeability values is a complex problem. A pumping test gives a value which is an average for radial flow around the pumped borehole. Regional flow models require values which are averages for linear flow under low head gradients. The average used may also depend on the grid size chosen, and the problem of up-scaling or down-scaling averaged values to different sized grid squares has been discussed above.

In general, given the low density of measured data points (see Table 2.2.1), averaging is not a problem for most modelling exercises. However the geostatistical methods described below do provide the capability for producing permeability values for ‘blocks’.

Interpolation

A problem that is more likely to be encountered is that of interpolation — estimating the permeability of an area where there are no measured values.

It is well accepted that aquifer materials are heterogeneous on a variety of scales and that this heterogeneity should be reflected in the values used in numerical models. However, as the true spatial variations in these parameters are not known it is necessary to develop ideas on why the parameters vary and to devise 'rules-of-thumb' to aid the modeller with the choice of the values to be used.

In the chapters of this report which refer to the various different aquifer materials found in the UK, suggestions are given as to the geological controls on aquifer parameters. In some aquifers there may also be geographical controls, e.g. differences between valley floors and interfluves. These controls will help the modeller when it comes to assigning parameter values to the, potentially, hundreds of nodes within the model.

Specialised interpolation techniques have been developed for use with numerical models. These techniques allow interpolation between measured values, based on statistical and spatial data known about the parameter. The commonest form of interpolation is drawing contours, but this does not use all the spatial data inherent within the data set. A technique used more widely within the geological community is kriging, which gives a *best linear unbiased estimate* of the spatial variation of the parameter. Programs are available for created kriged data sets from measured data which can be used as model input. Kriged estimates can be point values, comparable with those obtained from a small scale pumping test, or block values. These latter should be used for modelling as they give a value which is an average over the block, whose size has been specified.

When two or more variables are correlated then estimates of the variables can be made using all measured values together using *co-kriging* analysis. An obvious application is to use transmissivity and well specific capacity data together (e.g. Ahmed and de Marsily, 1987). It should also be worth considering the combined use of topographic and water-table depth data to improve transmissivity values (especially in the Chalk).

When working with transmissivities it is better to work with the logarithm of measured values than with the transmissivity values. There are two related reasons for this: (i) distributions of transmissivity often appear to be log-normally distributed, and (ii) when averaging over a mesh the resulting estimate represents a geometric mean which is considered for theoretical reasons to be the optimal estimate for the average given uniform flow conditions.

3.3.2 Storage parameters

The assignment of storage coefficients to models is fraught with the same difficulties as the assignment of hydraulic conductivity values. There are fewer measurements of S and the localities where reliable estimates exist are even more biased towards 'good' aquifers. (This is because a reliable S value from a pumping test requires the use of observation well data. Observation wells are generally only drilled in areas where the groundwater resource is expected to be good.)

In general, as storage parameters are scalar quantities, as opposed to permeability which is a tensor, the problems of averaging and scaling are not as complex. However storage parameters have their own problems, the most obvious of which is which of the many 'types' of porosity should be used.

The groundwater protection zone delineation is based on travel time to a source. In modelling, travel time is the ratio of flow velocity to distance. Transmissivity and head gradient give the *darcian* velocity and the flow velocity is this value divided by the *kinematic (or dynamic)* porosity. Kinematic porosity may be determined from tracer testing or model calibration but such determinations are rarely available. Therefore, specific yield has been used in the GPZ programme as a surrogate for this porosity.

It remains for the relationship between specific yield and kinematic porosity to be investigated. This gap in knowledge and understanding will to some extent be addressed by a recent initiative between BGS and the Agency, which aims to increase the use of tracer testing by providing a manual of practise and a protocol. However, it will be some years before a significant body of tracer test results is accumulated.

Where pumping tests are carried out in confined aquifers, no specific yield parameter is revealed. Therefore, over large aquifer areas the kinematic porosity must be inferred or extrapolated from values in neighbouring unconfined areas. How best those values are approximated needs careful consideration.

Kinematic porosity can differ significantly from total porosity and can also be directional. Both departures will be especially pronounced in fractured porous media.

3.4 POTENTIAL FOR THE FUTURE

3.4.1 Introduction

The database which underpins this report provides a starting point for the development of a more comprehensive, and thus more useful tool. As has been described in the previous chapter and above, the database is limited by the quality of the data that is available for inclusion. The construction of the present database has emphasised the variable (and often poor) quality of the data available and should provide a catalyst for the effort to acquire better data. The use of the present database is severely limited by the quality of the data available, and the best use that can presently be made of it is incorporated in the following chapters of this report. This takes the form of describing the data and attempting to explain its variability in terms of known variations in geology, topography and geomorphology.

However, it is worth spending some time on consideration of what would be possible if better data — both in terms of reliability and geographical spread — were available. A database which contained sufficient data to enable averages to be produced automatically could be used for a variety of purposes, some of which are listed below.

3.4.2 Scientific exploitation of the data

Probably the most fruitful use of the database in its present form will be in establishing correlations between parameters and geological factors.

To be more specific, the following activities, amongst others, should be considered:

(a) Attempts to determine the geostatistical correlation structure of parameters for different formations, in the form of variograms.

(b) Simple correlation of porosity with storage parameters; for example, to check on and improve the results of Younger (1993).

(c) Correlation of well specific yields with transmissivities (using geostatistics for interpolation).

(d) Correlation of specific yields and transmissivities with topography (and other quantifiable geographical factors) — following on from the work of Monkhouse (1984 and 1986).

(e) Correlation of specific yield with depth to water table.

(f) Factor analysis to distinguish physically distinct rock types.

The effect of different methods of averaging transmissivity data should also be investigated. The relationship between pumping test values and those required for models needs to be well understood before a comprehensive testing programme is undertaken. The problem of scaling from one grid size to another is also important in modelling. This is especially true if regional models on a large scale have been developed and the expertise and knowledge invested in them is to be used for a local model.

3.4.3 Use in hydrogeological mapping

Hydrogeological maps show, most importantly, head contours. These are normally constructed on the basis of water-level data by an experienced hydrogeologist, sometimes with the aid of a contouring package. Contouring packages interpolate on limited data and produce a continuous map on as fine a grid as is required. However, there is no reason for any standard interpolation method to be consistent with head variations as generated by groundwater flow.

In principle, a good groundwater model of a region would be capable of producing an excellent map of the potentiometric surface. Such models would use all available data in a calibration process (e.g. boundary effects, recharge variations, and the influences of pumping) and thus emulate in an objective manner the actions of a hydrogeologist drawing, by hand, a contour map of head.

It would not be unreasonable to ask that a future Aquifer Properties Database should include all of the information necessary to accurately construct a groundwater contour map.

3.4.4 Use in Support Systems

Introduction

As more data become available on databases, hydrogeologists increasingly find themselves in the position of having to make decisions which require inputs both from experts (from different disciplines), and from various databases (and possibly the analysis of those inputs). Almost by definition, it can be concluded that there is a growing need within hydrogeology for 'support systems'. Currently such systems are considered to fall into categories of Decision Support Systems, Expert Systems, and Geographical Information Systems, although the distinctions between these are often unclear.

Use in Decision Support Systems

A Decision Support System (DSS) is an interactive computer-based system that helps a decision maker to utilize data and models in the solution of unstructured problems. Such systems have been in use in a variety of fields for more than a decade and there has recently been a growing interest in their potential importance in environmental situations. Unstructured problems may be caused, for example, by lack of data or knowledge or by variables that are not quantified or by excessive complexity: all of these are typical in environmental problems.

The most obvious use of the Aquifer Properties Database in a DSS is as part of the database. However, this report contains not just, or even primarily, numbers but also knowledge about aquifers. This knowledge could be incorporated in the knowledge base of a DSS. One easy way to do this would be to include the text of this report in hypertext form.

Other uses of the data can be envisaged, for example, simple statistical analysis of the data might be used to form rules of thumb, also to be incorporated in a knowledge base.

Use in Expert Systems

Jackson (1991) defines an Expert System as: a computer program that represents and reasons with knowledge of some specialist subject with a view to solving problems or giving advice. Ahmad and Griffin (1991) give a similarly restricted definition: a computer program that uses knowledge and reasoning techniques to solve problems normally requiring the abilities of human experts.

DSS are less ambitious than Expert Systems in that they do not attempt to replace, only aid, the human decision maker; but more ambitious in that they aim to tackle problems with a dynamic element, which requires the use of models.

Use in Geographical Information Systems (GIS)

A GIS is a database management system which can deal with features that would normally be found on a map: points, lines, polygons and so on. The procedures in a GIS answer queries about these features. Naturally, most data in a GIS are indexed spatially. Currently, most GIS systems are currently restricted to a two-dimensional representation.

A term less frequently used than GIS is GSIS, which stands for Geoscientific Information System. Rather boldly, Turner (1989) suggested that (all) hydrogeological analysis should be considered to consist of four modules:

(i) subsurface characterization

(ii) three-dimensional GSIS (Geoscientific Information Systems)

(iii) statistical evaluation and sensitivity analysis

(iv) groundwater flow and contaminant transport modelling

This implicitly extends the functionality of GIS to all geoscientific data and also puts the GSIS in an important position.

In principle, all of the Aquifer Properties Database data, being associated with a point in space, could be accessed through a GIS or GSIS. The data will inevitably be used in that way, probably in a variety of different systems. No special attention would appear necessary in terms of such use other than to decide what processing of raw data (e.g. averaging over an area) might best be built into the database and which might best be handled at the GIS level.

3.4.5 Genetic modelling

It is obvious that aquifer properties are determined by the geological and geochemical histories of the aquifer rocks. If the processes determining the hydrogeological properties were well understood and the genetic history of the aquifer known, the aquifer properties could be predicted. This approach, in essence, is what has been attempted manually in the rest of the report — trying to relate measured values to geological and geomorphological features.

In the future however, we could consider the possibility of having models not of groundwater flow and transport but of the actual laying down and development of aquifer rocks. Such genetic modelling is already being undertaken and can at least generate possible distributions of aquifer material and hence aquifer properties. The work tends to be stochastic, it produces possible rather than probable distributions. But even that capability is of value to hydrogeologists who are more often than before using techniques — normally geostatistical — to evaluate uncertainty in groundwater modelling.

Even without genetic models, some useful information might even now be obtained from our limited knowledge. For example, transmissivity in the Chalk is controlled by the distribution of fractures. The occurrence and nature of fracturing in the Chalk is known to be enhanced under certain conditions (e.g. in the vicinity of the Palaeogene and close to the water table). If those conditions can be quantified in some manner, then prediction or interpolation of transmissivity values can be enhanced.

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4 The Chalk

4.1 OVERVIEW OF THE CHALK AQUIFER

4.1.1 Introduction

The Chalk is the most important aquifer within Great Britain. It accounts for more than half of the groundwater used in the country (53% in 1977, Monkhouse and Richards, 1982) and 18% of the total water used in England and Wales (Water Authorities Association, 1986). The importance of the Chalk as an aquifer is primarily due to its occurrence in the south of England, where population density is high, rainfall is low and there are few sites for suitable surface reservoirs. The Chalk also has a large outcrop area, over 21 500 km^2, more than all the other major aquifers added together (see Figure 4.1.1).

The hydraulic properties of the Chalk are complex and result from a combination of matrix and fracture properties. Groundwater flow in the saturated zone is primarily through fractures and as a consequence can be rapid; usable groundwater storage comprises storage within macro and micro fractures and also a little from within the matrix. Recharge through the unsaturated zone can occur very rapidly through fractures or slowly within the matrix.

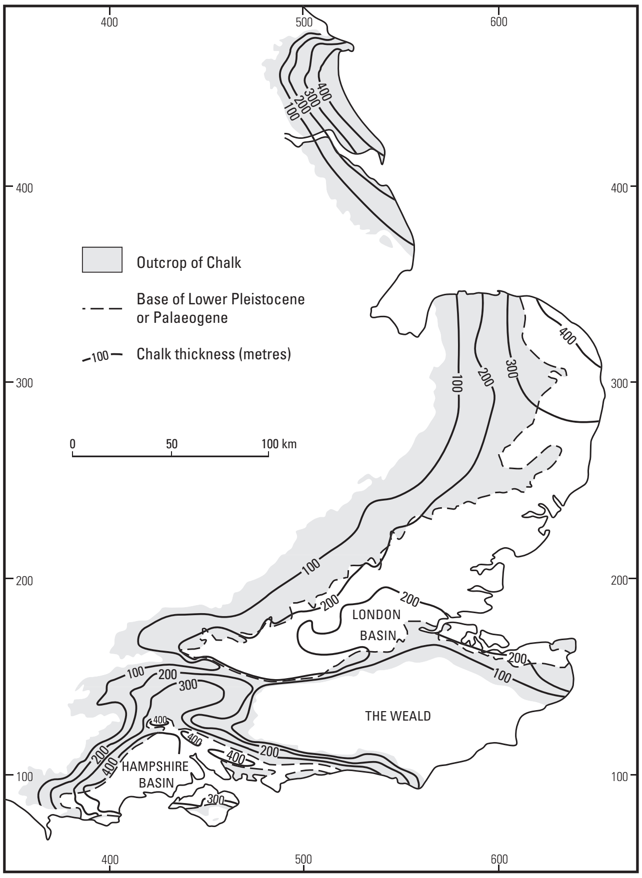


Figure 4.1.1 Outcrop and thickness of the Chalk in England (after Whittaker, 1985).

These attributes make the Chalk vulnerable to contamination. Contaminants are transported very quickly once they reach the water table; within the unsaturated zone, contamination may either build up slowly, over many years or, in some locations, occur almost instantaneously allowing very little time for remediation.

Within this section the Chalk aquifer is briefly described with particular attention to the flow mechanisms and development of its aquifer properties. An extensive bibliography is included to help the reader pursue particular aspects of Chalk aquifer behaviour. The section also includes a brief description of the Upper Greensand.

4.1.2 Introduction to the geology and stratigraphy of the Chalk

Lithology

Towards the end of Lower Cretaceous time a marine transgression flooded southern England. Sea levels subsequently rose through the Upper Cretaceous reaching a maximum in the late Campanian, when probably only parts of the Welsh massif remained above sea level (Rawson, 1992). As the sea level rose, the shrinking land mass supplied decreasing amounts of terrigenous material; instead a soft white ooze was deposited, formed from the skeletal plates of microscopic planktonic algae and shell fragments. This subsequently became the limestone known as chalk.

In general the Chalk (the term 'Chalk' is used when referring to the Chalk Group (i.e. in a stratigraphic sense) while 'chalk' refers to the material) is a very fine-grained (less than 10 μm), pure (c. 98% $CaCO_3$), soft, white limestone containing some marl bands and flint (Hancock, 1975). The algal skeletal fragments which form so much of the Chalk have three components (Hancock, 1993). The largest are 'coccospheres' with diameters of 10–20 μm. These commonly break down on the death of the algae to component rings or coccoliths with diameters of 1–20 μm. Each coccolith is composed of numerous tablet-shaped calcite crystals (often called laths) with diameters typically around 0.5–1 μm. Complete coccospheres are rare in the English Chalk. In addition to the algal debris the Chalk contains a coarse fraction (10–100 μm) which includes foraminifers, ostracods, bryozoans, echinoid plates and bivalve fragments (Hancock, 1975; Rawson, 1992).

Marl bands occur within the Chalk. They are up to several centimetres thick, some of them being laterally continuous for several hundreds of kilometres. Many were deposited on erosional surfaces and are thought to be of volcanic origin as they contain Mg-rich smectite (Pacey, 1984; Hancock, 1993).

Flint occurs predominately in layers parallel to bedding, either in tabular layers or as scattered discrete nodules (Mortimore and Wood, 1986). Locally it forms cross-cutting veins and vertical cylinders with a burrow at the core. The origin of flint is still debated but it is generally thought to be biogenic, forming soon after the deposition of the Chalk in several diagenetic stages (Hancock, 1975; Rawson, 1992).

Stratigraphy

The Chalk Group in England and Wales was deposited in two lithological and faunal provinces, generally ascribed to a northern and southern province. For convenience, East Anglia is here included in the southern province. The chalks of the northern province tend to be harder than their southern equivalents as a result of two phases of calcite cementation; tabular flints occur in parts of the sequence. In the southern province, by comparison, the chalks are generally softer, hardgrounds are common and continuous tabular flints are rare (Rawson, 1992).

In East Anglia and the northern province the thickness varies from 100 m near to the western outcrops to over 400 m at the coast (Figure 4.1.1). In southern England the Chalk is generally between 200 and 400 m thick, with less remaining in the London area. Table 4.1.1 illustrates typical remaining thicknesses of the Chalk subdivisions across England. There has been a long-established practice of dividing the Chalk Group into Lower, Middle and Upper Chalk based partly on lithological criteria and partly on biostratigraphy. This has proven problematic partly because some of the fossil zones are poorly defined or not present in the northern province; indeed, the boundaries between Upper, Middle and Lower Chalk may even have been drawn at different levels in the two provinces (Rawson, 1992). Recent work (Wood and Smith, 1978; Mortimore, 1986; Robinson, 1986; Rawson, 1992; Bristow, Mortimore and Wood, in press) has concentrated on providing lithostratigraphic subdivisions of the Chalk often using the widespread marl and flint bands. Tables 4.1.2 and 4.1.3 show the current lithostratigraphical units and their general relation to the old divisions. Since much of the hydrogeological data collected is tied to the old classification system), and because of the general familiarity of hydrogeologists with the traditional Upper, Middle and Lower subdivisions (particularly in the southern province) it is appropriate to use them here, despite the problems in correlation that they pose.

Table 4.1.1 Typical thickness of Chalk subdivisions across England (after Rawson et al., 1978).

	Upper Chalk	Middle Chalk	Lower Chalk
Dorset	up to 260 m	26–41 m	22–57 m
Hampshire	up to 400 m	43 m	up to 100 m
Sussex	up to 230 m	65–90 m	approx 60 m
Kent	up to 130 m	60–80 m	60–80 m
Chilterns	up to 125 m	58–76 m	50–60 m
North Norfolk	approx 320 m	46 m	18–41 m
Yorkshire	up to 300 m	approx 112 m	23–40 m

In the southern province the Lower Chalk is virtually devoid of flints but contains a high proportion of terrigenous sediment. It consists of a marly chalk, with the marl content decreasing upwards. In most areas within the southern province, the base is represented by up to 5 m of marly, glauconitic chalk with phosphatic nodules (Glauconitic Marl). In East Anglia, the Lower Chalk includes at its base the Cambridge Greensand, a thin bed of glauconitic sandy marl rich in phosphate nodules. The Lower Chalk has been divided into two lithological units: the Chalk Marls (interbedded chalk and marl) and the overlying, more massive Grey Chalk. Between East Anglia and the Berkshire–Chilterns shelf they are separated by the Totternhoe Stone, a brownish gritty chalk with phosphatic pebbles. Further south, the Totternhoe Stone disappears and it

Table 4.1.2 Current lithostratigraphic units for the Chalk in the southern province and their general relation to previous nomenclature.

<table>
<tr><th>Formation name</th><th colspan="2">Wessex and Sussex lithostratigraphy</th><th>North Downs lithostratigraphy</th><th colspan="2">Widespread hydrogeological nomenclature</th></tr>
<tr><td rowspan="6">UPPER CHALK</td><td rowspan="8">Sussex White Chalk Formation</td><td>Portsdown Chalk</td><td rowspan="3"></td><td rowspan="5" colspan="2"></td></tr>
<tr><td>Spetisbury Chalk</td></tr>
<tr><td>Tarrant Chalk</td></tr>
<tr><td>Newhaven Chalk</td><td>Margate Chalk</td></tr>
<tr><td>Seaford Chalk</td><td>Seaford Chalk</td></tr>
<tr><td>Lewes Nodular Chalk</td><td>Lewes Nodular Chalk</td><td colspan="2" rowspan="2">Top Rock
Chalk Rock</td></tr>
<tr><td rowspan="2">MIDDLE CHALK</td><td>New Pit Chalk</td><td>New Pit Chalk</td></tr>
<tr><td>Holywell Nodular Chalk</td><td>Holywell Chalk</td><td colspan="2">Melbourn Rock</td></tr>
<tr><td rowspan="2">LOWER CHALK</td><td colspan="2">Zig Zag Chalk</td><td rowspan="2">Lower Chalk: Plenus Marls
Grey Chalk
Chalk Marl
Glauconitic Marl</td><td colspan="2">Plenus Marls
Grey Chalk
Totternhoe Stone</td></tr>
<tr><td colspan="2">West Melbury Marly Chalk</td><td>Chalk Marl
Glauconitic Marl</td><td>Cambridge Greensand</td></tr>
</table>

Table 4.1.3 Current lithostratigraphic units for the Chalk in the northern province and their general relation to previous nomenclature.

NORTHERN PROVINCE	
Lithological unit	Name
Flamborough Formation 300+ m	Upper Chalk
Burnham Formation 150 m	
Welton Formation 53 m	Middle Chalk
Ferribly Formation 28 m	Lower Chalk

becomes difficult to draw a boundary between the Chalk Marls and Grey Chalk. In southern England the Lower Chalk has been divided into the West Melbury Marly Chalk and Zig Zag Chalk members. The top of the Lower Chalk is defined by the Plenus Marls, a thin sequence of alternating chalk and marl which form a distinctive lithological marker.

The Plenus Marls are overlain by the Middle Chalk which is generally flintless and is divided into the Holywell Nodular Chalk below, overlain by the New Pit Chalk of the new classification. At the base of the Middle Chalk the Melbourn Rock consists of nodular marls and hardgrounds. Locally, flints first appear regularly towards the top of the Middle Chalk, but become much more common at the base of the Lewes Nodular Chalk (see Table 4.1.2). This member is characteristically a nodular chalk which consists of rhythmic units, each of soft chalk locally with a marl band at the base, passing up into nodular chalk and terminating with a hardground. At the base of the Lewes Nodular Chalk, at the western end of the Wessex basin in the Chilterns, Kent and East Anglia areas is the Chalk Rock whose base also defines the boundary between Middle and Upper Chalk. The Chalk Rock consists of hard nodular chalk, with large flints, but it is not well developed in Sussex, where it is replaced by coarse, gritty, nodular chalks. Overlying the Lewes Nodular Chalk are predominantly soft white chalks with numerous flint bands.

The Chalk Group of the northern province was divided on lithological grounds into four formations in Yorkshire and Humberside by Wood and Smith (1978). These can be traced southward through Lincolnshire into north Norfolk (Rawson 1992). The basal Ferriby Chalk Formation is a slightly marly, whitish chalk with finely disseminated iron and has no flints. The overlying Welton Chalk Formation consists mainly of thickly bedded massive chalk with flint nodules. Its base is defined by a pebble strewn erosion surface which is overlain by a distinctive marker band of variegated, occasionally laminated marls known as the Black Band. The succeeding Burnham Chalk Formation is thinly-bedded with layers of laminated chalk, with distinctive tabular and semi-tabular flints in the lower part. The uppermost Flamborough Chalk Formation consists of well-bedded flintless chalk with stylolitic surfaces and marl partings (Rawson, 1992).

Tectonic history of the Chalk

In north-west Europe the Chalk was deposited in three tectonic settings: (1) above and against massifs of Palaeozoic and older rocks; (2) in basins between massifs; and (3) in fault-bounded troughs within basins (Hancock, 1993). In England, deposition occurred over the London–Brabant massif (in East Anglia), the London–Paris basin in the south, and in part of the complex of basins known as the Southern North Sea and North German area to the north. About 400 to 500 m of Chalk was deposited in the basins, and locally possibly more than 2 km.

Two principal periods of tectonic activity affected the Chalk. The first, in Late Cretaceous time influenced the deposition and the second, during early Oligocene to early Miocene time led to gentle folding and faulting (Hancock, 1993). Late Cretaceous and early Palaeogene tectonic inversions, associated with the opening of the North Atlantic, uplifted areas of the Chalk and caused widespread erosion (Downing et al., 1993). Minor erosional episodes during chalk deposition are thought to be associated with the formation of hardgrounds, channels and glauconitic and phosphatic cements. Alpine tectonics of Oligocene–Miocene age resulted in compressional movement south of a line from the Mendips to the Thames Estuary line, which deformed the Chalk into monoclinal and periclinal folds, induced by the reactivation of pre-Permian basement faults (Dunning, 1992). North of this line, the Chalk generally has a dip to the east, and has been flexed, domed, tilted and fractured probably by the late Cretaceous tectonics.

Three basic types of fracture can be recognised in the Chalk, faults, bedding plane fractures and joints (Bloomfield, 1996). Tectonic movements were responsible for the formation of faults in the Chalk and controlled the orientation of joint sets. Faults are difficult to identify in the Chalk, because of the lack of lithological contrast, and may be more common in the Chalk than previously thought. Joints generally form in three mutually perpendicular orientations: one parallel to bedding and two orthogonal sets perpendicular to the bedding plane. The stress regime initiated in the early Palaeogene generally produced NW–SE and NE–SW joint sets and fault orientations. In addition, in southern England a series of east–west flexures and fractures developed in Oligocene–Miocene time.

Diagenetic history

After the initial formation of the chalk ooze, porosity may have been as high as 80% (Downing et al., 1993). Cementation occurred in two phases, (1) soon after the sediments were deposited on the sea floor and (2) during deep burial (Scholle, 1977). Early diagenesis involved cementation caused by circulation of seawater through the upper few metres of sediment. Horizons of sea floor cementation are known as 'hardgrounds' in which porosity is reduced to 10–20% and the chalk tends to be hard and brittle. The formation of hardgrounds is associated with a reduction or cessation in supply of coccoliths. If the ooze surface was exposed long enough on the sea floor the hardground could have become phosphatized or glauconized (Hancock, 1993). Otherwise, compaction by overburden would have occurred giving porosity of 35–50% at about 250 m, reducing to 30–40% at depths of up to 1000 m. This compaction occurred by the mechanical re-organisation of the constituent grains. A second compaction mechanism, chemical or pressure solution compaction occurred below 30–40%. Pressure solution compaction was strongly dependent on the chemistry of the pore waters. If the pore water was essentially saline, large overburdens (1500–2000 m) would have been required to reduce the porosity to 15–20%, but if the pores had been flushed with relatively fresh water a similar degree of porosity reduction could be achieved with only 300–500 m overburden (Scholle, 1977; Hancock, 1993; Bloomfield, 1997). Diagenetic features such as stylolites have also formed in the Chalk as a result of pressure controlled dissolution and reprecipitation (e.g. Flamborough Head, Yorkshire). Such dissolution and reprecipitation are generally thought to have reduced the permeability of the Chalk (Hancock, 1993; Bloomfield, 1997), although some very fine fractures can be associated with stylolites (Foster and Milton, 1974). Tectonic diagenesis has been observed in south Dorset, where the Chalk has been hardened by folding (Mimran, 1975; Alexander, 1981).

There is some evidence that chalks are not simply the result of a gentle accumulation of debris. In some areas resedimentation has taken place in the form of slide sheets, slump deposits, turbidites, debris flows and laminated chalks (Hancock, 1993). Such reworked chalks have higher porosity than autochthonous chalk and are generally found in the North Sea Central Trough.

Palaeogene and Quaternary influences

Chalk was subaerially eroded from large areas during the late Palaeogene when a drainage system was developed towards the North Sea (Figure 4.1.2). It is probable that regional tilting has maintained this pattern to the present day (Jones, 1980; Goudie, 1990).

The Anglian glacier was probably the most extensive to affect England, reaching as far south as London and the Cotswolds about 0.5 million years ago (see Figure 4.1.3). During the Anglian glaciation the geomorphology of East Anglia was modified significantly, changing the landscape from a series of north-east sloping river terraces to a glacial terrain composed of till with a radial drainage pattern (Bowen et al., 1986). Many deep channels ('buried channels' or 'tunnel valleys') were eroded into or through the chalk and filled with sands, gravels and clay in varying proportions. The channels lying beneath present day valleys locally exceed 100 m in depth and are generally characterised by steep sides and narrow bases. The Anglian ice sheet is thought to be responsible for diverting the Thames southward from the Vale of St Albans into the present day Thames Valley (Goudie, 1990).

The most recent glacial episode occurred during the Devensian and ended about 10 000 years ago. This time the ice covered the Yorkshire and Lincolnshire Chalk and effectively removed all earlier Quaternary deposits. During this period sea levels fell to 120–150 m below present sea level.

The Chalk of southern England remained largely free of ice sheets but was significantly affected by ground ice (periglaciation). The permanently frozen sub strata was probably not seriously affected by periglacial activity. Close to the surface, however, the *active zone* underwent cycles of freezing and thawing, which has produced a weathered mantle frequently 1–2.5 m thick consisting of broken, rubbly chalk (Williams, 1987). In some places, just below the sub-soil, the Chalk is highly pulverised to 'putty chalk', which generally is structureless chalk with irregular sized blocks set in a soft to firm putty matrix. Also in the top 5–6 m of the Chalk there is an observed increase of fracturing in the Chalk due to weathering. In some valleys, periglacial activity led to fractures opening up to a depth of up to 20 or 30 m (Higginbottom and Fookes, 1970; Williams, 1987).

Solifluction deposits are extensive on the Chalk of southern England and are shown on Geological Survey

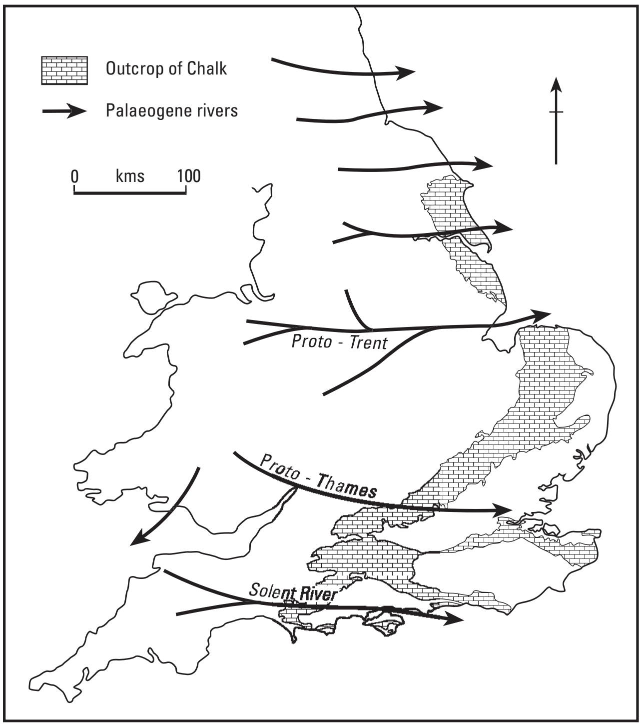


Figure 4.1.2 Presumed courses of palaeogene drainage developed on newly deposited Chalk (after Goudie, 1990).

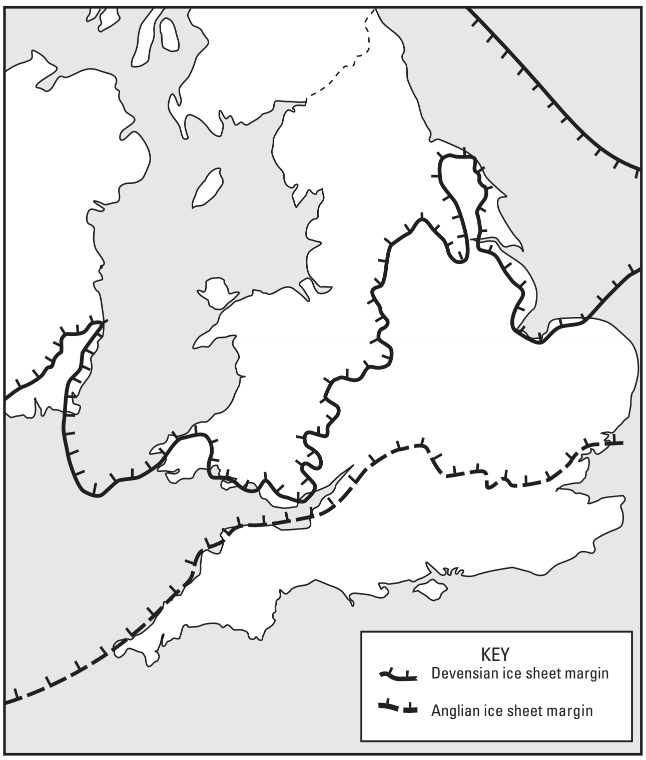


Figure 4.1.3 The limits of the Anglian and Devensian ice sheets in southern Britain (after Boulton, 1992).

maps as extensive areas of Head. It occurs at the foot of scarp slopes and is largely composed of soliflucted chalk and flints that have moved downslope due to periglacial activity. Soliflucted chalk may also occur on Chalk dip slopes. Other periglacial features observed in the Chalk are patterned, ground polygons and stripes (due to irregularities in the soil thickness), avalanche chutes and dells (steep gulleys on scarp faces, or serrated undulations on dip slope valleys), cambering and valley bulging. Loess and cover sands occur locally having been deposited by strong winds blowing across poorly vegetated tundra during cold periods.

The origin of the dry valley network of the Chalk is subject to much debate and a vast number of hypotheses have been developed to explain their origin (see Goudie [1990] for a review). The most commonly adopted theory involves periglacial activity when the cold climatic conditions reduced evapotranspiration and the permafrost layer reduced infiltration. In these circumstances, rapid melting of winter precipitation released a large volume of runoff, which easily eroded chalk that had been weakened by frost action.

4.1.3 Porosity and hydraulic conductivity characteristics of the Chalk matrix

This section reviews the porosity and hydraulic conductivity characteristics of the Chalk matrix. The physical properties of the Chalk matrix are characterised by high porosity, the high degree of interconnection of the porosity, and unusually small pore diameters and pore throat sizes. However, these characteristics show significant regional and stratigraphic variations. Trends in matrix porosity are described, as are the trends in pore size distribution. Typical hydraulic conductivity data are presented for the matrix of the Chalk, and a correlation is presented between matrix hydraulic conductivity and matrix porosity.

Variation in the porosity of the Chalk

The BGS Aquifer Properties Laboratory core analysis database contains the results of over two thousand chalk porosity tests, along with associated sample location, depth and stratigraphic information. The Chalk samples have mainly been obtained from cored boreholes, with a limited number of samples from surface exposures. Chalk samples have been tested from 75 sites in England, and there are over 40 sites with more than ten porosity measurements. Regional trends in the matrix porosity data have been described by Bloomfield et al. (1995); the following is a resumé of that work.

Figure 4.1.4 illustrates the Chalk outcrop in England and the geographical spread of the sites from which samples have been taken (sites are denoted by open circles). To enable an investigation of regional Chalk porosity trends, the data have been split into four geographical areas (see section 4.1.8). These are; (1) southern England consisting of the South Downs and Hampshire Basin, (2) the Thames Valley, including limited observations from Kent and the North Downs, (3) East Anglia, including limited observations from Cambridgeshire, and (4) northern England (observations restricted to north Humberside and North Yorkshire).

Generally, the lithological and detailed stratigraphic control on the core samples is limited, although sample depths (depth relative to ordnance datum, OD) are known. Despite this, it has been possible to assign each sample to a gross stratigraphical unit, either Lower, Middle or Upper Chalk.

Table 4.1.4 presents summary statistics for all the data and for each of the regions and the stratigraphic divisions or groupings that have been inferred to be statistically discrete. Various parameters are given: sample size (n), arithmetic mean values (mean), associated population standard deviation (s.d.), distribution skewness (sk.), and minimum (min.) and maximum (max.) values for the porosity data from each of the lithological units in each of the areas. In addition, Table 4.1.4 gives the 10 percentile (10%), 50 percentile (50%) and 90 percentile (90%) porosity values for the cumulative frequency distributions.

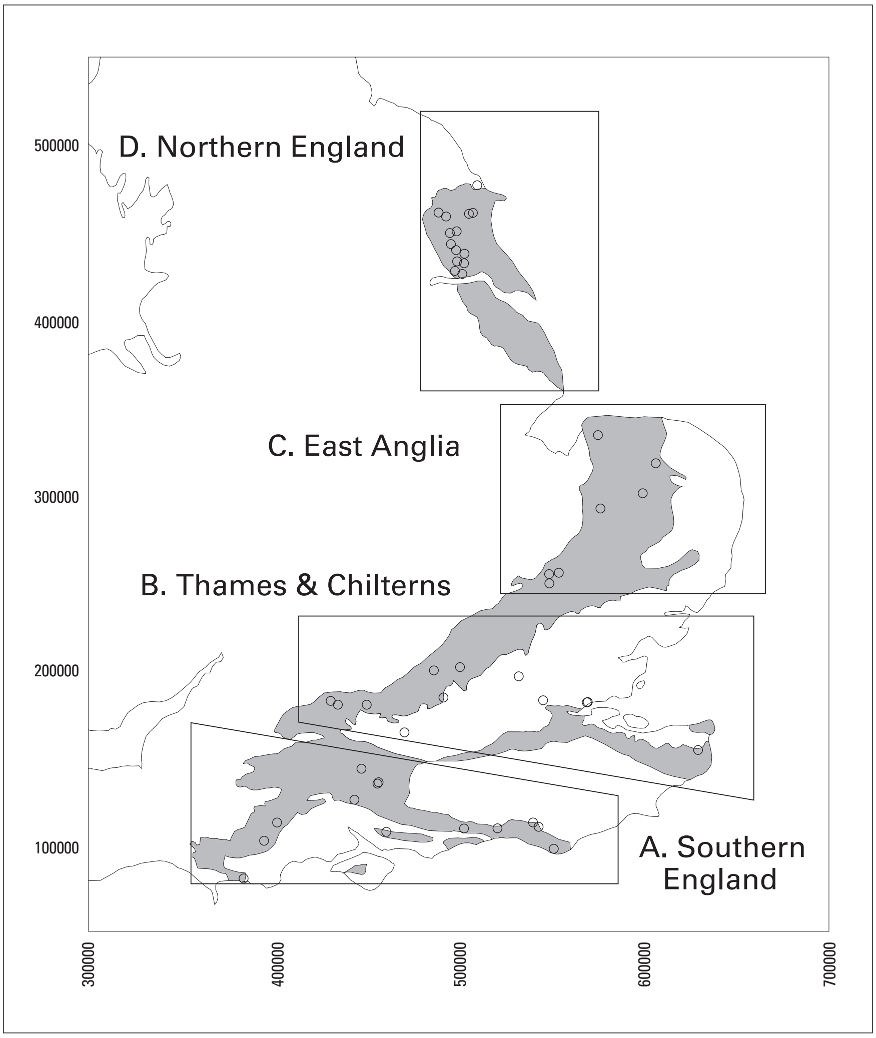


Figure 4.1.4 Geographical distribution of Chalk porosity data (after Bloomfield et al., 1995).

Table 4.1.4 Summary statistics for the Chalk matrix porosity data held on the BGS core analysis database (from Bloomfield et al., 1995).

	All regions	Northern England Upper Chalk	Northern England Middle Chalk	East Anglian Upper Chalk	East Anglian Middle & Lower Chalk	Thames & Chilterns Middle Chalk	Thames & Chilterns Lower Chalk	Southern/ T & C Upper Chalk	Southern Middle Chalk	Southern Lower Chalk
Porosity (%)										
n	2045	191	62	127	281	356	158	724	34	112
mean	34.0	35.4	18.9	38.4	34.3	31.4	26.6	38.8	28.4	22.9
s.d.	8.3	6.8	4.6	7.7	5.7	6.6	6.6	5.8	4.2	7.7
sk.	-0.61	-1.39	0.39	0.05	0.14	-0.37	-0.32	-1.45	0.06	0.53
min	3.3	3.3	6.7	24.1	18.4	9.5	11.6	5.6	20.5	9.7
max	55.5	45.3	31.4	55.5	47.8	52.6	39.5	48.9	35.9	46.5
10%	22.8	23.8	13.7	29.4	27.4	24.0	16.3	31.7	22.3	13.3
50%	35.1	38.0	18.0	37.1	33.6	31.8	27.0	39.8	28.3	22.9
90%	43.7	41.2	24.7	48.1	42.4	39.5	35.5	44.7	35.0	34.2
Dry Density (kg/m^3)										
n	2003	149	62	127	281	356	158	724	34	112
mean	1790	1780	2190	1670	1770	1850	1970	1650	1910	2080
s.d.	220	190	120	210	150	180	160	150	100	200
sk.	0.56	1.05	-0.59	-0.08	-0.15	0.47	0.13	1.40	-0.33	-0.59
min	1210	1530	1850	1210	1410	1280	1640	1380	1730	1430
max	2510	2510	2430	2040	2190	2460	2330	2430	2100	2450
10%	1520	1610	2040	1390	1560	1630	1740	1500	1740	1780
50%	1760	1700	2220	1710	1800	1830	1970	1630	1920	2090
90%	2090	2080	2340	1920	1960	2050	2230	1840	2030	2330

KEY: n, number of samples; mean, arithmetic mean; s.d., population standard deviation; sk., distribution skewness; min, value of minimum observation; max, value of maximum observation; 10%, value of 10 percentile in cumulative distribution; 50%, value of 50 percentile in cumulative distribution; 90%, value of 90 percentile in cumulative distribution.

For a given region, the average Upper Chalk porosity is consistently higher than that of the Middle Chalk, e.g. the fifty percentile (median) Upper Chalk porosities are 3.5 and 20.0 porosity percent greater than the comparative Middle Chalk porosities for the East Anglian and northern England areas respectively. For a given region there is little difference between the average Upper Chalk porosities. There is only 2.7 porosity percent difference between the 50 percentile values for the combined southern England/Thames and Chilterns area, the East Anglian area and the northern England area. There appears to be no strong regional or geographical trend to the Upper Chalk porosity data.

There is, however, a distinct geographical trend in the porosity data for the Middle Chalk, with a reduction in gross porosity from East Anglia, to Thames and Chilterns, to southern England, to northern England. The mean porosity values for the Middle Chalk of the East Anglian (combined Middle and Lower Chalk), Thames and Chilterns, southern England and northern England areas are 34.3%, 31.4%, 28.4% and 18.9% respectively. The Middle Chalk of the southern England and Thames and Chilterns areas is significantly more porous than the Lower Chalk, for example Middle Chalk mean porosity values are 5.5 and 4.4 porosity percent greater than the equivalent Lower Chalk values. The statistical tests indicated that the Middle and Lower Chalk porosity distributions for the East Anglian region are similar.

The Lower Chalk exhibits similar porosity trends to those of the Middle Chalk. The mean porosity values for the Lower Chalk of the East Anglian (combined Middle and Lower Chalk), Thames and Chilterns and southern areas are 34.3%, 26.6% and 22.9% respectively.

The distribution of porosity data from the northern England area is of limited geographical extent, for example there are no data in the core analysis database from the Chalk of south Humberside and Lincolnshire, and the subsample is dominated by observations from two relatively shallow boreholes. Barker (1994) described the petrophysical properties of chalk from three boreholes in South Humberside and gave mean values for the Ferriby, Lower and Upper Welton and Burnham Chalks (equivalent to Lower, Middle and Upper Chalk respectively) as follows; Ferriby Chalk 20.6%, Lower Welton Chalk 14.8%, Upper Welton Chalk 20.5% and Burnham Chalk 29.2%. The mean porosity of the Burnham Chalk (Barker 1994) is approximately six percent less than the mean porosity for the Upper Chalk of the northern England region data (Table 4.1.4). However, the Ferriby and Welton Chalk mean porosities of Barker (1994) are consistent with the data presented in Table 4.1.4.

Pore size distribution in the Chalk

Price et al. (1976) described pore size distributions for 52 samples from the Chalk, the average of the median (d_{50}) pore throat sizes for the data was 0.49 μm. Price et al. (1976) also identified a number regional and stratigraphic trends in the Chalk pore size distributions as follows; i) they identified two distinct provinces for the Upper Chalk, a ‘Northern Province’ with mean pore size of 0.41 μm, 0.24 μm less than that of a ‘Southern Province’, ii) they showed that within a ‘province’ the Middle and Upper Chalk pore size distributions were similar, and iii) they showed that pore size distributions from the Lower Chalk generally exhibited a greater range of pore sizes and smaller average pore sizes than the corresponding Middle and Upper Chalk distributions. Table 4.1.5 presents the summary results of Price et al. (1976).

Figure 4.1.5 illustrates 11 typical pore throat size distributions for the Chalk of Southern England. The data are for

Table 4.1.5 Summary of Chalk pore-size data (after Price et al., 1976).

	Number of samples	Median pore size (μm)	
		mean	sd
Chalk	52	0.49	0.2
Upper Chalk Southern Province	21	0.65	0.14
Upper Chalk Northern Province	7	0.41	0.08
Middle Chalk Southern Province	8	0.53	0.14
Middle Chalk Northern Province	8	0.39	0.08
Lower Chalk	8	0.22	0.11

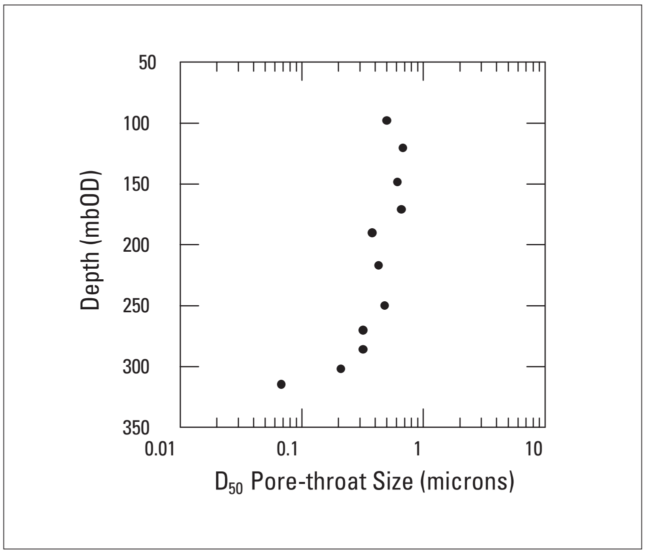


Figure 4.1.6 Distribution of dominant pore throat sizes (d_{50}) with depth in the Fair Cross borehole, Berkshire.

samples from the Faircross borehole, Hampshire. Median pore throat sizes are in the range 0.7 μm to 0.07 μm and exhibit an absolute range of approximately 10 μm to 0.01 μm. The d_{50} values from Figure 4.1.5 when plotted against depth, see Figure 4.1.6, illustrate the typical trend of a reduction in average pore throat size with burial depth.

Chalk matrix hydraulic conductivity

Figure 4.1.7 illustrates the distribution of hydraulic conductivity values derived from horizontal core permeability measurements performed on chalk samples. The distribution, based on 977 gas permeability measurements approximates to a lognormal distribution with a geometric mean of 6.3×10^{-4} m/d. Figure 4.1.8 illustrates the correlation between matrix porosity and matrix hydraulic conductivity for the same data. There is a general correlation between bulk matrix porosity and hydraulic conductivity and a linear regression to the data has the following form:

$$\log_{10} K\ (\text{m/d}) = 0.0654 \times \phi\ (\%) - 5.3378$$

The regression has an r^2 error of 0.651. A correlation between some function of the matrix pore size distribution and hydraulic conductivity is likely to be more significant, however such a correlation has yet to be established for the Chalk matrix.

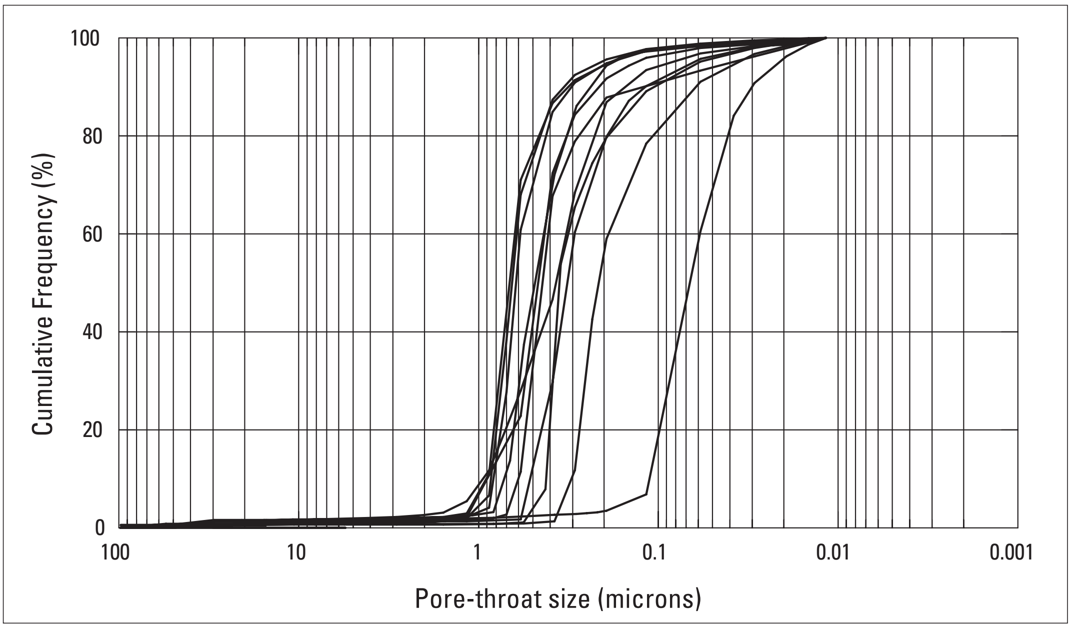
The average hydraulic conductivity of 6.3×10^{-4} m/day is extremely low, and it can be inferred that the hydraulic conductivity of the Chalk matrix is negligible with respect to the hydraulic conductivity of chalk fracture systems.

4.1.4 Groundwater flow and storage in the Chalk

Introduction

If Chalk permeability and specific yield relied solely on intergranular behaviour then it would not be considered to be an aquifer: intergranular permeability is very low and the porosity, although high, does not drain under gravity. It is the presence of fractures (the term ‘fracture’ is used throughout rather than the more imprecise ‘fissure’ to be

Figure 4.1.5 A typical suite of pore throat size distribution curves for 11 samples from the Fair Cross borehole, Berkshire. Dominant pore throat sizes range from approximately 0.07 to 0.7 microns.



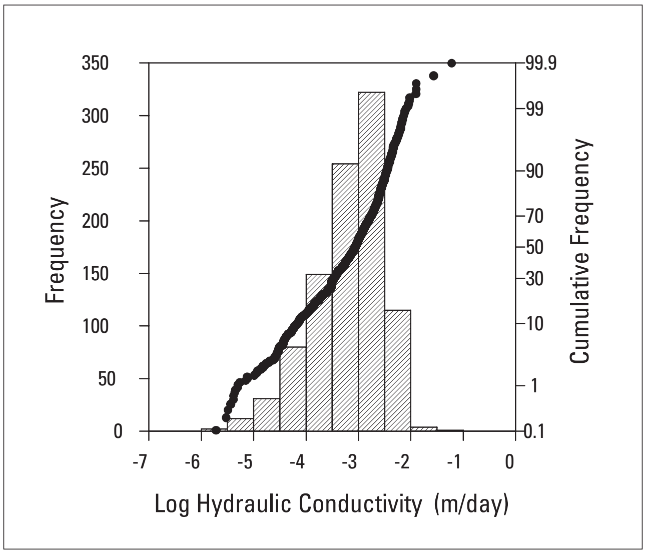


Figure 4.1.7 Distribution of horizontal hydraulic conductivity data from Chalk samples.

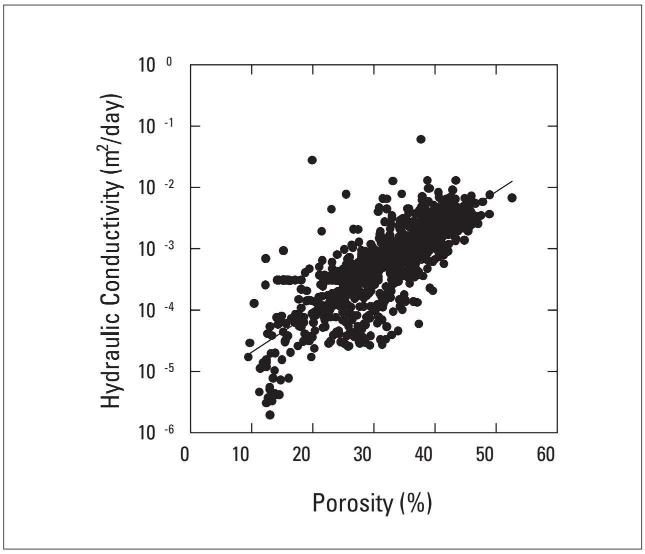


Figure 4.1.8 Correlation between matrix porosity and horizontal hydaulic conductivity for samples from the Chalk.

consistent with geological literature (see Bloomfield, 1994) for a glossary on hydraulically significant discontinuities in the Chalk) that give the Chalk the properties and characteristics of an aquifer. The factors controlling the development of fractures is discussed in the next section, the purpose of this discussion is to describe the general aquifer characteristics of the Chalk and consequently the movement and storage of groundwater.

The Chalk is often referred to as possessing *dual porosity* (Price, 1987; Barker, 1991; Price et al., 1993). In a classic dual porosity aquifer matrix pores provide the storage and fractures provide the permeable pathways to permit flow. Groundwater movement within the Chalk is more complex: the high porosity (created by the coccoliths) is not readily drained, due to the very small pore throats (Price et al., 1977), therefore effective groundwater storage is primarily within the fracture network and the larger pores. When considering transmissivity and storage coefficient in an aquifer dominated by fracture flow it is helpful to first understand the validity and application of the classical flow equations.

Darcy's law is valid for flow in fractures provided the Reynold's number is less than about 2300 (by analogy with flow through pipes). If the Reynold's number ($R_e = ud/v$ where v is the kinematic viscosity; u the velocity and d the aperture of the fracture) is significantly higher than 2300, turbulent flow can occur and Darcy's law does not apply; turbulent flow, however, is thought to be unusual within the Chalk (see Atkinson and Smart, 1981; Price et al., 1992). If this condition is satisfied each fracture can be ascribed a transmissivity. For a planar fracture of uniform aperture, a, and smooth surfaces, the transmissivity T_f is given by:

$$Tf = \frac{ga^3}{12v}$$

where g is the acceleration due to gravity and v the kinematic viscosity of the fluid (see Snow, 1968; Foster and Crease, 1975; Witherspoon et al., 1980; Barker, 1991, 1993). Therefore it is possible to assign a transmissivity to each fracture. Since the law is *cubic* it is highly dependent on the aperture of the fracture; for example, a transmissivity of 1000 m^2/d can be provided by 18 fractures with an aperture of 1 mm or just one fracture of aperture of about 2.5 mm.

Similarly it is possible to assign a measure of storage to each fracture, provided that it can drain completely. In this case the fracture storage is equivalent to fracture volume and therefore for a block of material with one set of fractures the specific yield can be given by the simple equation:

$$S_y = an$$

where $1/n$ is the average fracture separation. However this equation is not really appropriate for the Chalk, where contribution from the matrix and small fractures to storage is more significant than that from the fully drainable large fractures.

Overlying deposits, where present, can often make an important contribution to groundwater storage. Groundwater stored in drift deposits (e.g. in East Anglia) or in the overlying Palaeogene deposits (e.g. London Basin) can be drawn down into the Chalk fracture system. This effect can often be observed in pumping tests as 'leaky' responses, where the measured drawdown is significantly less than expected from the Chalk aquifer and attributed to an extra source of groundwater, usually from above.

Similar values of specific yield and transmissivity can be derived from an infinite number of combinations of hydraulic properties. Distinguishing the relative contribution of various fracture sets and also the matrix is impossible from a simple pumping test, but requires more sophisticated tools (e.g. packer tests, flow logs, core sampling, chemical modelling etc.). The following discussion illustrates the general mechanisms of groundwater flow and storage in the Chalk, and therefore should give some background to pumping test analysis in the Chalk and in particular the measurements of transmissivity and storage coefficient.

Permeability variation with depth

An important feature of the Chalk is that significant permeability is generally only developed towards the top of the aquifer. Deeper within the Chalk the frequency and aperture of fractures decline due to increasing overburden and a general reduction in circulating groundwater and hence dissolution. Much information can be gained on the vertical profile of permeability from flow logs and packer tests (Tate et al., 1970; Headworth, 1972; Foster and Milton, 1974; Foster and Robertson, 1977; Price et al., 1977; Owen and Robinson, 1978; Connorton and Reed, 1978; Southern Water Authority, 1979; Price et al., 1982; NRA, 1993). Several general observations can be made:

- permeability measured throughout the depth of a borehole is generally at least an order of magnitude higher than the matrix permeability, illustrating the importance of small fractures throughout the Chalk (termed 'primary fissures' by Price, 1987; Price et al., 1993)
- even with the increased permeability caused by small fractures, most of the saturated thickness of the Chalk has very low permeability — only a few fractures may provide the bulk of the transmissivity of the aquifer
- zones that have very high permeability corresponded to fracture locations
- the most important flow horizons are concentrated near the top of the Chalk, with little flow deeper than 50 m below groundwater levels (or below the top of the Chalk where confined)
- the presence of hardgrounds where shallower than approximately 100 m bgl can significantly increase the permeability of the Chalk. Hardgrounds (such the Chalk Rock and the Melbourn Rock) probably fracture more cleanly than other chalks due to their greater hardness and therefore, where they are not too deeply buried, will have a greater frequency of fractures and higher permeability.

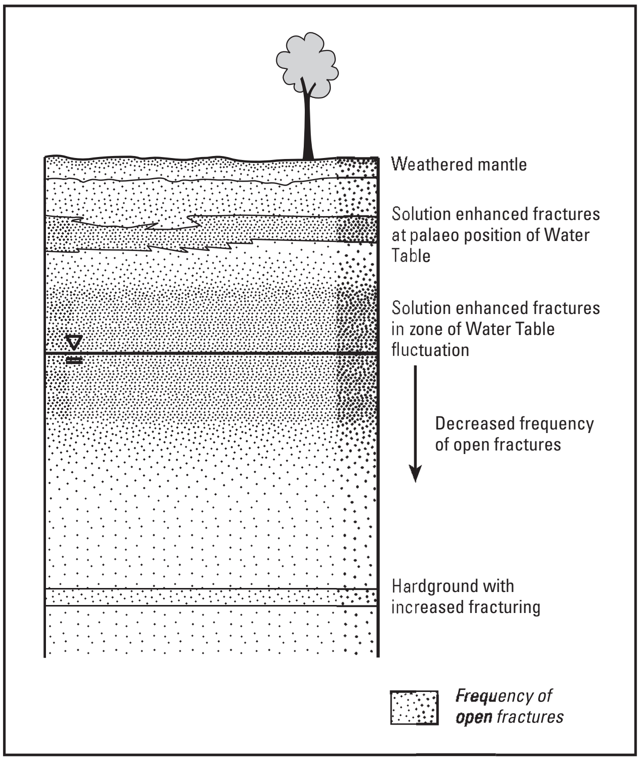


Figure 4.1.9 A schematic representation of the variation of open fractures with depth in the Chalk.

These observations are important in understanding how the Chalk behaves as an aquifer. Small fractures, which are present throughout the Chalk, increase the permeability of the matrix significantly. The increased permeability from the fracture component however is still not sufficient to give the Chalk the aquifer properties observed in the field. Significant groundwater flow usually occurs in only a few fractures near to the top of the aquifer, which generally have been enlarged by dissolution (Figure 4.1.9). Within the individual active fractures, permeability can be very high and therefore groundwater flow rapid. If these fractures are blocked by poor borehole construction, or are dewatered by over-pumping, the yield of the borehole will decline significantly. Although the majority of flow occurs in the top 50 m some smaller inflows can be found at depth (up to 120 m), especially close to the coast (e.g. South Downs and Dorset). They may have formed due to changes in sea level during the Pleistocene, or possibly sub-permafrost flow. Whatever their origin, they contribute little to the aquifer properties, but may be important in terms of the groundwater chemistry, especially where connected to the sea.

The greatest permeability in the Chalk is observed in the zone of water table fluctuation where the movement of groundwater can enhance the aperture of the fractures by dissolution. This highly transmissive zone can have the effect of buffering groundwater levels. When recharge is low, the water levels fall within the aquifer. As the water levels reach the base of the zone of enhanced aquifer properties recession reduces due to the reduction in permeability. Conversely as water levels rise within the aquifer the high transmissivity allows the groundwater to flow quickly down gradient, thus not allowing water levels to rise significantly. The majority of transient groundwater models created for the Chalk require this degree of self regulation to help replicate both water levels and stream flows (Rushton et al., 1989; Mott MacDonald, 1992; Halcrow, 1992; Cross et al., 1995). This degree of self regulation can be thought of as an overflow pipe within a cistern. Such an event occurred in Chichester during January 1994, when extreme recharge within the Chalk led to water levels rising until sufficient fractures were activated to discharge the water to the River Lavant, resulting in serious surface water flooding (Posford Duvivier, 1994).

The non-linear decrease of aquifer properties with depth has important implications for measurements of transmissivity and storage coefficient calculated from pumping tests. When water levels are high, more of the highly permeable fractures are saturated and therefore the transmissivity will be high. A pumping test undertaken at a different time of year when water levels are low would give a much lower estimate of transmissivity and storage coefficient. Therefore, since transmissivity and storage coefficient vary significantly with water level, it is very important to record the time of year and rest water level when reporting the results of pumping tests. For resource purposes often the aquifer properties measured at low water levels are quoted (to give a minimum estimation of the resource); in estimating the vulnerability of the aquifer to contamination, however, the aquifer properties at high water levels should be considered, giving the worst case conditions with rapid groundwater transit.

A similar pattern of permeability variation is observed where the Chalk is confined by younger deposits within the London and the Hampshire Basin. In the London Basin, flow logging has illustrated that the majority of the flow takes place within approximately the top 20 m. Recent drilling within the Hampshire basin indicated that only the top 50 m of the Chalk contributed significantly to yield (Cosgrove, T, personal communication). Seismic interpretation underneath the Sole Inversion in the North Sea has identified karstification of the surface of the Chalk, probably as a result of late Cretaceous erosion, which could lead to rapid fluid flow (Jenyon, 1987). It is possible that similar karstification of the surface of the Chalk occurred in other locations during this period; therefore where deeply buried by Palaeogene deposits, palaeo karst, along with the other influences of structure and groundwater flux, could account for the observed high permeability in the top few metres of the Chalk.

Changes in transmissivity related to topography

Transmissivity within the Chalk has long been observed to be greater in valleys than on the interfluves (Woodland, 1946; Ineson, 1962). The origin of this pattern is a matter of controversy and will be discussed in Section 4.1.5. However, the existence of this general pattern is not disputed and has resulted in large abstraction boreholes being located in valleys, and relatively few boreholes drilled on the interfluves. This has led to a marked bias in aquifer properties data towards high-value valley sites. The high permeability in the valleys results from the high density of active fractures (Figure 4.1.10). Because of the non-uniqueness intrinsic in the concept of 'transmissivity' the observed reduction in transmissivity away from valleys can have two different origins: (1) a reduction in permeability due to a smaller frequency of fractures; (2) a thinning of the high permeability layer. The first model is derived from understanding the development of aquifer properties along a flux type model (Owen and Robinson, 1978; Price, 1987; Price et al., 1993). The second model is derived from limited observation and is often adopted by groundwater modellers to help replicate stream flows (see above). Unfortunately, the lack of data available across interfluves hinders the understanding of the variations in transmissivity away from valleys.

One of the few places where boreholes were deliberately drilled on interfluves was the Berkshire Downs. Flow logging of the boreholes illustrated a general thinning of the transmissive zone compared with valleys. A packer test carried out in the Chichester Block also indicated a thin, but transmissive, zone just above the water table (NRA, 1993). The Chichester Flood discussed above also indicated rapid groundwater flow from the interfluves to the valleys, once water levels had risen sufficiently to intersect the fractures. These pieces of information point towards the existence of thin, but permeable, layers over some interfluves. The Chalk is complex however, and it is highly probable that both mechanisms of transmissivity reduction away from valleys exist throughout the outcrop.

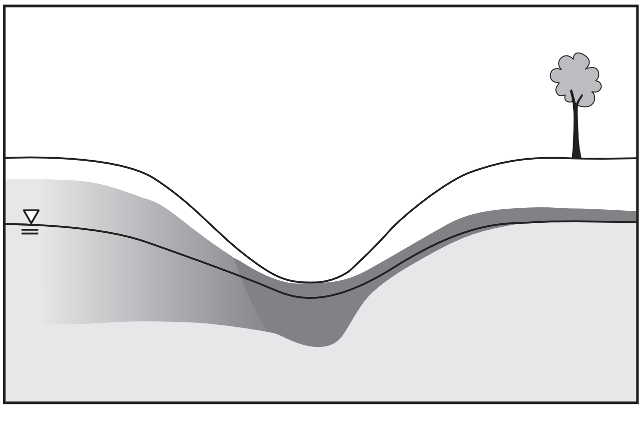


Figure 4.1.10 Variation in flowing fractures from a valley to interfluves; the left hand interfluve illustrates a general decrease in permeability; the right interfluve shows a decreasing thickness of a high permeability layer — both would reduce transmissivity.

Groundwater storage

The relative contribution to the storage coefficient from the matrix and fractures of various sizes is difficult to ascertain, and as yet has not been convincingly quantified (BGS, 1993). The contribution from the matrix depends on the size of the pore throats. Under gravity drainage, pore water suctions are unlikely to exceed 5 m, therefore pores with diameters less than 10 μm are unlikely to drain. Pore size distribution curves for the Upper Chalk suggest that, on this basis, about 3% of the total porosity, or 1% of the bulk volume of the Chalk represents usable storage (Price et al., 1976; Price, 1987; BGS, 1993). This proportion should be considered an absolute maximum due to the insensitivity of the mercury injection technique when measuring pore diameters of greater than 1 μm. Although this is a very small proportion of total porosity, the fact that the total specific yield is in the range 1–3% , suggests that the intergranular component forms a significant component of overall storage. Northern chalks and also the Lower Chalk, have lower intergranular porosity due to smaller pore diameters (Price et al., 1976; Scholle, 1977; Bloomfield et al., 1995). Foster and Milton (1976) suggested that the matrix was relatively unimportant for storage within the Yorkshire Chalk.

Groundwater held in fractures probably constitutes the largest component of specific yield. Large diameter fractures, which are responsible for the majority of the permeability of the Chalk contribute significantly to the storage but cannot support the total observed values of specific yield. Smaller fractures therefore have an important role in providing groundwater storage. When the groundwater head is lowered within a borehole, the larger fractures will drain initially. As the large fractures drain, the head is lowered within the aquifer, allowing the groundwater within the smaller fractures to move into the large fractures and be transported to the borehole. Continued pumping will lead to the drainage of the large pores within the matrix. This 'delayed drainage' effect is often observed in pumping tests, (e.g. Jones et al., 1993), where the drawdown curve illustrates a high degree of leakage.

Data from the Chilgrove Borehole in the South Downs (Institute of Hydrology/British Geological Survey, 1991; Price et al., 1993), illustrate the various mechanisms for storage within the Chalk. During the 1988–92 drought groundwater levels within the aquifer were low and much of the groundwater within the smaller fractures and large pores had drained. A period of heavy rainfall interrupted the drought during the winter of 1989–90, causing the water levels in the well to rise sharply, but then decline equally rapidly. Such a response to recharge could be expected if only the large fractures had been replenished during the recharge event. With time the recharge would drain from the large fractures to be stored within smaller fractures and the larger pores of the matrix causing water levels within the fracture network (and therefore the borehole) to decline.

Springs

Many springs issue from the Chalk. These fall into two main categories (Woodland, 1946):

- overflow from the main water table where it emerges at the surface
- at certain horizons determined by lithology.

Springs of the latter type result from the occurrence of marl bands, which impede water flow, and hard, well-fractured rock bands along which there is considerable lateral flow. Springs determined by lithology are common on chalk scarp slopes. Three main sets are recognised.

- Small flows at the base of the Chalk at its contact with the Gault or Upper Greensand.
- At various points along the outcrop of the Totternhoe Stone. The relatively impermeable beds of the Chalk Marl impede downward flow of groundwater, encouraging it instead to escape to the surface.
- The Melbourn Rock is underlain by a few metres of marly beds (the Plenus Marls) and gives out numerous springs.

Springs also occur at other levels in the Upper/Middle Chalk, but they are usually small and tend to dry up during the summer and autumn.

Springs which occur on the dip slope of the Chalk are nearly always in the bottoms of valleys and are of the overflow kind, i.e. where the water table intersects the surface. During the summer and autumn months, when the water table is falling, these springs dry up successively down the valley; in the winter, as the water table rises, they become active at increasingly higher levels. These seasonal streams are called 'bournes'.

Karst

The term 'karst' is associated with terrain with distinctive landforms and hydrology. In hydrogeological terms the importance of karst is that groundwater is concentrated in, and flows rapidly through, a network of fractures, conduits (significantly enlarged fractures) and caves (conduits that are large enough to be explored physically by man). Karst characteristics are more developed in some terrains (e.g. Carboniferous Limestone) than others (e.g. Jurassic limestone, Chalk). This prompted Atkinson and Smart (1981) to suggest that carbonate aquifers should be considered as possessing varying degrees of karst, rather than being wholly karstic or wholly non-karstic.

The extent to which the Chalk aquifer can be considered karstic is of great significance when trying to understand groundwater flow and protect the aquifer from contamination. Normal hydrogeological techniques of investigation (e.g. pump test analysis and classical groundwater flow modelling) break down in karstic conditions leaving less standard types of analysis (e.g. spring hydrograph analysis and tracer tests). Within a karstic aquifer, the concepts of transmissivity and storage coefficient have little meaning. Therefore it is necessary to identify the extent of karstic phenomenon and assess their influence on hydrogeology.

Speleologists have long recognised and explored the karstic nature of the Chalk (e.g. Reeve, 1976, 1977, 1981, 1982; Proctor, 1984; Fogg, 1984; Lowe, 1992). Explorable caves are seen in the Chalk at many locations, (e.g. Sussex, Devon, Kent) mostly around the coast. Although some are of marine origin, a large proportion are connected to palaeo-solution features of fresh-water origin. These caves are now often dry, but some extend down into the saturated zone where they are less easily explored.

Geomorphological evidence of karst characteristics are widespread (e.g. Fagg, 1958; Docherty, 1971; West and Dumbleton, 1972; Sperling et al., 1977; Edmonds, 1983; Goudie, 1990). Dolines, solution pipes and swallow holes are all observed in the Chalk (Dolines can be considered as depressions, that do not necessarily have water flowing into them; a swallow hole is the point at which a stream sinks underground; and solution pipes are large subvertical pipes within the Chalk usually backfilled with sands and gravels). Although the regional frequency of these features is lower than in other limestones, locally the frequency can be comparable. The highest density is found in Dorset (e.g. >150 per km^2 at Puddletown Heath) with other important areas within the Chilterns, Pewsey area, Kent Downs, and the Surrey and West Kent Downs (Figure 4.1.11). The lowest density areas are the Salisbury Plain and Yorkshire and Lincolnshire (Edmonds, 1983; Goudie, 1990). Swallow holes and dolines are found both on recharge areas (i.e. interfluves) and discharge areas (i.e. valleys). In addition, the surface of the Chalk, where overlain by some sort of cover, has undulations quite similar to the clints and grykes observed in harder limestones (such as the Carboniferous Limestone). These can be exposed in quarries are excavations. It appears that the Chalk is too soft to maintain them at outcrop.

The relation between surface karst and deep, karstic features resulting in enhanced permeability within the aquifer, is unclear, although a little localised evidence exists from direct observation of such features during recharge events. For example, a tributary of the River Colne flows down a series of swallow holes at Water End in Hertfordshire and re-emerges in a different catchment. At a series of swallow holes in Little Bedwyn, Berkshire surface water

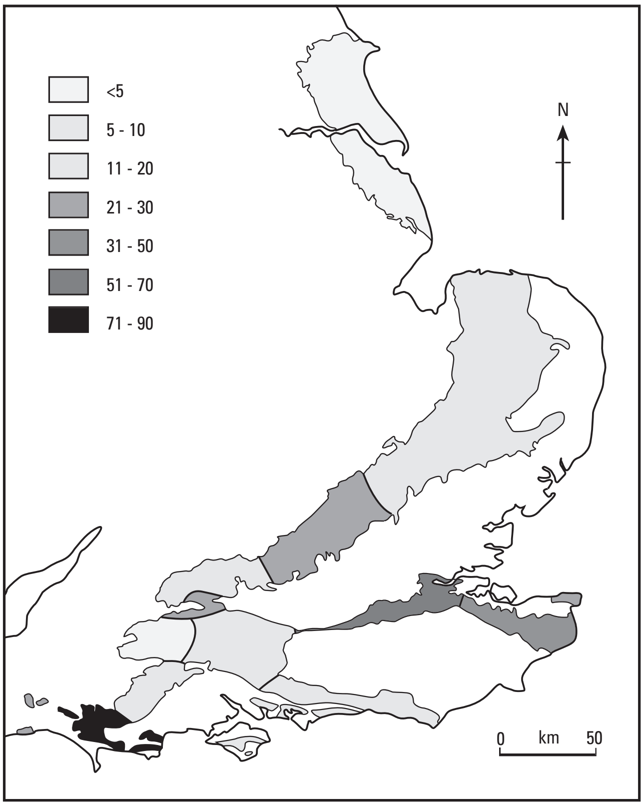


Figure 4.1.11 The density of solution features on the outcrop of the Chalk per 100 km^2 (after Edmonds, 1983).

streams were observed to flow through the bottom of the swallow holes, directly into the Chalk: the flow rate into the Chalk would require a well-developed fracture system to accommodate the water. There are other localised examples of swallow holes being associated with rapid groundwater flow, however, direct evidence from a number of swallow holes would be required to gain a better understand of the link between the two.

The drainage of the Chalk is also characteristic of karstic environments. Surface drainage is poorly developed. The dendritic river patterns that are seen on most other geological formations are not observed; instead the valley patterns tend to be orthogonal, possibly defined by the fracture directions (e.g. the Lower Darent Basin, east Kent). In addition, groundwater catchment boundaries are often not coincident with the surface water catchment boundary e.g. the Alre in Hampshire, Frome valley and Lulworth Cove in Dorset. Some of the most interesting evidence of karst behaviour is the characteristics of ephemeral streams within the Chalk. In an unpublished study, Stanton (Stanton, W, personal communication) recorded flow over two seasons in ten winterbournes throughout the south-west Chalk. Each winterbourne dried up in different, but well-defined stages with springs and swallow holes defining the start and end points of each stage (Figure 4.1.12). Some winterbournes had stages high up the valley that flowed almost continuously throughout the year, while stages downstream dried up

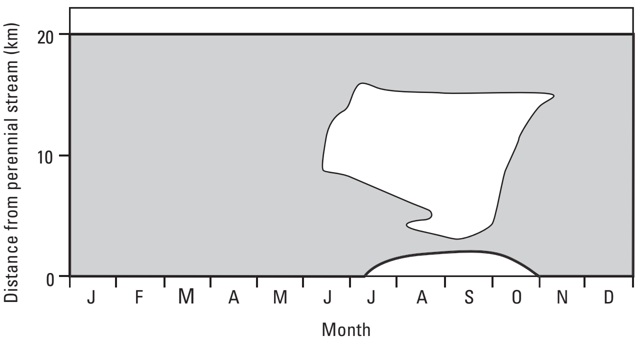


Figure 4.1.12 Characteristic patterns of winterbourne recession observed in the southern Chalk — the shaded area indicates flow (data from NRA, Southwest Region, 1993).

quickly. Such disappearance and re-emergence of streams is a characteristic of karst environments.

For the hydrogeologist the main attribute of karst is that groundwater is concentrated within, and flows through, a network of fractures, conduits and caves which have been enlarged by dissolution. Evidence of hydrogeologically significant subsurface karstic features in the Chalk can be gained by direct observation and sections, tracer tests, drilling and to a lesser extent pumping tests:

1. Several tracer tests have been undertaken at various locations within the Chalk aquifer (Morris and Fowler, 1937; Atkinson and Smith, 1974; Alexander, 1981; Ward, 1989; Price et al., 1992; Banks et al., 1995; Ward and Williams, 1995). At some locations extremely rapid groundwater flow through a discrete fracture system is observed (e.g. Banks et al. (1995) report 6 km/d at the Blue Pool in Berkshire), while at others groundwater flow is rapid but thought to be through a network of small fractures.
2. Boreholes within the Chalk of the South Downs have been pumping sand (Southern Science, 1992). The sand is located within large, solution enhanced bedding plane fractures and is probably of Palaeogene age. In cliff sections in France, large subvertical solution pipes connecting with horizontal features are observed, illustrating karstic development of the fractures. Numerous examples of karst development can be seen in cliff and quarry sections, e.g. Castle Hill (Newhaven), Caversham, and in France (Dieppe West, Beauville, Tilleul Plage). At some localities solution enhanced bedding plane fractures have been infilled with sand. The sand within fractures in southern England is likely to have a similar origin.
3. Extensive adit systems were built in different parts of the Chalk aquifer during the second half of the 19th and early part of the 20th century (e.g. Mustchin, 1974). Notes made during their construction often refer to very few producing fractures (possibly as little as one every 30–50 m) with large inflows (>4000 m^3/d). This implies groundwater flow through the Chalk in these areas through quite widely spaced but high yielding subvertical fractures — a characteristic of karst areas. Such direct evidence of productive fractures is unfortunately limited within the Chalk (Allen, 1995).
4. Different water levels are recorded in boreholes in close proximity. Pumping can have a very rapid effect on water levels in a borehole or spring several kilometres away from the pumping borehole, for example Swanbourne Lake, South Downs (Southern Science, 1994) and south Dorset (Alexander, 1981; Houston et al., 1986). Such effects can be attributed to discrete, highly directional fracture zones that allow rapid flow.

Therefore, there is widespread evidence that the Chalk exhibits many karst-like features. Geomorphologists have noted various surface expressions of karst on the Chalk outcrop. Limited data from the saturated zone show the widespread importance of discrete, solution enhanced fractures with channelled, rapid, groundwater flow. With such evidence of rapid groundwater movement, much could be learned about the nature of the Chalk by studying it in an innovative manner, using the tools developed for the karstic aquifer.

Summary

The Chalk is a unique aquifer with many interesting and complex characteristics. Flow, and therefore transmissivity, are governed by the frequency and aperture of fractures. Groundwater storage within the Chalk is derived from the major fracture system as well as the small, micro fractures and the matrix. This has often lead the Chalk to be described as possessing dual (or multi) porosity. Several patterns are observed with regard to the aquifer properties of the Chalk:

- the most important fractures occur within the top 50 m or so of the saturated aquifer, often within the zone of water table fluctuation; this leads to a decline in both transmissivity and storage coefficient with depth
- high transmissivity and storage is usually observed within valleys, with the aquifer properties of the Chalk declining with distance away from the valleys

- in some areas a thin highly transmissive layer around or above the water table may be present within the interfluves, which is active only at certain times of the year
- variations in aquifer properties, which do not conform to the basic topographic distribution are observed, depending on the presence of fractures and dissolution
- rapid groundwater flow or 'karst' like behaviour is widespread throughout the Chalk, both over interfluves and in valleys.

4.1.5 The development of aquifer properties in the Chalk

Introduction

A discussed previously, it is the presence and development of fractures that gives the Chalk the properties of an aquifer. Without fractures the permeability and storage coefficient of the Chalk would be negligible. Furthermore, without solution enhancement of the fractures, the high transmissivity of the Chalk would be impossible, and without further concentration of groundwater flow and dissolution of chalk the conduits and karstic features would not be observed. In this section the factors that control the occurrence of fractures in the Chalk are examined, along with the factors that contribute to the dissolution of chalk. The section is divided into two parts: (1) factors that contribute towards the general 'topographic' distribution of aquifer properties; and (2) factors that contribute to other, localised variations in aquifer properties.

Before discussing the various factors that increase Chalk permeability it is important to understand the controls on the dissolution of calcite. Typically the pH of the soil zone is alkaline (7.5–8.3). Under normal diffuse recharge conditions calcite saturation is rapidly established, possibly within the first few centimetres (Edmunds et al., 1992). Concentrations of carbon dioxide in the soil are high (10–50 times greater than that in the atmosphere) due to soil biological activity; high partial pressure of CO_2 increases the calcite saturation limit. Carbon dioxide is dissolved by recharging water producing carbonic acid (H_2CO_3) which then reacts quickly with carbonate minerals (Price et al., 1993). Measurements of the chemical composition of pore waters has shown that the solution of calcium carbonate by carbonic (and organic) acids predominates within the soil zone and upper few metres of the unsaturated zone, with little dissolution below 2 m in the unsaturated zone (Edmunds et al., 1992).

Since recharging water becomes saturated with calcite within the first few metres of the unsaturated zone, the question remains as to how fractures within the saturated zone become enlarged. This is still an area of research which is poorly understood, but the answer is thought to lie in the chemistry changes resulting from the mixing of different groundwaters (Saniford and Konikow, 1989; Edmunds et al., 1992). When recharging waters become saturated and supersaturated there is a tendency for calcite to be precipitated (Edmunds et al., 1992; Shand and Bloomfield, 1995). This leaves the opportunity for further dissolution to occur especially when the water reaches the water table and mixes with groundwater of different chemistry. Rapid recharge through the fracture network occurs at certain times of the year. The resulting groundwater has less time to become saturated and therefore has a greater dissolution potential (Downing et al., 1978).

The origin of the general 'topographic' distribution

Throughout the Chalk aquifer transmissivity and storage appear to have a close link with topography. Within valleys, the aquifer properties are good, while over the interfluves both transmissivity and storage significantly reduce. Several factors probably contribute to a higher frequency of open fractures along valleys: (Ineson, 1962; WRB, 1972; Price, 1987; Price et al., 1993):

- many valleys follow lines of structural weakness, with probably a higher frequency of fractures. (It should be noted however that some dispute the increase in fracture frequency towards valleys [Younger, 1989; Younger and Elliot, 1995]).
- erosion along valleys reduces effective stress which can lead to the opening of horizontal fractures

The concentration and mixing of groundwater towards valleys is probably a more important factor in developing permeability than the frequency of fractures (Rhoades and Sinacori, 1941; Robinson, 1976; Owen and Robinson, 1978; Price, 1987; Price et al., 1993). As groundwater flows from the recharge areas of a catchment towards the discharge areas (valleys) the flux of groundwater increases. This concentration of flux results in higher velocities of groundwater flow as the discharge points are approached. In addition, the mixing of various groundwaters of different chemistry towards discharge points could lead to perturbations in groundwater chemistry and possibly dissolution. In an isotropic, homogeneous carbonate aquifer Price (1987) adapted a model originally proposed by Rhoades and Sinacori (1941) to illustrate how the increased flux could give rise to high permeability within the valleys and the development of a single zone of dissolution enhanced fractures (see Figure 4.1.13). (Such a model was also adopted by Robinson (1976) to explain the transmissivity distribution of the Kennet Valley). Therefore, a higher frequency of fractures within valleys is not necessarily a prerequisite to high permeability — it can develop even if fracturing is limited.

Periglaciation could also have contributed towards the enhanced permeability along valleys. Under periglacial conditions, most of the Chalk would have been frozen. Repeated freezing and thawing within the active layer would have broken down the top few metres providing a mantle of weathered chalk which could be easily eroded; within the valleys, repeated freeze-thaw may have opened up fractures to a depth of 20–30 m (Higginbottom and Fookes, 1970; Williams, 1980; Gibbard, 1985; Williams, 1987).

Furthermore, in the valleys, the flow of surface water would have kept the ground unfrozen to a greater depth for large parts of the year forming a talik within the Chalk of the valley floor (Figure 4.1.14). Chalk is dissolved more easily under cold conditions due to the inverse relation between carbon dioxide solubility and temperature. Therefore, the concentrated flow of groundwater within these taliks and the low temperature of groundwater would combine to dissolve Chalk from fracture surfaces and consequently greatly enhance permeability.

Younger (1989) suggested that the permeability observed within the Thames Valley was highly influenced by periglaciation. In narrow reaches of the valley, perennial taliks would have developed giving rise to zones of high permeability. Where the valley widens, however, braided streams would develop which probably froze during the winter, fusing with the underlying permafrost. The sub-

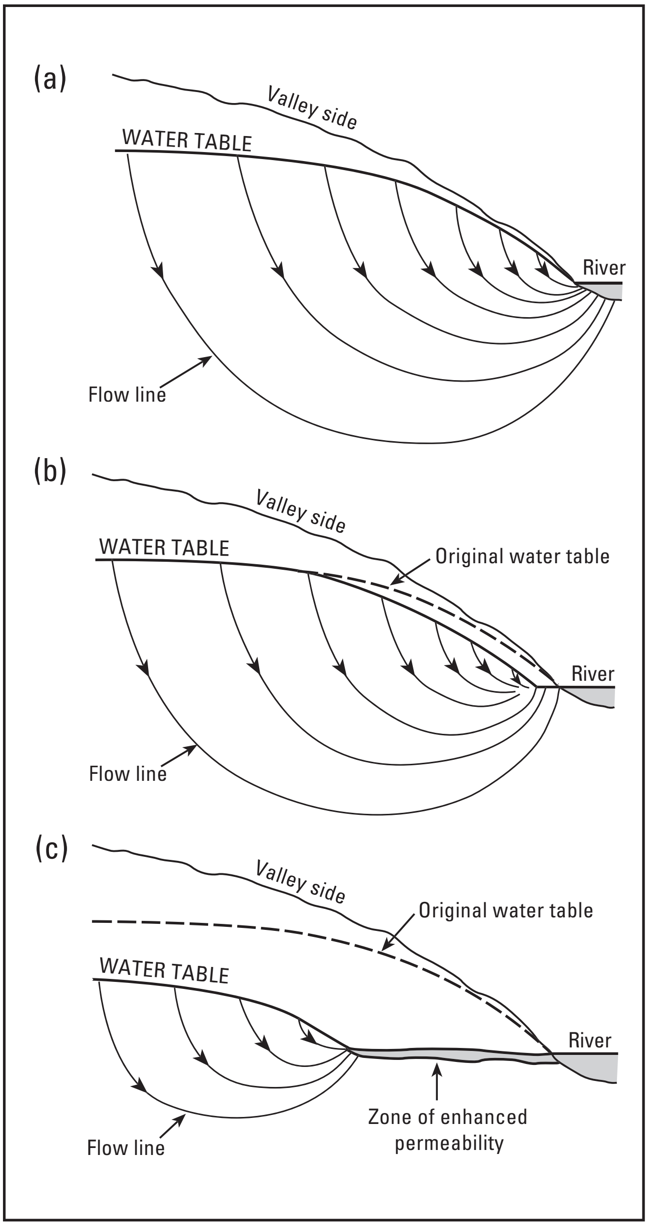


Figure 4.1.13 The development of high transmissivity in valleys in an isotropic, homogeneous carbonate aquifer (after Price, 1987).

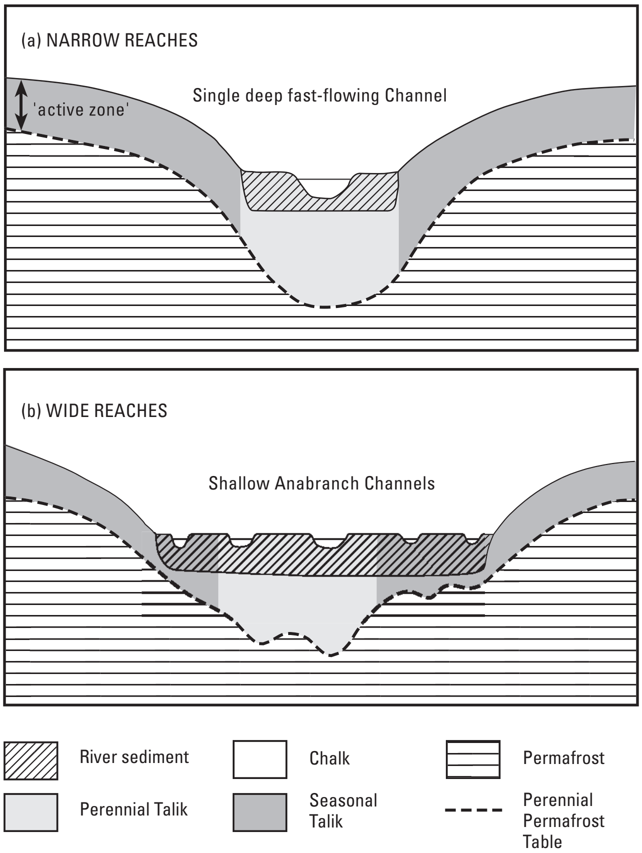


Figure 4.1.14 Likely periglacial conditions beneath (a) narrow reaches and (b) wide reaches of river valleys during Devensian times (after Younger, 1989).

sequent freeze–thaw action underneath minor channels produced a thick layer of putty chalk, and the persistence of permafrost would have reduced the flux of groundwater leading to a reduction in dissolution and therefore permeability.

Factors contributing to non-topographic patterns in aquifer properties

Variations in topography do not fully account for the observed distribution in transmissivity and storage. Several other factors have helped to develop the aquifer properties of the Chalk, e.g. lithology, marls and flints, structure, glacial and periglacial history and nature of cover. In this section a brief description will be given of each.

Lithology

Different lithologies within the Chalk may have different aquifer properties largely due to the lithological control on fracture distribution. The homogeneous, soft to medium hard Chalk of the Seaford Tarrant and Spetsburg Chalk members of the Upper Chalk comprise blocky chalk with regular orthogonal joint sets. Mortimore (1993) suggested that storage within these members may be high due to the large number of fractures; high permeability, however, might not develop due to the small aperture of the fractures (cf. the cubic law). In Sussex, within the Newhaven, Lewes Nodular, New Pit and Holywell Nodular Chalk members steeply inclined conjugate fractures are common (Mortimore, 1993). At the intersection of the fractures, cavities can develop which could give rise to rapid groundwater flow and therefore high permeability. The lower fracture frequency, however, may reduce the fracture volume, thus reducing the available groundwater storage.

The aquifer properties of the Chalk Marl of the Lower Chalk are poor due to the high clay content (approximately 30%). Fracturing within the alternating clay and limestone bands of the Chalk Marl are quite different: subhorizontal joints are common in the marly layers and vertical joints within the limestone (Mortimore, 1993). As a consequence, perched water tables develop as vertical groundwater flow is restricted, sometimes resulting in springs.

Hardgrounds (e.g. the Chalk Rock and Melbourn Rock) can significantly increase the permeability of the Chalk. Historically, many boreholes were drilled specifically to target hardgrounds. Recent flow logging and packer testing however, has illustrated that hardgrounds are generally only significant if shallower than 100 m bgl (see above). The higher permeability is generally attributed to cleaner fracturing (Price, 1987). Since the hardgrounds are better cemented, fractures within them tend to be remain open at greater depths than softer chalk. The open fractures allow groundwater to flow through them generating preferential flow paths which may then be enhanced by dissolution. Buckley et al. (1989) have shown from borehole logging that the location of hardgrounds may control the levels of solution enhanced fractures for an area in East Anglia.

Marl and flint layers can be important providing preferential flow paths which can 'seed' the development of larger solution features. Marl layers within the Chalk are important in accommodating stress. In field samples small displacements are observed either side of marl layers, and some marl layers may have been removed completely by shear movements. Mortimore (1993) found evidence of solution enhanced cavities above many marl seams and also linked springs to the presence of marl layers. At one location within the Middle Chalk he noted intense conjugate fracturing above the marl layer; groundwater leaked downwards through the fractures to the marl layer where a small karstic layer dissipated the groundwater horizontally.

Solution enhanced fractures have also been noted associated with flints (mainly tabular flints), although more study is required to consolidate the observations. One striking description is given within a guide to a Chalk cave at Beachy Head (Reeve 1981). Here a flint layer is observed throughout the length of the cave, the floor of which has several vertical steps to follow the flint layer across faults. Several factors could contribute to the development of solution features near to flint layers: (1) slight variations in the geochemistry of the Chalk are observed near to flint bands which could lead to preferential dissolution (Lowe, 1992); (2) the flint (especially tabular flints) could act as impermeable barriers channelling groundwater flow above the flint and (3) the difference in hardness between the flint and chalk may lead to the development of small voids when accommodating stress.

Structure

Since groundwater flow within the Chalk is through fractures, structure must have a significant effect in developing aquifer properties. The role of structure in providing the general topographic distribution of aquifer properties has been discussed previously; in this section the *direct* influence of structure on aquifer properties is described.

Observing the distribution of aquifer properties and also the structure that exists within the Chalk it is apparent that no simple predictive correlation exists between the two. In some areas (e.g. Water End, Hampshire) high permeability is associated with synclines, in others, it is linked with anticlines. Likewise, faults can locally increase or decrease the permeability of the Chalk. For example a fault zone is thought to be responsible for the rapid groundwater flow observed at Lulworth in south Dorset (Houston et al., 1986). Within the London Basin much work has been undertaken relating aquifer properties to structure (Water Resources Board, 1972; recent unpublished studies by Thames Water plc). A complex pattern emerged with an anisotropic pattern of aquifer properties (Sage, R, personal communication). In this area some faults appear to reduce permeability, acting as barriers to flow.

Despite the complexity of the relation between structure and permeability several generalisations may be made:

1. Folding tends to increase the fracturing of the Chalk; where these fractures have been enlarged by solution, permeability will be high.

2. Where anticlines bring the less permeable Chalk members near to the surface the aquifer properties tend to reduce (e.g. Singleton Anticline in the Chichester area). Likewise if a syncline is filled with younger, low permeability material, the permeability of the Chalk does not develop (e.g. Chichester Syncline).

3. If much fault gouge is produced by faulting, groundwater flow can be inhibited and permeability is limited.

4. Rapid groundwater flow is often associated with fault zones in the Chalk. This can produce anisotropy in groundwater flow: parallel to the fault groundwater flow is rapid, while it is impeded perpendicular to the fault (e.g. London Basin).

5. Deep burial of the Chalk beneath Palaeogene deposits tends to reduce permeability and storage. Data from the London Basin illustrate that Chalk transmissivity was inversely proportional to overburden thickness.

The effect of cover

Rapid groundwater flow is often associated with Palaeogene cover. Atkinson and Smith (1974) in a tracer study of the Bedhampton Springs in south Hampshire ascribed the development of such a system to the presence of Palaeogene cover. Rapid groundwater flow is observed at points on the Chilterns near to the feather edge of the Palaeogene deposits. In addition, geomorphological karstic features are often associated with cover, for example, the dolines of south Dorset (Sperling et al., 1977) are formed beneath Palaeogene cover; swallow holes and solution pipes in the Chilterns are formed beneath both Palaeogene deposits and clay-with-flints (Edmonds, 1983). Figure 4.1.15 illustrates the distribution of plateau drift and clay-with-flints over the southern Chalk.

Several factors could account for the high degree of solution activity associated with cover:

1. Soils associated with Palaeogene deposits and clay-with-flints tend to be quite acidic (Edmunds et al., 1992).

2. Chalk soils are generally permeable, but those associated with cover can be quite clayey and therefore concentrate runoff to discrete points.

3. As recharge drains through the cover, it remains undersaturated with respect to calcite until it reaches the Chalk surface, thus allowing the acidic recharge to be channelled to discrete points.

West and Dumbleton (1972) illustrated how rainwater, if targeted to 10% of the Chalk surface could produce pipes 3 m deep within the last 10 000 years. Such features are often observed in quarries where the Chalk surface is exposed beneath cover. Once a feature has been initiated, recharge will continue to be channelled to that one point and dissolution will continue (Figure 4.1.16a). Fractures on the Chalk surface, variations in the permeability of the cover, or even tree roots could all serve to focus groundwater to discrete points. Once the cover has been removed, the surface features could gradually be eroded away, leaving very little evidence of swallow holes or solution pipes on exposed Chalk surfaces.

Solution pipes and swallow holes can allow acidic recharge to penetrate deep into the unsaturated zone, and in mature areas even below the water table. Therefore the

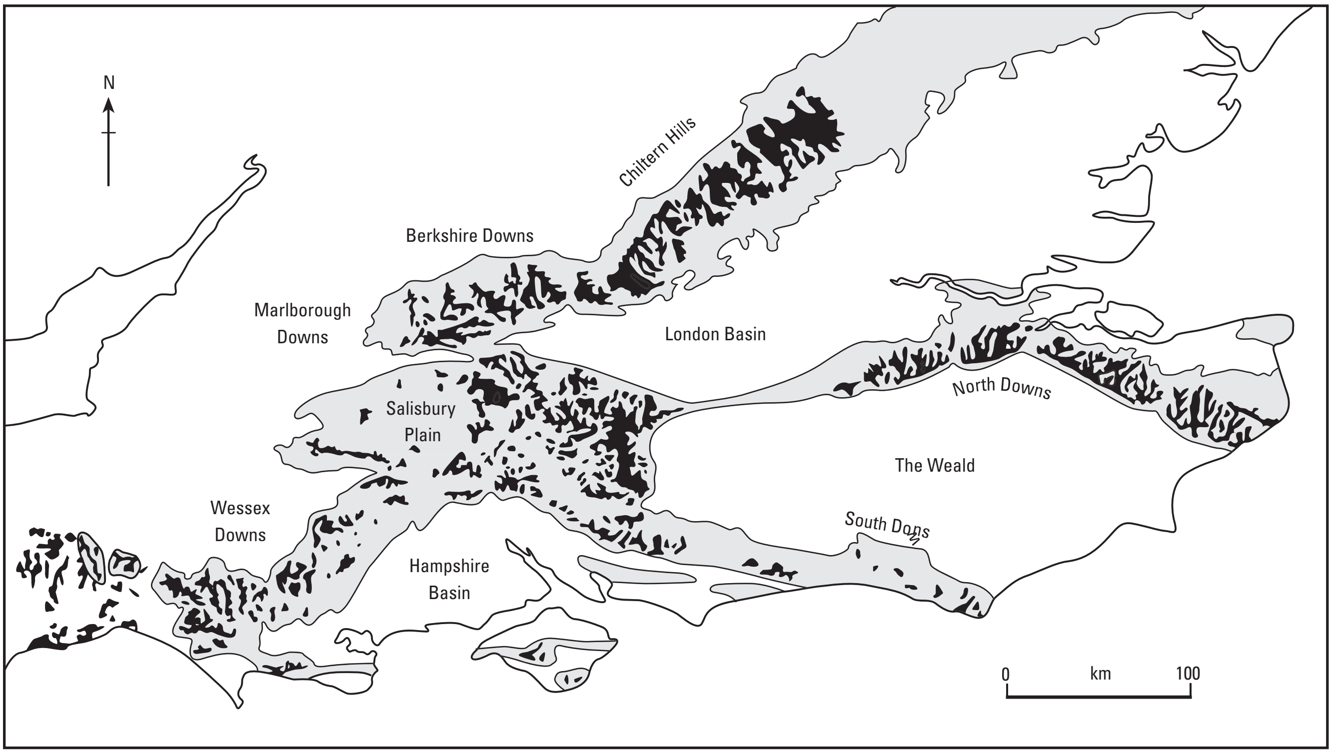


Figure 4.1.15 Distribution of plateau gravels and clay-with-flints over the Southern Chalk (after Goudie, 1990).

acidic recharge can link up with fracture systems within the aquifer and allow enlargement of fractures to conduits. This is probably the mechanism for the observed rapid groundwater flow near to cover. Even once the cover and geomorphological features have been removed by erosion, the deeper hydrogeological features will remain, providing rapid groundwater flow and preferential flow paths.

Hydrology

Rapid groundwater flow and swallow holes are also often observed on valley bottoms, associated with flowing streams. Tracer tests at the Blue Pool in the Pang Valley and in the Colne Valley at South Mimms in Hertfordshire (Morris and Fowler, 1937; Banks et al., 1995), surveys of the Mole Gap, Surrey (Fagg, 1958) and observations of ephemeral streams in Dorset and Wessex (Stanton, W, personal communication) have all pointed towards the importance of dissolution features on valley bottoms.

These 'karst' type features may have a different origin from those observed on Chalk interfluves associated with cover. Surface water flowing within streams has different chemistry from the groundwater, therefore mixing can produce water that has a high dissolution potential. This aggressive water coupled with the high flux through the

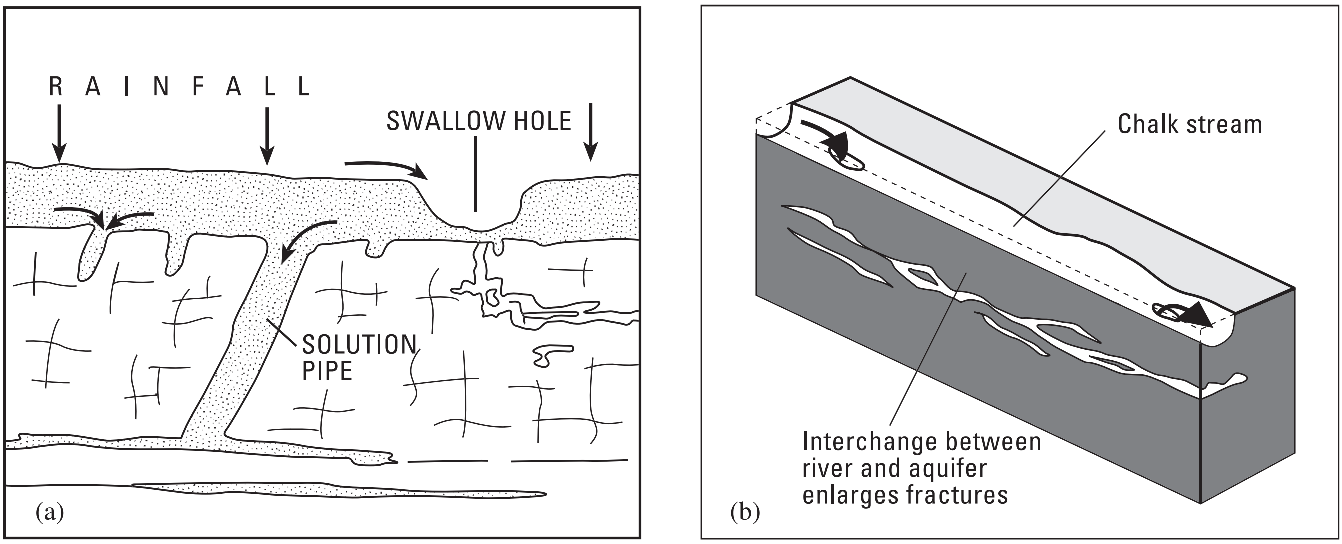


Figure 4.1.16 The deveopment of high transmissivity and rapid groundwater flow: (a) in association with cover; and (b) associated with hydrology.

valleys and the dynamics of surface water flow can produce sink holes and springs in stream beds, probably linked with conduits (Figure 4.1.16b). Therefore, as in more classic 'karst' environments, surface water can flow in discrete channels underground within valleys. This mechanism could explain the formation of the various examples given above. Docherty (1971) when reviewing the work of Fagg in the Mole Gap, suggested that such features might exist in many valleys that used to contain flowing streams, although recently the surface expressions might be concealed by drift.

Glacial and periglacial influence

The glacial and periglacial history of the British Isles affects the distribution of aquifer properties in a number of ways. Glacial till, deposited in East Anglia by the Anglian glaciation confines the Chalk in places, restricting the circulation of groundwater (Bonell, 1972; Lloyd, 1980; Yorkshire Water Authority, 1985; Hiscock and Lloyd, 1992). Where the till is permeable significant recharge can occur which allows aquifer properties to be enhanced. Hiscock and Lloyd (1992) suggested that the nature of the till restricted groundwater movement primarily to valleys, therefore enhancing the observed 'topographic effect'. Groundwater flow beneath glaciers and permafrost may also account for permeable fracture zones within the Chalk — especially those observed at depth. Groundwater flow may have been more focused and under greater pressure due to the confining layers of the ice. The lower temperatures of the water and greater flux would have lead to greater dissolution.

Glaciation in East Anglia has produced steep-sided buried channels that have a significant effect on the hydrogeology of the Chalk. Generally the channels are found beneath present day valleys, with some exceptions. Their effect on the hydrogeology depends on their composition. Buried channels filled with sands and gravels have high permeability, but the Chalk beneath is often reduced to relatively impermeable putty Chalk due to freeze thaw action (Foster and Robinson, 1977). Alternatively, buried channels filled with clay act as a barrier, forcing groundwater beneath or to the sides of the channel, increasing the permeability of the surrounding Chalk. Recently Anglian Water Services (AWS) have been targeting the Chalk below buried channels for water supply primarily because of the low nitrate of the groundwater (AWS, personal communication).

Conclusion

Many factors have contributed to the development of aquifer properties within the Chalk (Figure 4.1.17). The general topographic pattern of transmissivity has developed through a number of processes: the concentration of groundwater flux within valleys; the structure of the Chalk; the removal of overburden; and periglacial erosion particularly within taliks. Superimposed upon the general distribution are other effects which sometimes result

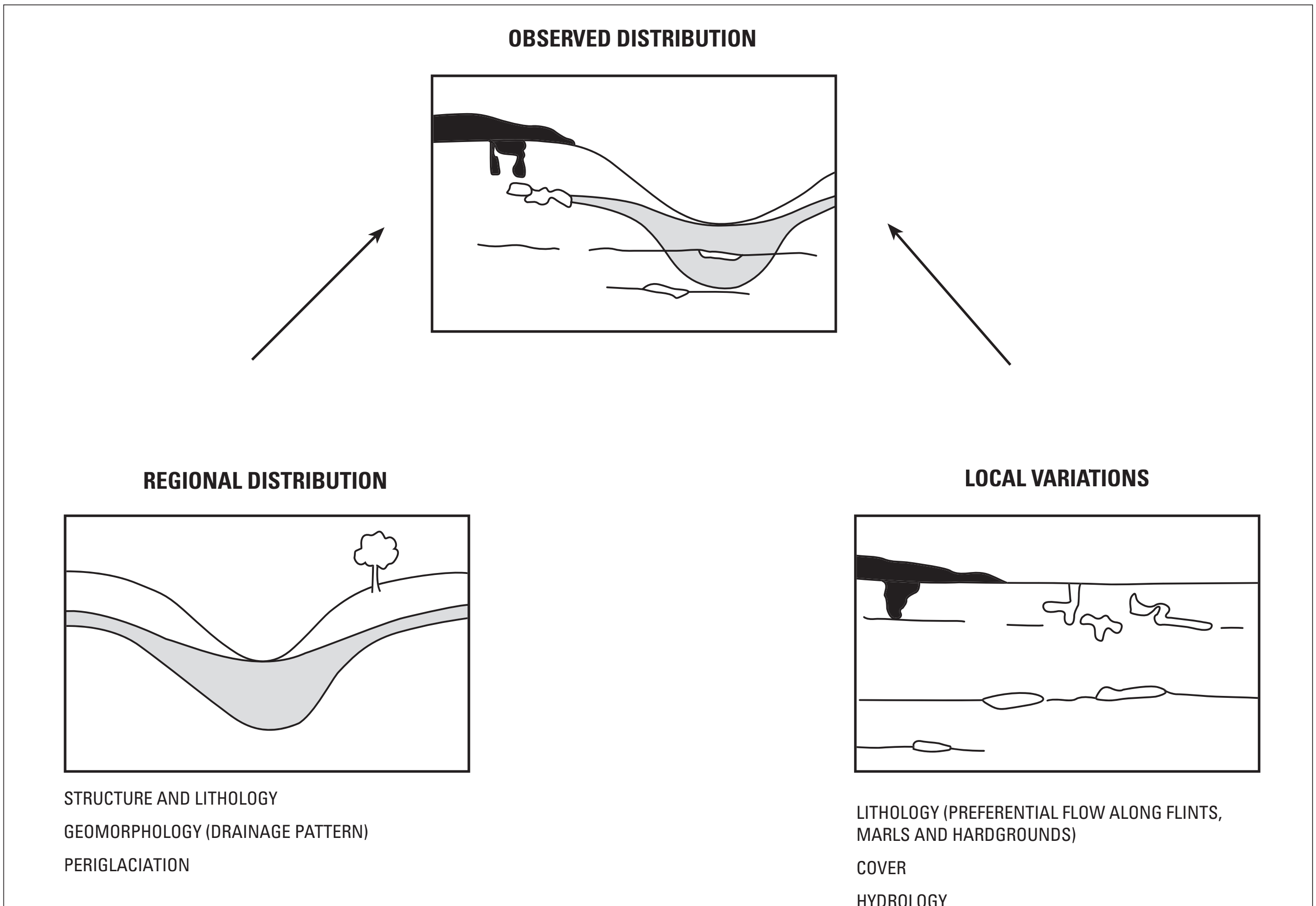


Figure 4.1.17 Various factors that can contribute to the development of aquifer properties in the Chalk of England (after Jones and Robins, in press).

in high permeability and even karstic behaviour. The lithology of the Chalk has an important effect on aquifer properties, especially the presence of marl layers, flints or hardgrounds. The structure of the Chalk can also affect the aquifer properties, depending on whether significant fracturing has developed and also the presence or absence of fault gouge. Palaeogene or other, younger cover, can be instrumental in developing solution features and groundwater conduits, as can the recent or historic presence of rivers, and periglacial activity. Glacial till within East Anglia can restrict groundwater flow and therefore the development of transmissivity. Buried channels within the Chalk of East Anglia also affect Chalk aquifer properties, however their effect on the hydrogeology is inconsistent and dependent on the composition of the fill.

Considering the variable quality and often sparse distribution of aquifer properties data throughout the Chalk of England, understanding the *processes* that helped to develop the aquifer properties of the Chalk can help to predict areas of high and low permeability and storage.

4.1.6 Measuring aquifer properties within the Chalk

Pumping tests

Pumping tests are the most widespread technique for measuring transmissivity and storage coefficient within an aquifer. The principle of a pumping test is quite simple:

> "..if we pump water from a well and measure the discharge of the well and the drawdown in the well and in piezometers at known distances from the well, we can substitute these measurements into an appropriate well flow equation and calculate the hydraulic characteristics of the aquifer" [Kruseman and de Ridder, 1990, p.27]

Unfortunately, because undertaking pumping test analysis is so simple, it is open to misuse. Aquifer parameters can be calculated using the wrong model therefore giving spurious results. Understanding the flow mechanisms within the Chalk aquifer, especially in response to pumping, can aid the choice of the correct method of analysis and help reduce anomalous results. In the following sections the approximations and assumptions of pumping test analysis are briefly described along with an explanation of how valid such assumptions are in the Chalk aquifer.

The common methods of pumping test analysis used on Chalk boreholes (e.g. Theis, Jacob, Boulton etc.) rely on many basic underlying assumptions about the aquifer condition: (see Kruseman and de Ridder, 1990):

- the aquifer is infinite
- the aquifer is homogeneous, isotropic and of uniform thickness over the test area
- the piezometric surface is initially horizontal
- the borehole penetrates the entire thickness of the aquifer
- flow to the borehole is horizontal
- the diameter of the borehole is small, so there is no well/borehole storage.

In addition, other assumptions are made about the test conditions, e.g. the discharge rate remains constant and there is no recharge during the test period. If all these assumptions are adhered to, a 'type' response is found depending on aquifer properties and the condition of the aquifer, i.e. confined, unconfined or leaky. Deviations from these assumptions are represented on the drawdown curves as changes in slope and curvature. Since drawdown curves are non-unique, similar shapes of curves can be produced from radically different scenarios. Ambiguity in interpretation can therefore result unless other (possibly circumstantial) information is taken into account.

Many authors have illustrated that classical pumping test analysis is possible in fractured rocks subject to several basic conditions (e.g. Snow, 1968; Freeze and Cherry, 1979; Domenico and Schwartz, 1990; Barker, 1991). The approach involves the replacement of the fractured media with a representative continuum in which values of aquifer properties can be assigned. A sufficiently large section of the aquifer needs to be tested to ensure that a representative measure of aquifer properties is given. A borehole that does not penetrate the important flowing fractures will not give a representative measurement of aquifer properties of the area. This is especially important in the Chalk where boreholes a few metres apart may penetrate different fracture systems and consequently give very different measures of aquifer properties.

The second important factor to consider when analysing pumping tests within the Chalk is the time scale over which water moves in response to pumping. In particular, how quickly water can diffuse from the low permeability matrix, to the relatively high permeability fracture system and subsequently to the large flowing fractures. If the small fractures and matrix can respond rapidly to the pressure changes initiated by the pumping test then the system can be analysed using the continuum approach; if there is a long time delay before the matrix responds, problems with analysis can arise. Barker (1991, 1993) undertook some simple calculations which suggested that the hydraulic diffusion within Chalk blocks was sufficiently rapid to allow classical pumping test analysis; however, such calculations are necessarily simplifications of an extremely complex system, and should be treated with caution.

With so many assumptions involved in pumping test analysis within the Chalk it is important to examine and interpret drawdown curves carefully, with as much additional information about the geology and hydrogeology of a site as possible. Then an appropriate model of analysis can be chosen (often the simplest is most appropriate due to the many unknown variables) and the data interpreted noting any deviations from 'type' behaviour. It is often the deviations from the norm that give valuable information about how an aquifer behaves.

Within this programme of data collection, over 1500 drawdown curves were examined and several common deviations from the 'type' curves were observed. In addition, although confidence may be placed in the transmissivity estimates from good pumping tests, estimates of the storage coefficient, even from very good tests, are usually lower than expected for the aquifer (see later). The following common deviations from 'type' curves were observed (see Figure 4.1.18):

a) *Gradual decrease in drawdown* (Figure 4.1.18a) This effect was widespread throughout the Chalk making the aquifer appear 'leaky'. There are several ways in which such a drawdown curve could be generated: leakage from overlying drift deposits; delayed drainage from matrix to fractures (possibly also associated with the often substantial thickness of the Chalk); partial penetration; leakage from above or below marl layers;

the cone of depression intersecting recharge boundaries (possibly associated with vertical fractures); delayed yield in unconfined Chalk. Unfortunately it is not possible to choose the correct model of behaviour without additional information from the site.

b) *Gradual increase in drawdown* (Figure 4.1.18b) A gradual increase in drawdown is often observed if a pumping test borehole is located within a valley (e.g. Owen and Robinson, 1978). This may be for two reasons. Firstly transmissivity is high within valleys reducing laterally up the valley sides. Therefore as the cone of depression moves outwards it intersects parts of the aquifer that have progressively poorer aquifer properties. The result is a gradual increase in drawdown. A second reason for an anomalous increase in the rate of drawdown is due to the decreasing permeability of the Chalk with depth; therefore as drawdown increases, the higher permeability Chalk near to the top of the aquifer is dewatered near to the well, which in turn increases the rate of drawdown.

c) *Sudden increase in drawdown* (Figure 4.1.18c) A sudden increase in drawdown (or 'dog leg' as it is often called) can result from the dewatering of important fractures (i.e. as a special case of (2) above), or possibly — and less commonly — the intersection of a hydraulic barrier in the aquifer. Since most of the important flowing fractures are near to the top of the Chalk aquifer, within the zone of water table fluctuation, a drawdown of only a few metres can actually dewater some of the most important fractures; the result is a significant decrease in transmissivity and therefore a change in gradient of the drawdown curve. Similarly, if the cone of depression intersects a barrier, the provision of water to the borehole is decreased and the drawdown increases.

d) *Initial high drawdown in pumping borehole* (Figure 4.1.18d) Initially high drawdown is occasionally observed because of poor borehole design. Since the most productive fractures in the Chalk are generally near to the top of the borehole, they can, on occasion, be blocked by casing. This would radically reduce the efficiency of the borehole and therefore increase the drawdown in the pumping well.

e) *Initial low drawdown in pumping and observation boreholes* (Figure 4.1.18e) This can usually be attributed to groundwater storage within the borehole or well. For example a borehole with a diameter of 1 m, pumped at 10 l/s, would take over a minute before the water held in storage within the borehole dropped by 1 m. This stored water initially masks the aquifer response to the pumping, acting as a buffer.

f) *Significantly different drawdowns in different observation boreholes* (Figure 4.1.18f) As a result of the anisotropy of the fracture network in the Chalk, aquifer properties measured in different observation boreholes can be very different. For example, an observation borehole along the axis of a valley is likely to give a different response to a borehole the same distance away from the abstraction borehole but perpendicular to the valley. Regional hydraulic gradients present across a test site affect the response of individual observation boreholes depending on their orientation. During long term pumping tests background water level fluctuations can also distort the response of distant observation boreholes, making analysis difficult.

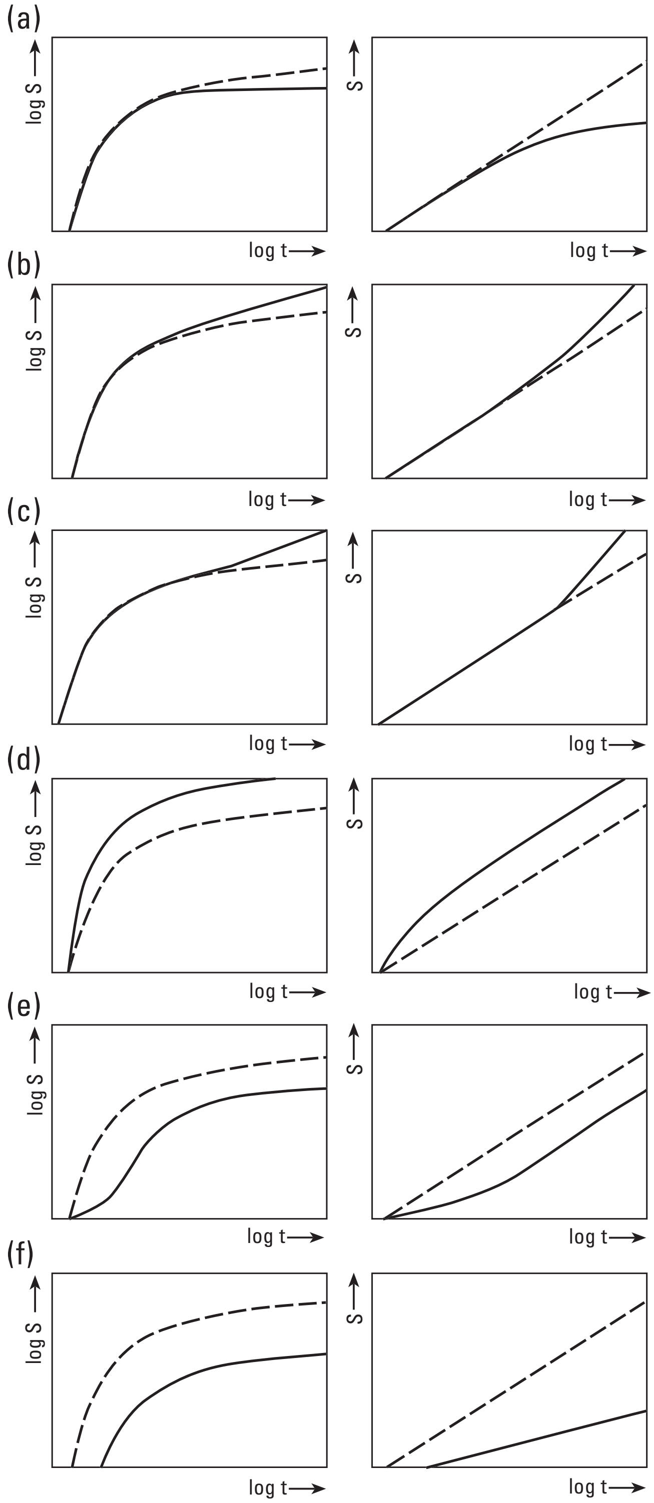


Figure 4.1.18 Various shapes of drawdown curves in the Chalk of England. For explanation see text.

It is impossible to unravel the various deviations from the 'type' response from observing only the drawdown data. It is important to know as much about a site as possible to help identify the correct conceptual model for the aquifer at the test location. Much could be learned about the way that groundwater flows through the Chalk by undertaking

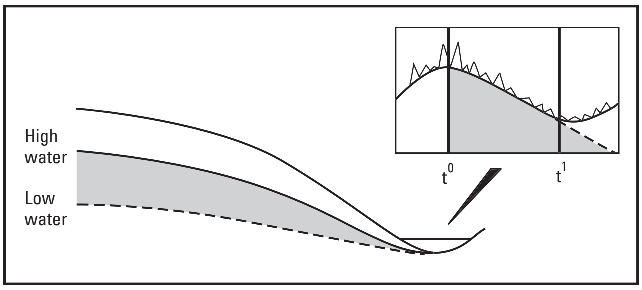


Figure 4.1.19 Illustration of the methodology for estimating the storage coefficient from groundwater level recession.

pumping tests that are properly instrumented with piezometers measuring the response of the various layers and hydraulic components of the aquifer.

Other methods of determining aquifer parameters

Various methods other than constant rate pumping tests have been used to calculate the aquifer parameters of the Chalk. Most of these are well known to the hydrogeologist and will not be discussed here, e.g. packer tests (see Price et al., 1978; Price et al., 1982; Price, 1994), tracer tests (e.g. Atkinson and Smith, 1974; Price et al., 1992; Banks et al., 1995) and flowmeter profile logs (Owen and Robinson, 1978). Where tests have been undertaken they will be discussed in the appropriate regional section.

Within fractured aquifers the geometry of the system is not well known, but is required to be specified for pumping test analysis. Systems of pumping test analysis are being developed for fractured aquifers which allow the geometry and dimension of the system to be arbitrary (e.g. Barker, 1988; Black, 1995). These techniques, however, have not yet been applied to the Chalk.

A method of calculating storage from recession curves has been applied to the Chalk, the results of which are of widespread importance to the estimation of storage throughout the Chalk (Headworth, 1972; Toynton, 1983; BGS, 1993). The method provides a regional value of the storage coefficient for a groundwater catchment by calculating the volume of groundwater flow (from river hydrographs) and calibrating it against the change in volume of the saturated aquifer (see BGS, 1993 and Headworth, 1972 for a detailed description of methodology). Figure 4.1.19 illustrates the basic concept of the technique. The results from the application of the technique to individual catchments is described in the appropriate regional sections — in general values of storage are found to be much higher than those calculated by standard pumping test analysis and are more in line with those used in regional models.

Values of unconfined storage coefficient obtained from pumping tests have long been understood to be underestimates, probably due to scaling effects, the short time period of the test and interference from borehole storage. Calculating borehole storage coefficient from groundwater level recessions measures the Chalk over a much longer time scale (about six months of the year), therefore should give a more accurate estimate of the regional storage available within the Chalk. BGS (1993) however, found that drainage between high and low water levels significantly underestimated the baseflow to streams and rivers. This was attributed to slow drainage from the unsaturated zone — in effect a delayed yield which continues to drain to the water table even after the recession has started.

4.1.7 The Upper Greensand aquifer

The Upper Greensand is generally a poor aquifer and is only considered here because of its hydraulic relation to the Chalk. It is not always present beneath the Chalk, and is absent in East Anglia, Yorkshire and Lincolnshire, and also east of a line drawn through Eastbourne, Sevenoaks and Dunstable (Rawson, 1992). The Upper Greensand reaches a maximum thickness (approximately 60 m) in the Weald, near Selborne, and at the western end of the Wessex basin — where it forms a substantial aquifer — thinning to the east (Gallois, 1965). The formation thins to the west over the Portsdown Swell, thickening again in the Vectian Basin where it oversteps the Gault.

The Upper Greensand shows great lithological variety, but the facies are generally fine grained, calcareous and glauconitic. The sands can be cemented forming 'malmstone'; a pale coloured rock containing abundant sponge spicules and a high proportion of colloidal silica, calcareous material and some clay and mica.

Flow within the Upper Greensand is both intergranular and through fractures depending on the degree of cementation. The lithological variety within the Upper Greensand results in hydrogeological complexity. Where poorly consolidated, flow is generally intergranular. The 'malmstone' however can act inconsistently: it has negligible primary porosity and permeability and can therefore act as a barrier to groundwater movement forming spring lines. Where the 'malmstone' is fractured however, the permeability can be quite high. The Upper Greensand generally has limited outcrop area and therefore receives little direct recharge. Where it lies beneath the Chalk, however, much of its recharge is thought to result from leakage through the Lower Chalk. The Chalk Marl is poorly fractured and has generally low transmissivity. The Upper Greensand, near to outcrop, generally has more favourable aquifer properties than the Chalk Marl, therefore the Chalk can act as a reservoir of water for the thinner Upper Greensand. Slow vertical leakage from the Chalk recharges the Upper Greensand which can transport the groundwater horizontally to boreholes or springs at the boundary of the Gault. Where deeply confined by the Chalk the aquifer properties of the Upper Greensand are generally poor.

4.1.8 Overview of aquifer properties data in the Chalk

Aquifer properties data for the Chalk are available from 2000 pumping tests at approximately 1300 locations throughout the England. As discussed in Chapter 2 these data are of varying quality having been calculated from pumping tests of different lengths analysed using both observation and production borehole measurements.

The geographic distribution of the available data is summarised in Appendix 4. The data are not evenly spread over the Chalk outcrop; the majority of sites are clustered within East Anglia, with a much lower density over the Hampshire and Thames Basins and also to the north in Yorkshire and Lincolnshire. At a larger scale the data are even less randomly distributed. Data are calculated from pumping tests undertaken in boreholes that have generally been drilled for production and are therefore located in areas that are known to be high yielding. Throughout the Chalk outcrop, data tend to be clustered within valleys, where the transmissivity and storage tend to be high. The data should therefore not be treated as indicative of the aquifer properties of the entire Chalk, but only of the *measured* sites, which are by their nature highly biased.

The Chalk outcrop has been divided into four different geographical regions to help the description and analysis of the aquifer properties distribution. Various factors were considered including the depositional, structural and glacial history. By dividing the Chalk on physical grounds, some of the problems arising from the clustering of the data should be overcome. The four regions are: (1) The Hampshire Basin and South Downs; (2) the Thames Basin (including the North Downs); (3) East Anglia; and (4) Yorkshire and Lincolnshire. Within these regions the Chalk is further divided into smaller areas to help describe regional variations. The structure of the chapters relating to each region, however, are slightly different, reflecting variations in the Chalk aquifer.

The distribution of transmissivity (test values) for the four regions are shown in Figure 4.1.20. To aid comparison between the regions the cumulative frequency distributions calculated for transmissivity have been plotted together (see Figure 4.1.21). All the regions show negatively skewed, approximately lognormal distributions. Several factors could contribute to this distribution: (1) the bias in the data towards high values (2) the difficulties in measuring extremely high transmissivity values and (3) the physical impracticability in the Chalk of gaining very high transmissivity, due to fracture aperture and turbulence. The data from Yorkshire and Lincolnshire have the highest values (median 1800 m^2/d), in part due to the hardness of the Chalk and therefore the possibility of fractures with larger apertures. Data from the Hampshire Basin also show a high proportion of high values (median 1000 m^2/d), possibly due to the high degree of structure in the Chalk and therefore increased fracturing. East Anglia and the Thames data illustrate similar distributions of transmissivity (medians 410 m^2/d and 580 m^2/d respectively). Both areas have a high degree of exploitation and therefore have more data from boreholes in poorer yielding situations than the other regions.

Storage coefficient data (tests values) for the four regions are plotted in Figure 4.1.22. Estimates of the storage coefficient greater than 0.1 have been omitted from the analysis. There are two reasons for such large values: (1) errors in the data; or (2) estimates of Upper Greensand or overburden storage. Either way, such high estimates

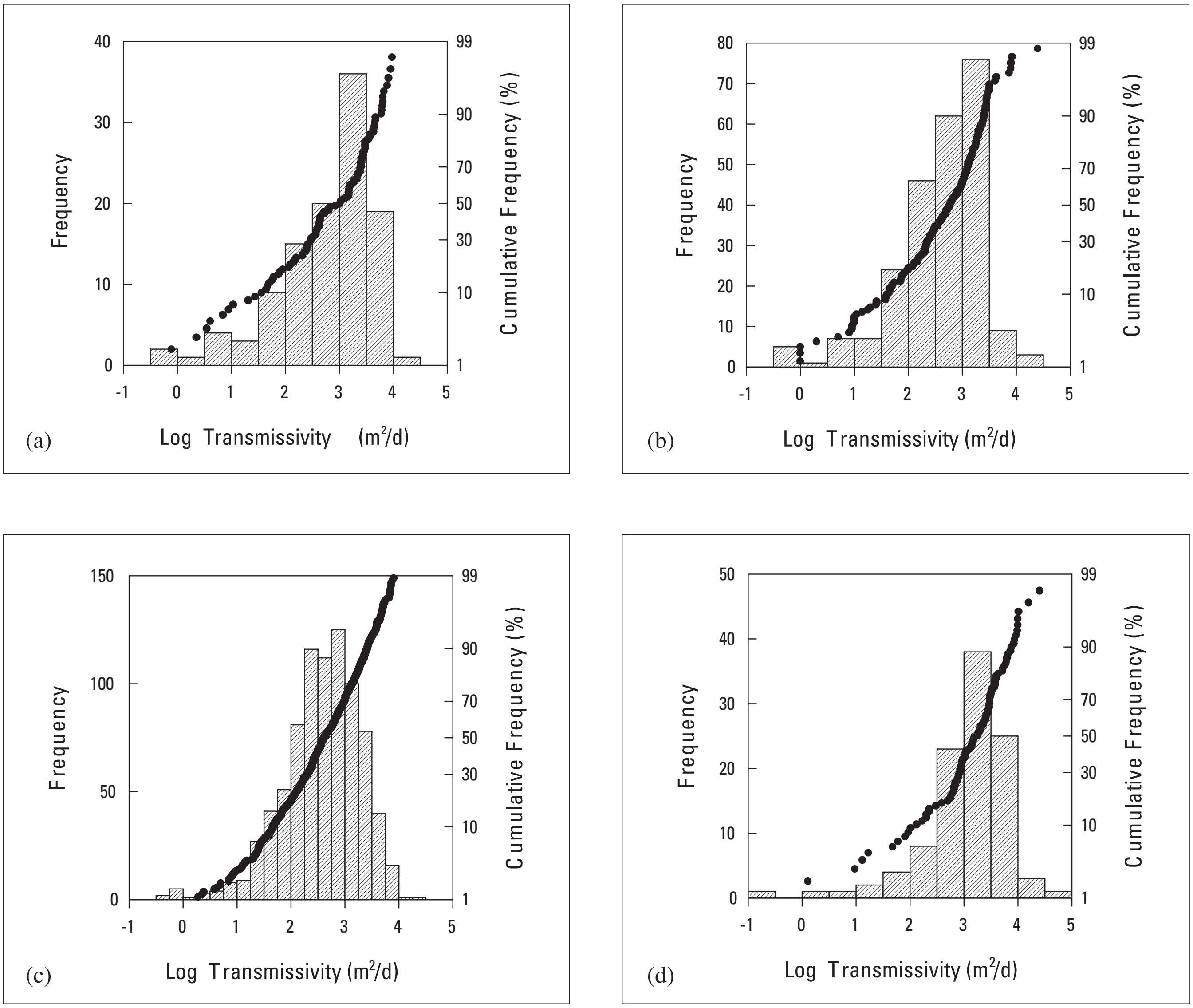
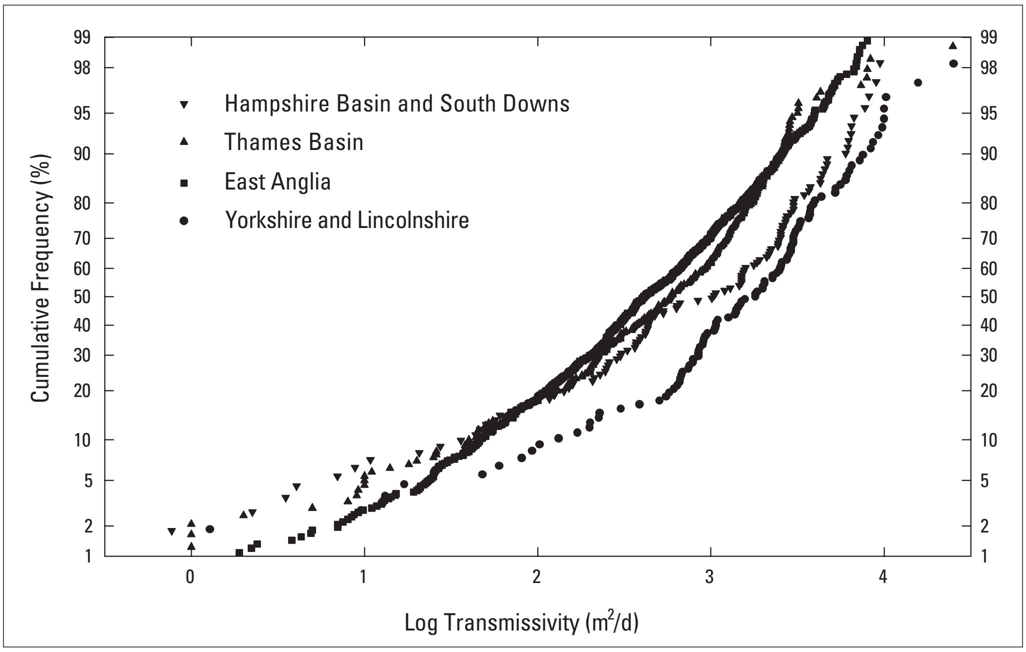


Figure 4.1.20 Distribution of transmissivity data from pumping tests throughout the Chalk:
(a) Hampshire basin and South Downs, (b) Thames Basin (including North Downs), c) East Anglia, and (d) Yorkshire and Lincolnshire.

Figure 4.1.21 Cumulative frequency distributions of transmissivity data from pump tests throughout the Chalk.



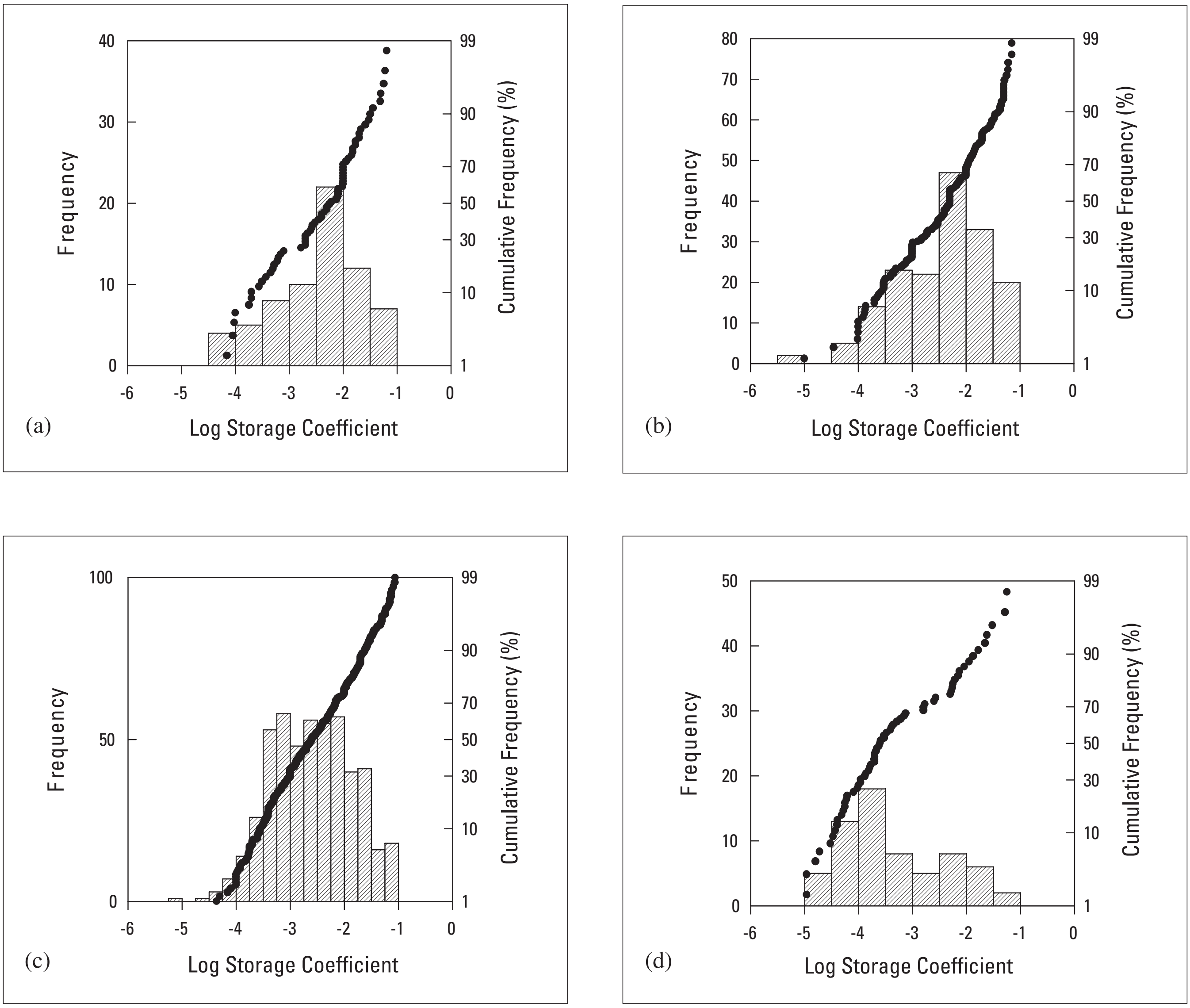


Figure 4.1.22 Distribution of storage coefficient data from pumping tests throughour the Chalk: (a) Hampshire Basin and South Downs, (b) Thames Basin (including North Downs), (c) East Anglia, and (d) Yorkshire and Lincolnshire.

were thought to obscure trends in the Chalk data and were therefore omitted.

There are significantly fewer estimates of storage coefficient than transmissivity. Both confined and unconfined data have been plotted together since few data were distinguished as one or the other. However, data are generally from unconfined Chalk. The median value of storage coefficient for the southern regions, Hampshire Basin and South Downs, Thames Basin and East Anglia show roughly similar distributions of data. The data approximate roughly to a lognormal distribution with the high value tail missing. This shape is exacerbated by data processing which omitted any data larger than 0.1 (see above). The median value and modal range of the storage coefficient both lie between 0.001 and 0.01 for these three regions with data ranging from 10^{-5} to 0.1. In Yorkshire and Lincolnshire the data distribution is bimodal. The most common values are about 10^{-4} and 0.01. In Yorkshire and Lincolnshire much of the aquifer is confined, therefore the two peaks probably represent the confined and unconfined values respectively.

It is generally recognised that estimates of storage coefficient from pumping tests in the Chalk are less than values required in groundwater models. Often the unconfined Chalk is quoted as having a storage coefficient from 0.01 to 0.03. An initial estimate for the confined Chalk is usually taken to be 10^{-4}.

As part of a project calculating the volume of groundwater stored in the Chalk aquifer, BGS (1993) analysed the regional distribution of the storage coefficient. The Chalk aquifer was divided into layers dependent on the depth from the top of the Chalk and the position in the stratigraphical sequence. Table 4.1.6 and Table 4.1.7 show the ranges of storage coefficient estimated for different areas of the Chalk.

Within each sub-area the distribution of both transmissivity and storage coefficient is discussed in considerably more detail, giving statistics for each area and any other information and data that is relevant to the aquifer properties. Maps are included in Appendix 1 which show data distribution and the areal distribution in aquifer properties.

4.2 The Aquifer Properties of the Hampshire Basin and the South Downs

4.2.1 Introduction

Within the Hampshire Basin and South Downs, the Chalk has been affected by Alpine tectonics, resulting in more structural complexity than in other areas in England. Large folds and faults exist which affect the hydrogeology of the region, while smaller fracture zones and flexures also have an impact. The area was not glaciated, but was significantly affected by periglaciation. The topography is characteristic of chalk downland, with steep escarpments and long gently sloping dip slopes containing ephemeral streams and dry valleys. Clay-with-flints is found over much of the higher ground, with Head (Coombe) deposits and alluvium found within the valleys. The hydrogeology of the area is complex, with many factors affecting the development of aquifer properties.

Aquifer properties data are not distributed evenly over the Hampshire Basin and South Downs: some areas (e.g. the Candover and Alre Catchments in Hampshire and parts of the South Downs) have been investigated in detail, while information is lacking in other areas.

Table 4.1.6 Storage coefficients for the Chalk in the southern province (after British Geological Survey, 1993).

	<10 m below top Chalk		10–30 m below top Chalk		>30 m below top Chalk	
	Sy	Ss (m^{-1})	Sy	Ss (m^{-1})	Sy	Ss (m^{-1})
RWL above top of Chalk	$1–3 \times 10^{-2}$	$1.5–1.6 \times 10^{-5}$	$2–7 \times 10^{-3}$	$1.5–1.6 \times 10^{-5}$	1×10^{-3}	$0.68–1.6 \times 10^{-5}$
RWL in Upper Chalk	$3–5 \times 10^{-2}$	$1.5–1.6 \times 10^{-5}$	$0.5–2 \times 10^{-2}$	$1.5–1.6 \times 10^{-5}$	$1–2 \times 10^{-3}$	$0.68–1.6 \times 10^{-5}$
RWL in Middle Chalk	$1–3 \times 10^{-2}$	$7.3–7.6 \times 10^{-6}$	$2–7 \times 10^{-3}$	$7.3–7.6 \times 10^{-6}$	1×10^{-3}	$6.8–7.6 \times 10^{-6}$
RWL in Lower Chalk	1×10^{-2}	$6.8–7.3 \times 10^{-6}$	2×10^{-3}	$6.8–7.3 \times 10^{-6}$	1×10^{-3}	$6.8–7.3 \times 10^{-6}$

Sy = specific yield; Ss = specific storage; RWL = rest water level in Spring 1975.

Table 4.1.7 Storage coefficients for the Chalk in the northern province (after British Geological Survey, 1993).

	<10 m below top Chalk		10–30 m below top Chalk		>30 m below top Chalk	
	Sy	Ss (m^{-1})	Sy	Ss (m^{-1})	Sy	Ss (m^{-1})
RWL above top of Chalk	$0.5–2 \times 10^{-2}$	$1.5–1.6 \times 10^{-5}$	$2–7 \times 10^{-3}$	$1.5–1.6 \times 10^{-5}$	1×10^{-3}	$0.66–1.6 \times 10^{-5}$
RWL in Upper Chalk	$0.5–2 \times 10^{-2}$	$1.5–1.6 \times 10^{-5}$	$0.5–2 \times 10^{-2}$	$1.5–1.6 \times 10^{-5}$	$1–2 \times 10^{-3}$	$0.66–1.6 \times 10^{-5}$
RWL in Middle Chalk	$0.5–2 \times 10^{-2}$	$6.6–7.1 \times 10^{-6}$	$2–7 \times 10^{-3}$	$6.6–7.1 \times 10^{-6}$	1×10^{-3}	$6.6–7.1 \times 10^{-6}$
RWL in Lower Chalk	$0.5–1 \times 10^{-2}$	$6.6–7.1 \times 10^{-6}$	2×10^{-3}	$6.6–7.1 \times 10^{-6}$	1×10^{-3}	$6.6–7.1 \times 10^{-6}$

Sy = specific yield; Ss = specific storage; RWL = rest water level in Spring 1975.

For the purposes of this study the region has been further subdivided into five areas (see Figure 4.2.1), which are treated separately in subsequent sections. The subdivisions were chosen primarily for convenience in dealing with the data rather than for strictly hydrogeological reasons. Within each section, a general description of the geology and physiography is given along with an indication of the groundwater investigations that have been undertaken within the area. Then the data-holdings within the Aquifer Properties Database are described, with a summary of pertinent statistics. A discussion of the vertical and areal distribution of both transmissivity and the storage coefficient follow, and where appropriate a discussion of the various controls on aquifer properties or other additional information is included.

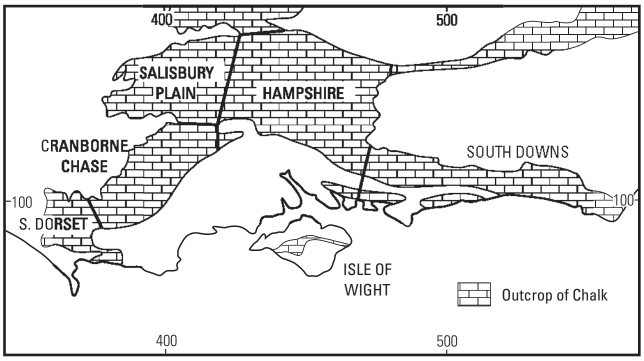


Figure 4.2.1 The Chalk of the Hampshire Basin and South Downs.

4.2.2 South Dorset

Introduction

Geological and geographical setting

The Chalk in south Dorset is extensively deformed. Consequently, the geomorphology, hydrology and hydrogeology of the area are complex and do not conform to the patterns observed in other chalkland areas. The area is drained to the south-east by the rivers Frome and Piddle and their tributaries (see Figure 4.2.2). Boundaries of the surface water and groundwater catchments are not, however, coincident. Much of the southern part of the area drains southward and discharges to the sea via two large springs at Lulworth Cove and Arish Mell, and also indirectly via the Portland Sands within the Jurassic sequence (Alexander, 1981).

The structure of the area is dominated by the Purbeck Monocline which strikes east–west. The structure is thought to have resulted from the reactivation of Variscan faults in the underlying Palaeozoic strata by Cenozoic tectonics. Associated with the monocline are a number of smaller folds and faults.

Most of the area is underlain by Upper Chalk with the Middle and Lower Chalk having very narrow outcrops. Some of the higher ground has a thin cover of Pleistocene or recent deposits. The Chalk is overlain eastwards the east by the relatively impermeable Palaeogene deposits.

There are several Chalk and Upper Greensand outliers beyond the western escarpment. The Upper Greensand has the dominant outcrop with only a small, relatively thin, Chalk outcrop. The outliers towards the coast include Upper, Middle and Lower Chalk, while further inland the Upper and Middle Chalk may be absent. There is a thick covering of clay-with-flints over most of the outcrop of the outliers.

The Chalk and Upper Greensand aquifer also outcrops to the south of the Hampshire Basin on the Isle of Wight. The strata form the southern limb of a monocline which dips to the north at about 20–30°. Chalk also outcrops on the south of the island on the southern limb of a denuded anticline forming the Southern Downs which rise to about 240 m OD. The Chalk and Upper Greensand outcrop on the island is actually quite small but the aquifer is significant in terms of the water resources of the island.

Groundwater studies in the area

Several studies have been undertaken in south Dorset. An investigation by Wessex Water Authority into the water resources of the Chalk of north Lulworth was conducted in the early 1970s. This work was continued and then written into a PhD thesis by Alexander in 1981. A resistivity survey was conducted in the South Winterbourne valley to ascertain the depth of the Grey Chalk–Chalk Marl interface and therefore the variations in the effective aquifer thickness (Robins and Lloyd, 1975). A further study by the Wessex Water Authority was carried out to locate high transmissivity zones identified in the initial study. During this study down-hole logging and surface geophysics were successfully integrated (Houston et al., 1986).

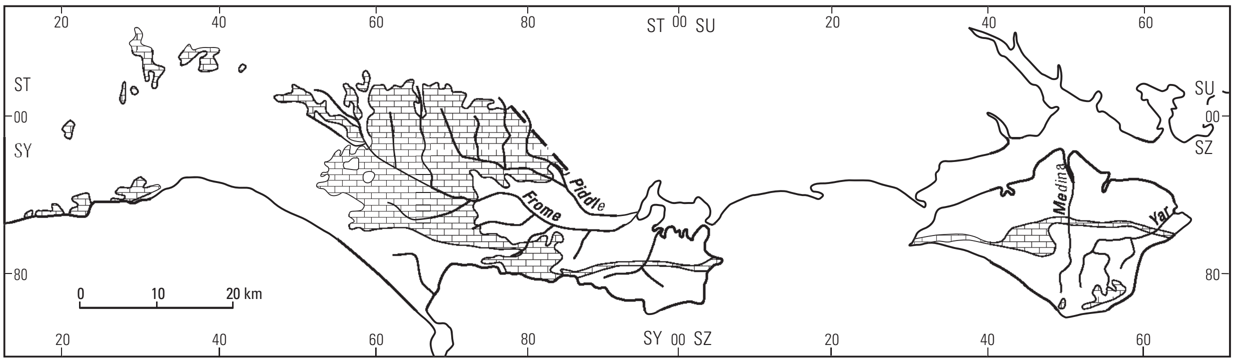


Figure 4.2.2 Location map of the Chalk of south Dorset, illustrating the Chalk outcrop and the river network.

Aquifer properties

General statistics

Pumping test data exist at 28 locations in the South Dorset area. Thirty-eight pumping tests have been undertaken giving 38 test estimates of transmissivity and 19 of the storage coefficient. Figures 4.2.3 and 4.2.4 show the transmissivity and storage data respectively. Transmissivity data vary from 0.8 to 3000 m^2/d, with a geometric mean of 210 m^2/d and median of 330 m^2/d. Twenty-five percent of the data are less than 49 m^2/d and 75% are less than 1500 m^2/d. Storage coefficient data (values of storage coefficient >0.1 have been omitted from analysis; see section 4.1.8 for further details) vary from 9×10^{-5} to 0.064 with a geometric mean of 0.003 and median of 0.0039. The data approximate to a lognormal distribution; 25% of the data are less than 6.3×10^{-4} and 75% less than 0.015. The majority of the Chalk data are unconfined although some are confined by drift deposits in the outliers. The high storage values are dominated by Upper Greensand data. A direct relation is given between specific capacity and transmissivity from nine pumping tests having the available information (see Figure 4.2.5).

The effect of structure

As South Dorset is the most deformed area of Chalk in England, it is important to consider how the structure has affected the aquifer properties. The dominant structure is provided by the Purbeck Monocline. Associated faults and folds extend over the outcrop of the Chalk and are significant in controlling the aquifer properties of the area.

Laboratory work has illustrated that highly folded chalk has lower porosity and intergranular permeability than undisturbed chalk (Alexander, 1981) (Figure 4.2.6). Folding

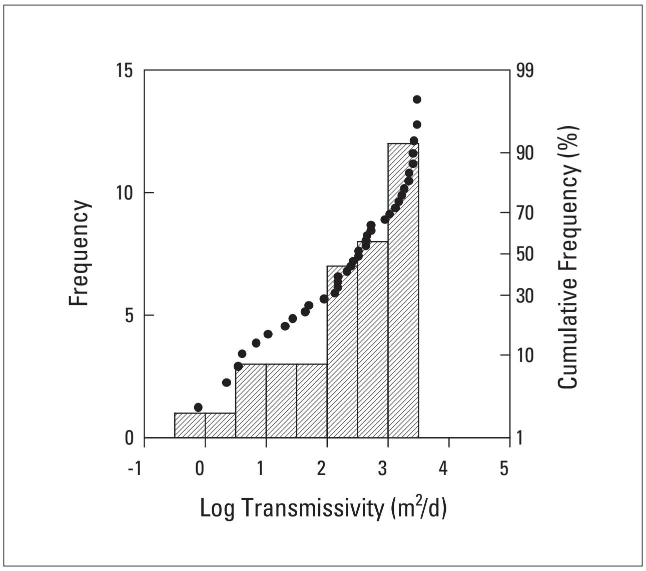


Figure 4.2.3 Distribution of transmissivity data from pumping tests in the Chalk and Upper Greensand of south Dorset and the Isle of Wight.

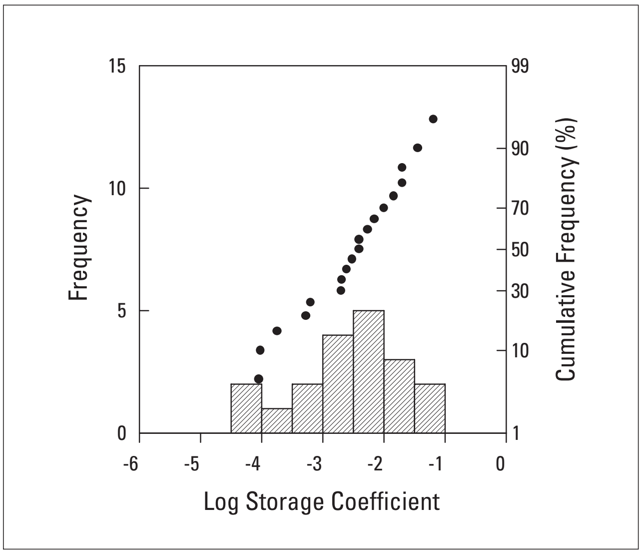


Figure 4.2.4 Distribution of storage coefficient data from pumping tests in the Chalk and Upper Greensand of south Dorset and the Isle of Wight.

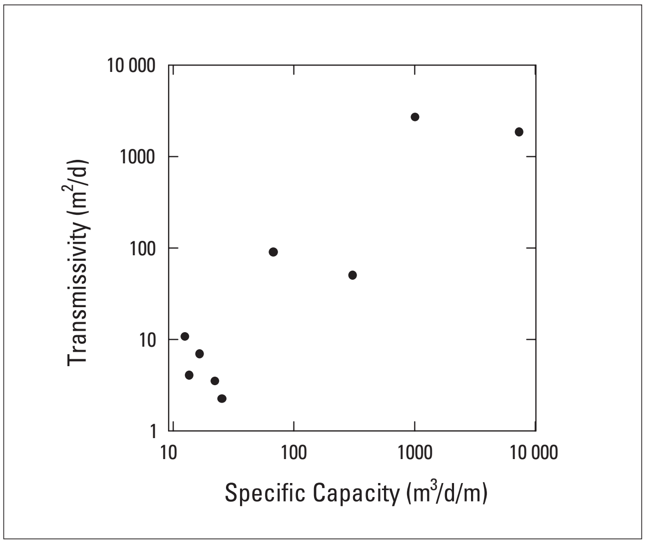


Figure 4.2.5 Plot of transmissivity against specific capacity (uncorrected) for the Chalk of south Dorset and Isle of Wight areas.

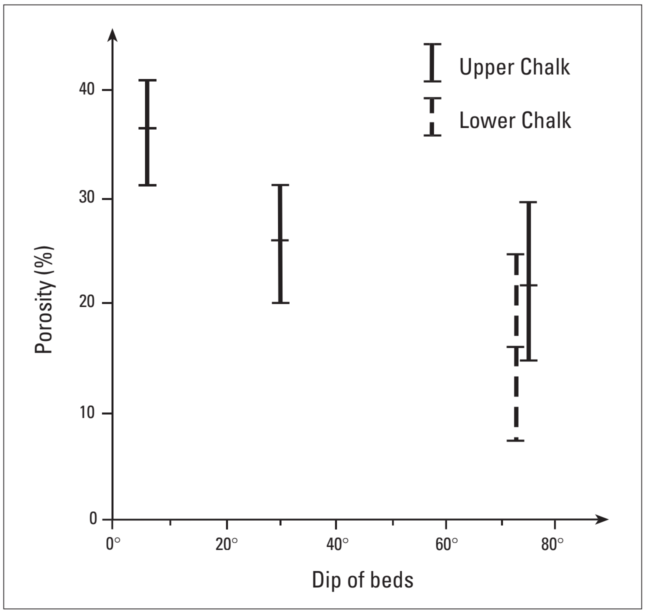


Figure 4.2.6 Plot of porosity against dip for the Chalk of south Dorset (after Alexander, 1981). As the Chalk becomes increasing deformed, the porosity reduces.

therefore can change the chalk from a soft highly porous material into a harder limestone. From the same study it was observed that generally, where the Chalk has been tectonically hardened, the transmissivity and storage coefficient are reduced, suggesting that the fracture distribution within the Chalk has also been altered. The mechanism for this is unknown but is possibly a result of chemical and mechanical diagenetic processes closing fractures.

Faulting associated with the folded Chalk, however, appears to have had a significant effect in locally *increasing* transmissivity. The faults have provided a preferential zone for rapid groundwater flow, which has been further enhanced by dissolution. An example of faulting increasing transmissivity is seen at Lulworth (Houston et al., 1986).

Vertical variations in aquifer properties

The effective base of the aquifer is taken to be the middle of the Upper Greensand at the top of the Exogra Sandstone. This horizon is well cemented and has low permeability. The Chalk Marl at the base of the Lower Chalk has low permeability (Robins and Lloyd, 1973; Alexander, 1981), but the lack of springs emerging at the top of the marls imply a large component of vertical leakage to the Upper Greensand. On the scarp slopes most of the springs emerge from within the Upper Greensand at the top of the Exogra Sandstone (Figure 4.2.7). The Chalk Rock and Melbourn Rock can also be important flow horizons when near to the water table. Minor flows can be detected when these horizons are found at depth. As found in other chalkland areas, the groundwater does not circulate deeply within the aquifer, rather the most important flow horizons are within the top 50 m of the water table where fractures and bedding planes have been enlarged by solution.

Areal distribution of aquifer properties

LULWORTH

The transmissivity distribution in the east of the area around Lulworth is strongly controlled by structure, which appears to be discordant with the general topography. Groundwater level maps of the area do not give the usual subdued version of topography but are rather a reflection of various structures within the Chalk (Figure 4.2.8). Due to the tectonic hardening of the Chalk and consequent reduction in intergranular porosity, permeability and open fractures, the general transmissivity and storage of the Chalk has been reduced. Transmissivity values from pump tested sites generally vary from around 250 m^2/d to about 1000 m^2/d with typical values from

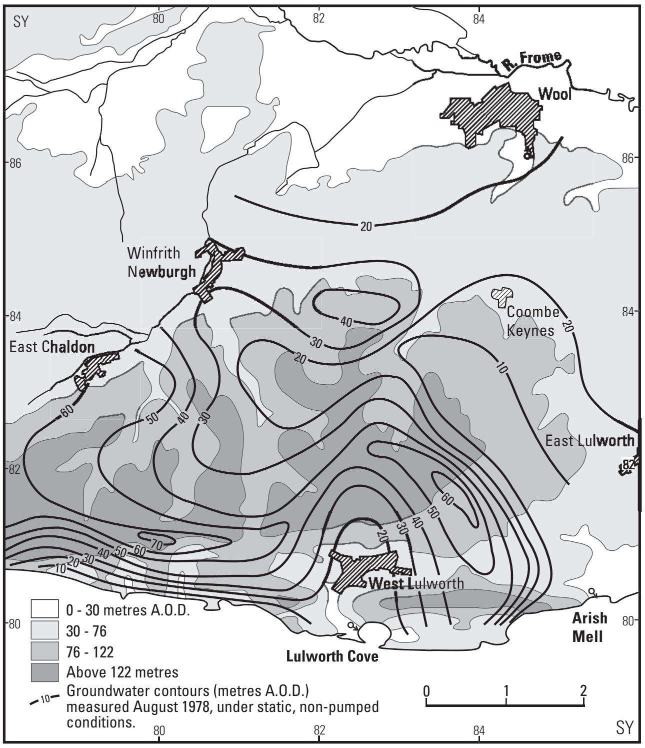


Figure 4.2.8 Groundwater levels and topography at Lulworth. The surface water and groundwater catchments are not coincident, and rapid groundwater flow is observed both at Lulworth Cove and Arish Mell (after Institute of Geological Sciences and Wessex Water Authority, 1979).

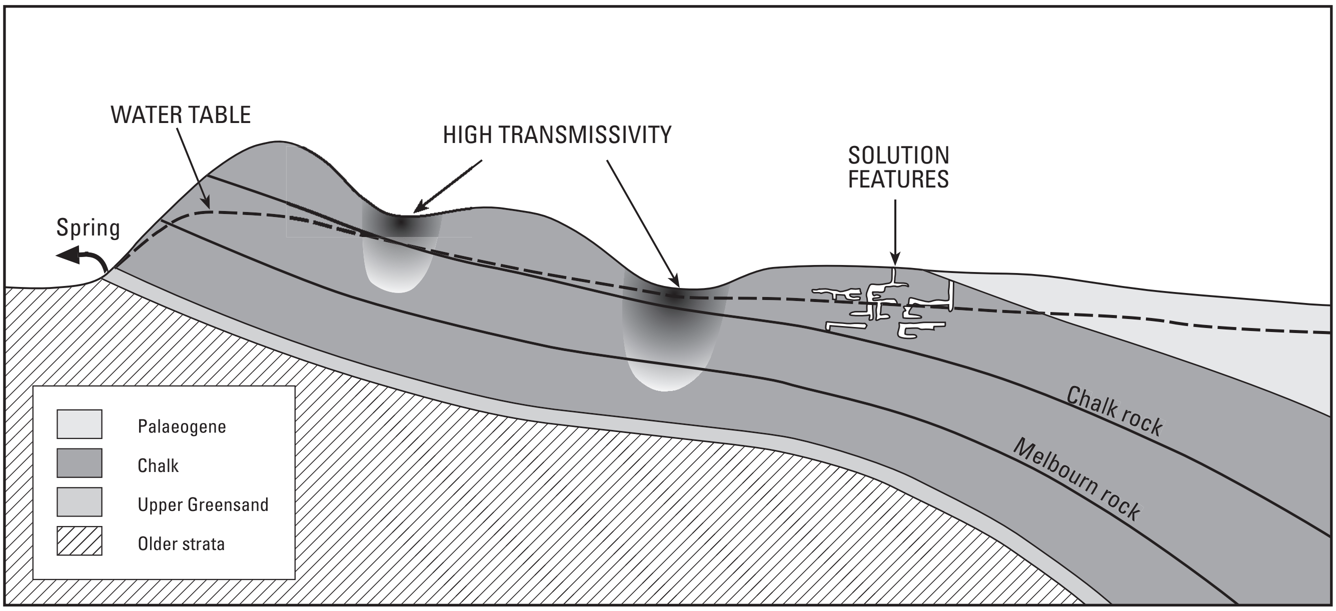


Figure 4.2.7 Schematic cross-section through the Chalk of south Dorset, illustrating the high transmissivity values in the valleys, solution features near to the Palaeogene outcrop, and the emergence of springs within the Upper Greensand.

300 to 500 m^2/d. The calculated storage coefficient for various tests was very low, usually about 1×10^{-4}. There are no pumping test data from the Purbeck Hills on top of the monocline. It is thought, however, that the aquifer properties will be poor as a result of the steep inclination and low water levels.

In certain areas, however, the transmissivity has been significantly enhanced by fracture zones which have been enlarged by solution to form groundwater conduits. Tracer tests and pumping tests have proved local rapid transport towards a series of springs at Arish Mell [SY 854 807] (Figure 4.2.8). A very low hydraulic gradient exists in the area and large water level fluctuations have been observed in response to recharge. These two observations, in conjunction with drilling, indicate a narrow network of discrete solution enhanced fractures, which if intersected would yield very high transmissivity values. Another such feature is noted at Lulworth cove (Figure 4.2.8). These high transmissivity solution features probably developed after the sea breached the Chalk aquifer during the Holocene. Groundwater flow was reversed, flowing southward along the fracture zones and discharging at discrete points along the cliff line (Houston et al., 1986). Pumping tests in these high transmissivity zones indicate values ranging from around 1500 m^2/d to in excess of 2500 m^2/d and storage coefficients of 0.0025 to 0.04.

Frome/Piddle

There is some evidence of rapid groundwater flow between the tributaries of the River Frome and the River Piddle (Stanton, W, personal communication). The discharges from the Frome catchment are larger than the calculated recharge over the catchment. It is suggested that the deficit is met by groundwater flow from the River Piddle. Rapid groundwater flow could take place along faults or enhanced transmissivity zones created under different hydrological conditions. At the present time no such features have been intersected by drilling, although discrete springs and sinks have been identified in both rivers. Geomorphological solution features in the Chalk associated with the Eocene and other overlying deposits are well documented in this area, especially between the Rivers Frome and Piddle (Sperling et al., 1977). These features include dolines, solution pipes and swallow holes, which could permit rapid recharge to the aquifer (Figure 4.2.10). As yet there is no direct evidence linking such geomorphological features to zones of high transmissivity. Their existence, however, indicates the increased solution activity close to, and beneath, Eocene cover which could help to develop higher transmissivity zones.

In the South Winterbourne catchment, the structure in the Chalk is less pronounced, and the aquifer properties become more predictable. Here, groundwater levels are a reflection of topography and transmissivity reverts to a more classical model of low values in the interfluves and high values in the valleys. Transmissivity data from valley sites indicate values ranging from around 500 to 1000 m^2/d, typically 800–1000 m^2/d and storage coefficient of 5×10^{-4} to 0.035. A range of small pumping tests have been carried out on interfluve locations throughout the west of the south Dorset areas (Alexander, 1981). Although these tests are probably unreliable due to the very short duration of the tests, they do give a general indication of the variation of aquifer parameters. Transmissivity values ranging from 0.04 to 340 m^2/d have been measured, although typically values were less than 50 m^2/d.

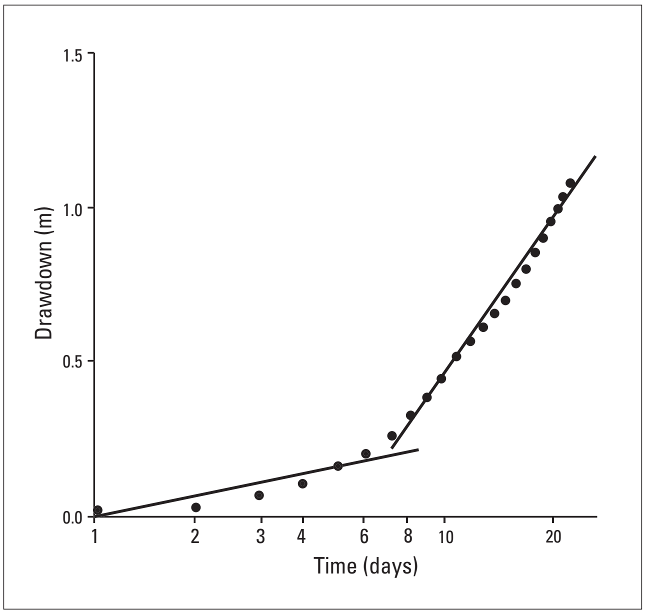


Figure 4.2.9 Semi-log plot of drawdown frrom a pumping test in the South Winterbourne Valley. The sharp break in slope has been interpreted as the cone of depression intersecting the low permeability Chalk Marl (data from Alexander, 1981).

The distribution of aquifer properties is slightly complicated by the presence of the low permeability Chalk Marl towards the base of the Lower Chalk (Robins and Lloyd, 1975). This low permeability layer occurs near to the surface either due to faulting, or, further up the valley, due to denudation. Although no aquifer properties data are directly available for the Chalk Marl, its influence can be observed in drawdown curves from other boreholes. As the cone of depression from a borehole expands, breaks in the drawdown curve are observed as the Chalk Marl is intersected (see Figure 4.2.9). The scarp edge of the Chalk outcrop, defining the edge of the aquifer, also affects nearby boreholes, resulting in a break in the drawdown curve.

Empool

In the Empool area where the Chalk becomes confined by Palaeogene deposits, high transmissivity values have been recorded (2000–15 000 m^2/d). Low hydraulic gradients are associated with the high transmissivity, and it is possible that the aggressive water from the Palaeogene through-flow has enhanced the solution of fractures and led to the development of high transmissivity. There are no data to illustrate any reduction in transmissivity with increasing degree of confinement.

The outliers

There have been a number of pumping tests undertaken in the outliers. The Upper Greensand is more important for supply than the Chalk because of its larger exposure. Transmissivity values from the Upper Greensand vary from 2 to 25 m^2/d, although they are commonly less than 10 m^2/d. There have been very few pumping tests undertaken in the Chalk outliers. Transmissivity values of less than 10 to 2500 m^2/d were recorded. It is believed, however, that the aquifer properties of the Chalk are generally poor within the outliers (Cosgrove, T, personal communication). This could be due to their small size and thick covering of clay-with-flints which could limit the circulation of groundwater and therefore development of secondary permeability.

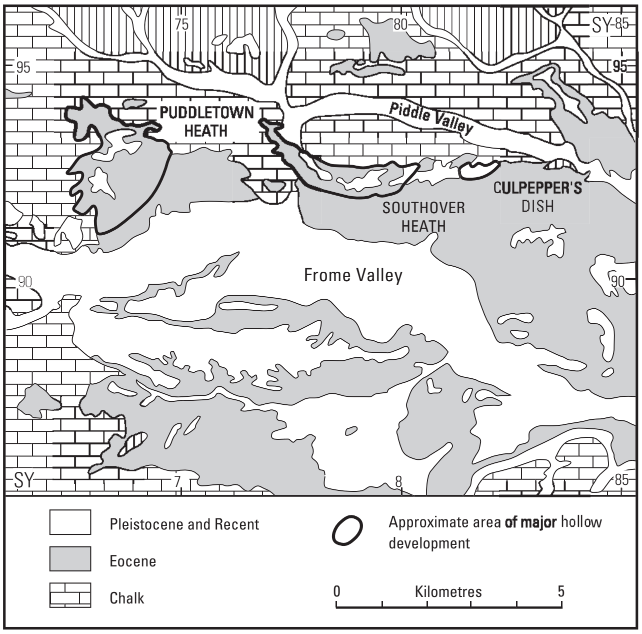


Figure 4.2.10 The distribution of solution features in the Chalk of the Dorset Heathlands, illustrating the association with the younger strata (after Sperling et al., 1977).

The Isle of Wight

Little aquifer properties information exists for the Isle of Wight. Within the Central Downs, the Upper Greensand and Lower, Middle and Upper Chalk all outcrop and are used for public supply — with the Upper and Middle Chalk used most extensively. The Upper Greensand is also quite significant as an aquifer. Springs within the area emerge from within the Upper Greensand indicating that groundwater can leak from the Chalk into the Upper Greensand. The base of the aquifer is taken as being the top of the Passage Beds (micaceous silts of low permeability). The effective thickness of the Upper Greensand aquifer is generally 20–30 m and the hydraulic conductivity approximately 1 m/d (Shaw and Packman, 1988). The Plenus Marls at the top of the Lower Chalk and also the chert beds at the top of the Upper Greensand are both thought to have low hydraulic conductivity and may limit groundwater flow. Pumping tests within the Chalk indicate transmissivity values ranging from around 100 to over 300 m^2/d.

Upper Greensand, Lower and Middle Chalk outcrop within the Southern Downs. However, as the Chalk is rarely saturated, the Upper Greensand forms the aquifer. The spring line is located within the Upper Greensand at the top of the Passage Beds, indicating that only the top of the Upper Greensand can be considered as an aquifer. Fracture flow predominates within the sandstone, although it can be quite friable (Shaw and Packman, 1988). A rough estimation of the hydraulic conductivity of the aquifer has been made from water level measurements; these indicate a hydraulic conductivity of 0.7 m/d.

4.2.3 North Dorset Downs and Cranborne Chase

Introduction

Geological and geographical setting

The North Dorset Downs and Cranborne Chase form a beautiful area of Chalk downland. Upper Chalk crops out over the majority of the area, with Middle and Lower Chalk exposed in the upper reaches of some valleys and on the escarpment edge. The Upper Greensand is exposed occasionally in deep valleys and has quite a large outcrop at the foot of the escarpment, particularly around Shaftesbury (Figure 4.2.11). The Chalk dips to the south-east where it is overlain by younger rocks. The river and dry valley network in the area is highly developed, with the valleys cutting back far up the dip slope. Towards Salisbury, in the north of the area, the Chalk is relatively strongly folded.

Many interfluves in the east of the area have a cap of Eocene deposits. The bottom of most river valleys contain alluvial deposits or valley gravels and clay-with-flints is evident on interfluves, especially high up on the dip slope.

The outcrop is drained to the south-east by tributaries of several river networks, such as the Frome, Piddle, Stour and Ebble. The River Stour rises in the Lower Cretaceous and Jurassic strata to the north-west of the Chalk outcrop. North of the Stour the Chalk downland is known as Cranborne Chase, while to the south it is referred to as the North Dorset Downs.

Groundwater investigations

Only a limited amount of aquifer properties information was available for this area. There are no records of any groundwater investigation or research into the aquifer properties, therefore the suggested distribution relies heavily on the knowledge and experience of the local hydrogeologists in the Agency and Wessex Water.

Aquifer properties

General statistics

Aquifer properties data exist at 11 locations in the Cranborne Chase area. Sixteen pumping tests have been undertaken giving 16 estimates of transmissivity and 8 of the storage coefficient. Figures 4.2.12 and 4.2.13 show the transmissivity and storage data respectively. Transmissivity data vary from 0.2 to 20 000 m^2/d, with a geometric mean of 1600 m^2/d and median of 2800 m^2/d. Twenty-five

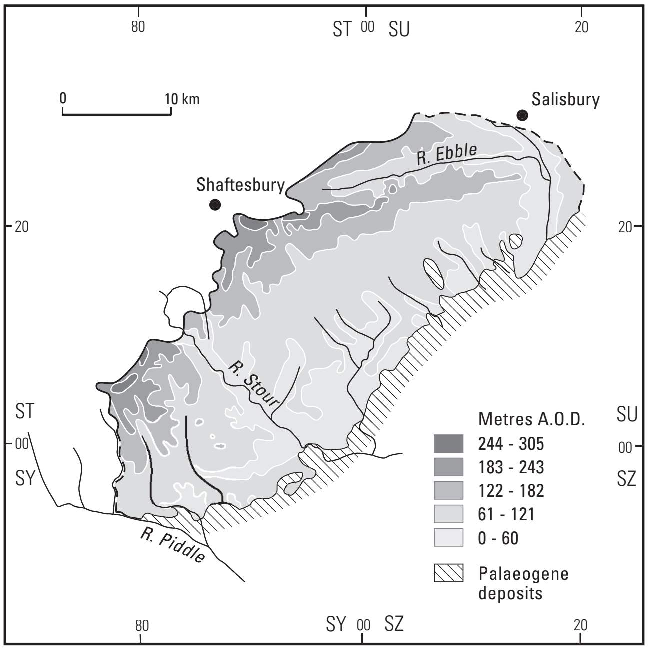


Figure 4.2.11 Location map of the Chalk of the North Dorset Downs and Cranborne Chase, illustrating the Chalk outcrop and the river network.

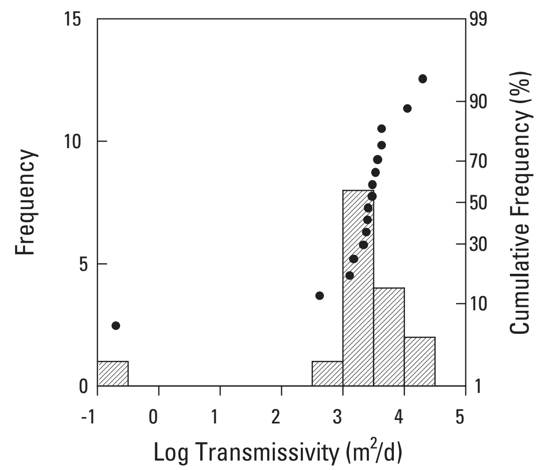


Figure 4.2.12 Distribution of transmissivity data from pumping tests in the Chalk and Upper Greensand of the North Dorset Downs and Cranborne Chase.

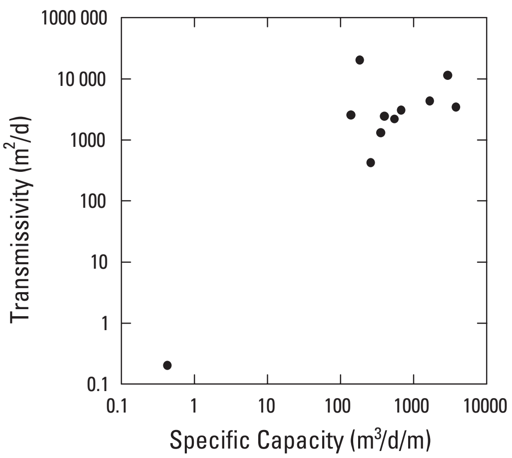


Figure 4.2.14 Plot of transmissivity against specific capacity (uncorrected) for the Chalk of Cranborne Chase and the North Dorset Downs.

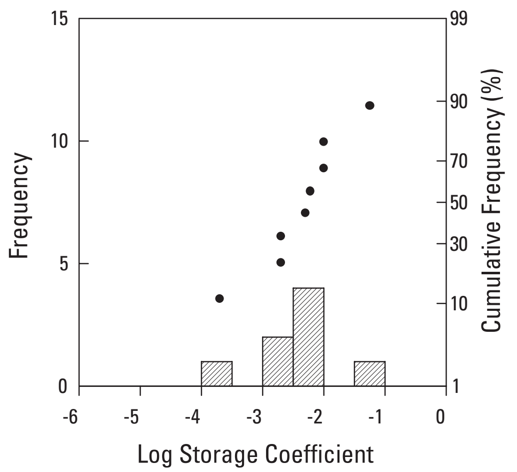


Figure 4.2.13 Distribution of storage coefficient data from pumping tests in the Chalk and Upper Greensand and the North Downs and Cranborne Chase.

percent of the data are less than 1600 m^2/d, with 75% less than 4100 m^2/d. Storage coefficient data (estimates of storage coefficient greater than 0.1 have been omitted; see section 4.1.8 for explanation) vary from 2×10^{-4} to 0.057 with a geometric mean of 0.0044 and median of 0.0055. Twenty-five percent of the data are less than 0.002 and 75% less than 0.01. The area has very few data points to describe the aquifer properties and this limited information is very biased towards high values in the valleys; therefore the statistics should be treated cautiously. However, sufficient data exist to suggest a direct relation between log transmissivity and log specific capacity (see Figure 4.2.14).

Aquifer thickness

The thickness of the aquifer is governed by the depth to which open fractures exist. No data are available concerning the vertical variation in aquifer properties, but there appears to be no evidence to suggest that the area is atypical. Therefore, by comparison with other areas, the most productive fractures are probably in the top 50 m of the aquifer. The Chalk Marl within the Lower Chalk is relatively impermeable and may represent a zone of reduced transmissivity.

Areal distribution of aquifer properties

The pattern of transmissivity tends to follow the topographic model: transmissivity and storage are low in the interfluves and high in the valleys. Boreholes that have been drilled on the interfluves for farming or domestic use have, in general, very low yields and on occasion are dry. The water table is deep, often within the Middle or Lower Chalk, giving a thick unsaturated zone. This can have the effect of reducing the solution potential of recharge and limiting the development of solution enhanced fractures. Occasionally, where hardgrounds (e.g. Chalk Rock) and other important bedding features are close to the ground surface, and within the zone of water table fluctuation, high transmissivity can develop.

Within the valleys, transmissivity can be quite high. Disappointing yields, however, have been encountered in valley bottoms very close to highly productive boreholes. This highlights the discrete nature of the high transmissivity zones that have resulted from the solution enhancement of faults and fractures. High transmissivity values will only be recorded where a borehole intersects productive fractures. Although the fracture systems are better developed in the valleys than the interfluves, a high yielding borehole is never guaranteed.

The transmissivity of the Chalk aquifer is thought to be better developed close to the feather edge of the Eocene strata. Although no pumping test results are available for this zone, it is accepted by local hydrogeologists that the yields of boreholes located close to the Eocene deposits are higher.

The Upper Greensand outcrops as a narrow band in the south and as a wider band at the foot of the Chalk escarpment in the north, and forms an important local aquifer at outcrop. The thickness of the Upper Greensand varies from about 16 m to 57 m, although the formation cannot be considered as an aquifer throughout the whole of the area. There are no available aquifer properties for the Upper Greensand within the area, although transmissivity values of around 300 m^2/d and a storage coefficient of 0.03 are typical for other areas. The springs on the escarpment are usually located at the base of the Upper Greensand, illustrating a sharp boundary with the underlying Gault, although some springs do emerge from within the Upper Greensand and others from the boundary with the Lower Chalk. The presence of springs at different horizons indicates the heterogeneity of the various members of the Upper Greensand, which do not always behave in a hydraulically consistent manner.

A chert bed, known as the Boyne Hollow Chert, occurs towards the top of the Upper Greensand. It is not present consistently throughout the area, but is lenticular, and can be up to 20 m thick. When fractured, the chert can be highly permeable, providing rapid groundwater flow. The layer can be particularly important when overlain by the Lower Chalk, where it can act as a horizontal drain to vertical leakage through the less permeable marls (Figure 4.2.15). This cherty layer occurs throughout the western section of the area from just beneath the escarpment south of Shaftesbury to just east of Westbury in the north. Where not fractured, the Chert can act as a hydraulic barrier at the top of the Upper Greensand resulting in springs issuing from the top of this layer.

4.2.4 Salisbury Plain

Introduction

Geological and geographical setting

The chalklands to the north of Salisbury comprise a large, relatively flat, upland plain known as the Salisbury Plain.

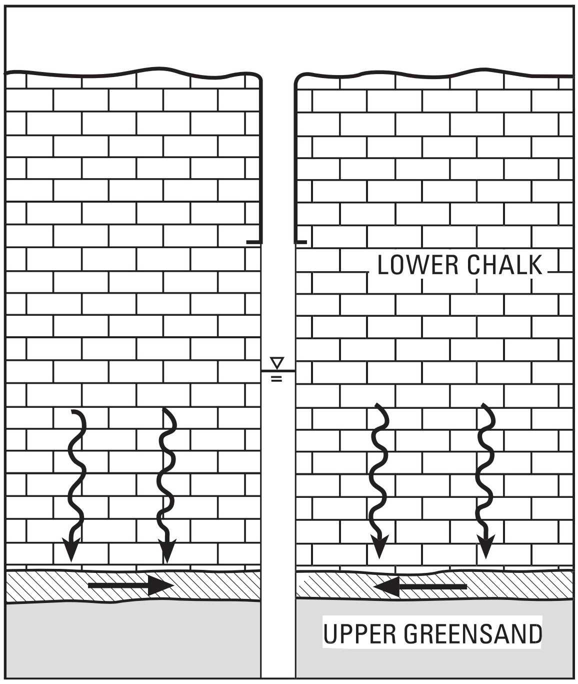


Figure 4.2.15 Hydraulic effects of the Boyne Hollow Chert (Upper Greensand). Where the Boyne Hollow Chert is fractured, it can be highly permeable. Significant groundwater storage can be provided by the less permeable Chalk Marl.

The area is drained by the River Avon and its tributaries the Bourne and Wylye (Figure 4.2.16), and also the Nadder draining from the west. The River Nadder rises in Jurassic strata before flowing eastward over the Chalk, the other rivers all rise in the Upper Greensand and flow intermittently over the Chalk outcrop, before reaching a confluence at Salisbury. Most of the area is underlain by the Upper Chalk with the Lower and Middle Chalk exposed at the fringes of the plain and in the Wylye valley. A large area of the Upper Greensand is exposed south of Warminster and also in the Pewsey Valley.

The regional dip of the strata is shallow and towards the south-east with superimposed gentle folds trending east–west. The most pronounced of these folds are the anticlinal structures which form the Vale of Wardour, Wylye Valley and Vale of Pewsey. The topography largely reflects the structure with the larger east–west valleys located in the anticlines and the relatively flat Salisbury plain formed where the dip of the Chalk is low. The Great Ridge to the south of the area separates the Wylye valley from the Vale of Wardour.

River gravel and alluvium are found in most valleys, clay-with-flints however is absent over much of the interfluves. Throughout the area there are numerous dry valleys and winterbournes. Discrete springs and diffuse seepages discharge to the winterbournes, which have been observed to dry up in a pattern distinct to each. In some winterbournes the upstream section dries up first of all. Others dry up in sections, with some of the middle sections drying up first. It is clear that distinct springs and sinks are present within the stream bed which control the groundwater flow to the stream.

Groundwater investigations

There have been two major groundwater investigations within the Salisbury area. The first was a study of the Upper Wylye to assess the impact of long term groundwater abstraction on the flow of the River Wylye (Avon and Dorset River Authority, 1973). Another study has recently

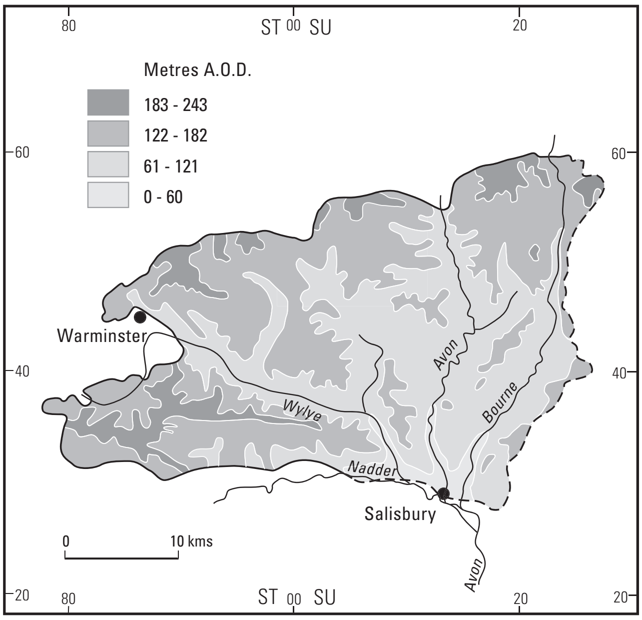


Figure 4.2.16 Location map of the Chalk of the Salisbury Plain, illustrating the Chalk outcrop and the river network.

been completed which again looked at the influence of groundwater abstraction on river flows. Part of this study involved construction of a groundwater model of the Salisbury Plain (Halcrow, 1992).

Aquifer properties

General statistics

Data on Chalk aquifer properties exist at 13 locations over the Salisbury Plain. Twenty-three pumping tests have been undertaken giving 23 estimates of transmissivity and 22 of the storage coefficient. Figures 4.2.17 and 4.2.18 show the transmissivity and storage data respectively. Transmissivity data vary from 50 to 8200 m^2/d, with a geometric mean of 1400 m^2/d and median of 1600 m^2/d. The 25 and 75 percentiles of the data are 450 and 3300 m^2/d respectively. Storage coefficient data vary from 1×10^{-4} to 0.05 with a geometric mean of 0.0052 and median of 0.0099. Data have a bimodal distribution with modal values of the order of 10^{-3} and 10^{-2}. Insufficient data exist to describe the relation between transmissivity and specific capacity.

Vertical variations in aquifer properties

As part of the Upper Wylye investigation (Avon and Dorset River Authority, 1973) geophysical logging was undertaken. Logging was carried out at three locations: Brixton Deverill, Heytesbury and Chitterne. At Chitterne, a borehole which penetrated Upper, Middle and Lower Chalk was tested. Fractures were present down to depths of 100 m although 90% of the flow came from the top 47 m of the borehole, which included the Upper and Middle Chalk. The most productive fractures were in the top 35 m (Figure 4.2.19). At Brixton Deverill the Lower Chalk is about 46 m thick, and the borehole continues for another 27 m into the Upper Greensand. Temperature logging indicates only one zone of groundwater flow at about 49 m. This possibly coincides with a well fractured chert layer in the top of the Upper Greensand similar to that detected south of Shaftesbury (see previous section). At Heytesbury, (Lower Chalk), logging

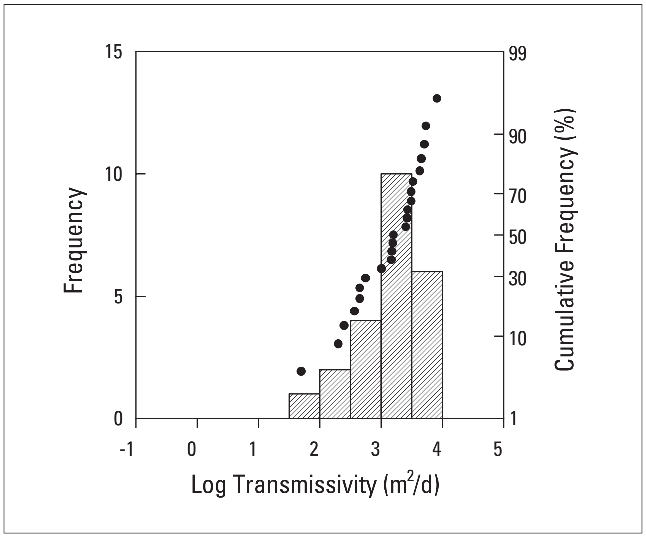


Figure 4.2.17 Distribution of transmissivity data from pumping tests in the Chalk of Salisbury Plain.

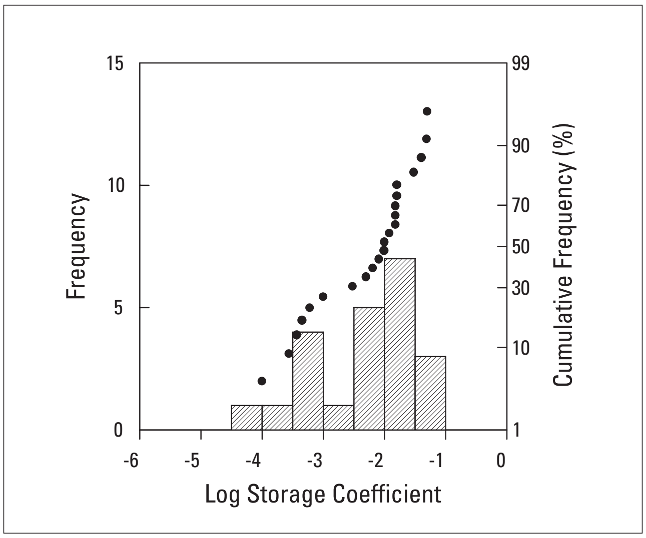


Figure 4.2.18 Distribution of storage coefficient data from pumping tests in the Chalk of Salisbury Plain.

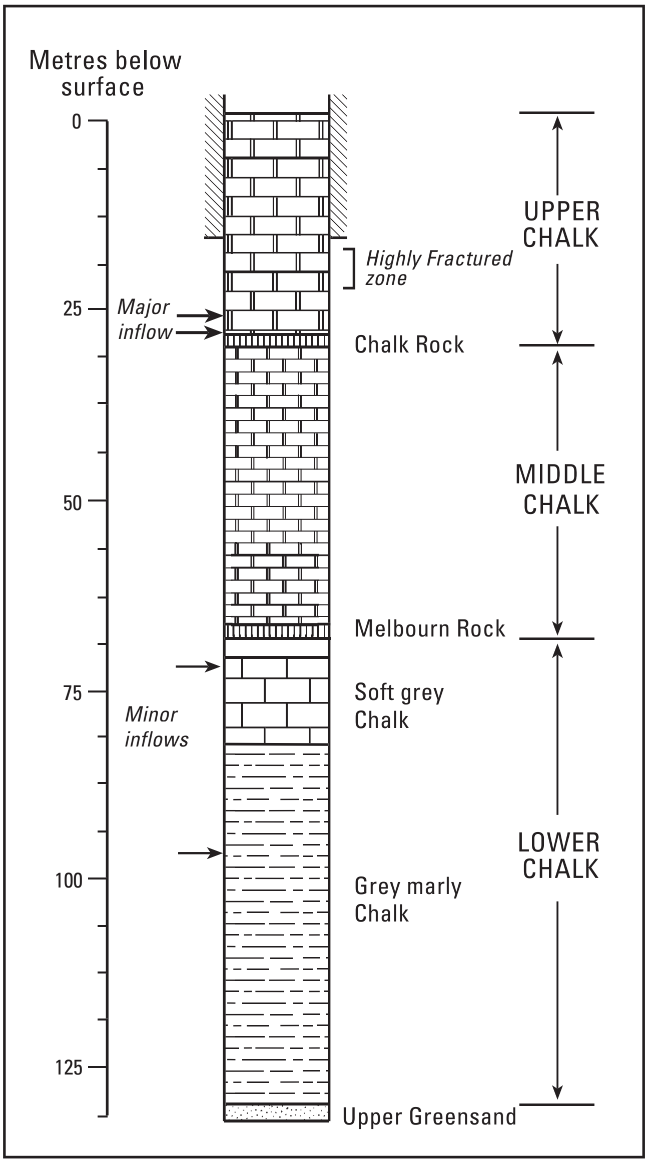


Figure 4.2.19 Geophysical logging at Chitterne; fractures are present to a depth of 100 m but 90% of the flow comes from above 47 m, with the most productive fractures above 35 m (after Avon and Dorset River Authority, 1973).

was inconclusive. Temperature logs did imply a possible inflow at 55 m with static water beneath.

Although it may be unwise to extrapolate these results, certain general statements can be made. Within the Upper and Middle Chalk, and upper part of the Lower Chalk, the most important flow horizons are probably within the top 50 m of the aquifer. The Chalk Marl of the Lower Chalk is relatively unproductive and may define the base of the Chalk aquifer. In the top of the Upper Greensand, however, flow may increase, with water draining vertically through the Lower Chalk to more permeable horizons.

The areal distribution of aquifer properties

The aquifer properties in general reflect the structure and topography of the area. The transmissivity and storage tend to be highest in the valleys and lowest over the interfluves, reflecting the density of fractures enhanced by dissolution of calcite.

From the limited data available for the area it appears that boreholes located in the Lower Chalk have a lower transmissivity than those located in the Upper and Middle Chalk. Valley pumping tests in the Upper and Middle Chalk yield transmissivity values ranging from around 450 to nearly 7000 m^2/d, with most results between 700 and 1000 m^2/d. Pumping tests carried out in the Lower Chalk and Upper Greensand indicate transmissivity values ranging from around 100 m^2/d to 1500 m^2/d. Most results were within the range 100–300 m^2/d. There are no records of pumping tests carried out in the Upper Greensand alone.

As part of an investigation into the effects of groundwater abstraction on river flows a numerical model was made covering the whole of the Salisbury Plain (Halcrow, 1992). The aquifer properties distribution was estimated from pumping tests, packer tests, well yields and inferred from hydrogeological maps. The distribution was further refined during calibration. The transmissivity distribution used ranged from 250 m^2/d in the interfluves to 2500 m^2/d in the valleys (Figure 4.2.20). The storage coefficient varied from 0.001 over the interfluves to 0.15 in the valley bottoms (Figure 4.2.21). The model gave a good represen-

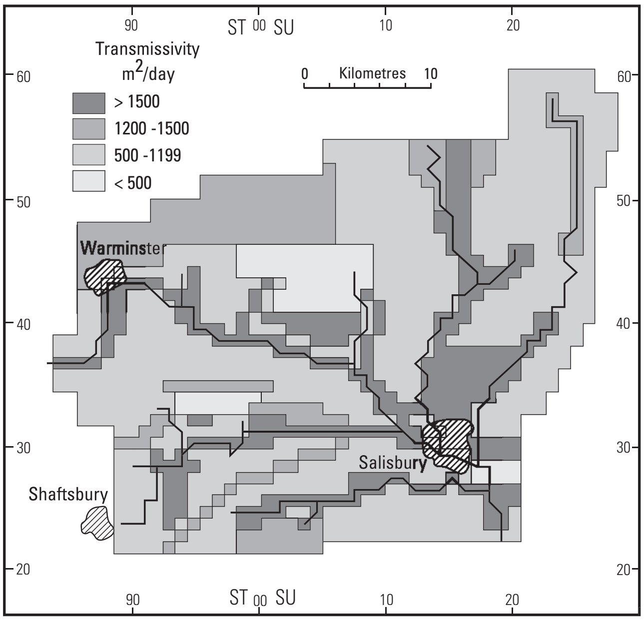


Figure 4.2.20 Transmissivity distribution used in the groundwater flow model of the Chalk of Salisbury Plain (after Halcrow, 1992).

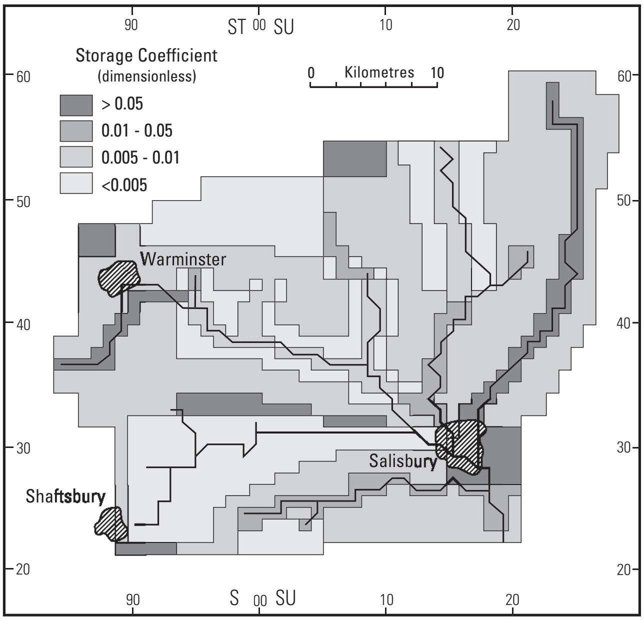


Figure 4.2.21 The distribution of storage coefficients used in the groundwater flow model of the Chalk of Salisbury Plain (after Halcrow, 1992).

tation of water levels and stream flows and was used in simulation runs to help understand the relationship between pumping and stream flows. A more refined model is currently under preparation covering only the River Wylye catchment.

4.2.5 Hampshire

Introduction

Geological and geographical setting

The chalklands of Hampshire constitute rolling downland and open countryside. Despite the low population density and limited use of groundwater for public supply in the north of Hampshire, the area has been the subject of an unusually high proportion of groundwater studies. This is primarily due to interest in river augmentation which is used to support surface water supply in the urban areas to the south during drought periods.

Upper Chalk underlies most of Hampshire (Figure 4.2.22). At outcrop it is commonly 80–150 m thick but can be as thick as 400 m where uneroded and confined by Palaeogene deposits (Institute of Geological Sciences and Southern Water Authority, 1979). At the base of the Upper Chalk is the Chalk Rock, a nodular hard limestone 2–4 m thick. The Middle and Lower Chalk (both approximately 60 m thick) have a limited exposure in Hampshire. They are exposed principally at the escarpment edge, in the core of the Winchester and Warnford anticlines and locally in dry valleys, for example in the upper reaches of the River Test. The Upper Greensand (30–50 m thick) outcrops as a narrow band at the foot of the Chalk escarpment.

In the south the Chalk is overlain by Eocene strata. Drift deposits comprising alluvium and valley gravel are found in the main river valleys with thinner restricted deposits in the tributary valleys. Clay-with-flints cap only the high ground to the east. The area is drained by three rivers, the River Test, the River Itchen and the River Meon, which flow predominately flow north–south.

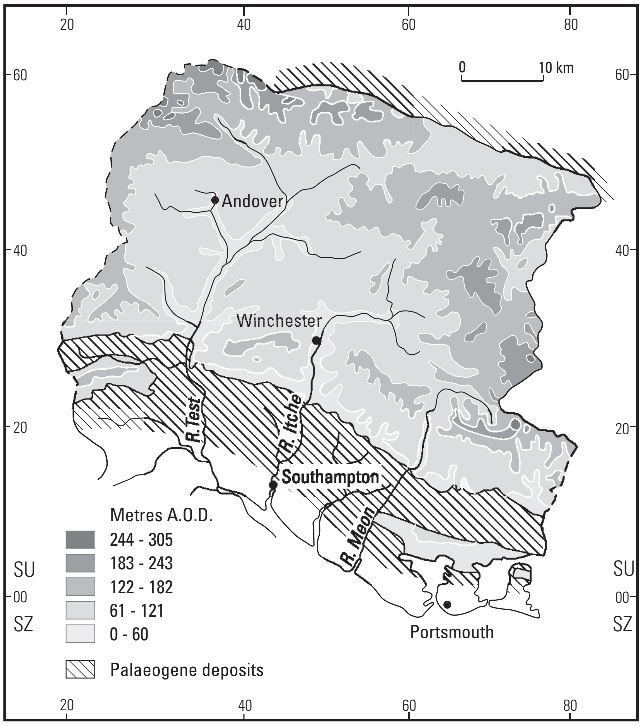


Figure 4.2.22 Location map of the Chalk in Hampshire, illustrating the Chalk outcrop and the river network.

The structure of the Chalk is relatively simple. A series of gentle east–west flexures extend westward from the Weald towards the Salisbury Plain. The dip on the flanks of the folds is quite small, not usually exceeding 1°. Despite the low dip values they appear to have influenced the development of the drainage pattern as tributaries of the Test, the middle section of the Itchen and its tributary the Alre follow synclinal axes.

Groundwater investigations

There have been several investigations of the aquifer properties of the Chalk in Hampshire. The first was an estimation of aquifer properties using recession curves from boreholes and river hydrographs (Headworth, 1972). Subsequently the planning and implementation of a river augmentation scheme during the mid 1970s provided opportunity to study in more detail the hydraulic structure of the aquifer. The scheme was developed to augment the flow of the River Itchen during drought years. Initially, the behaviour of artesian boreholes located at watercress farms was studied (Headworth, 1978). Then a tributary catchment, the Candover, was investigated in detail and six production boreholes eventually drilled near the head of various dry valleys. These were then pump tested individually and as a group and a mathematical model made of the catchment (Southern Water Authority, 1979a, Keating, 1978; Headworth et al., 1982; Keating, 1982).

In parallel with the river augmentation project, the Institute of Geological Sciences (now BGS) carried out permeability tests using a variety of different techniques (Price et al., 1977; Price et al., 1982). Three boreholes were studied in the Candover catchment using packer tests, core analysis and geophysical logs.

As an extension of the river augmentation scheme another tributary catchment of the Itchen, the Alre, was investigated. A number of pilot boreholes were drilled and four production boreholes completed. As with the Candover scheme the boreholes were tested together and individually (Giles and Lowings, 1991; Southern Water Authority, 1984a; Southern Science, 1991a). Recently a groundwater model of the Alre and Cheriton catchments has been developed (Irving, 1993).

There have been several smaller studies in other locations throughout Hampshire, some of which have involved the examination of aquifer properties. One such study was at Bedhampton in the south of the area where rapid groundwater flow was examined by tracer tests (Atkinson and Smith, 1974). Another study examined the hydrogeology of the Wallop Brook catchment to establish whether or not the catchment was being over-abstracted (Mott MacDonald, 1992).

Aquifer properties

General statistics

Data exist at 29 locations in the Hampshire area. Many of these locations have been researched intensively, consequently 63 pumping tests have been undertaken giving 63 estimates of transmissivity and 53 of the storage coefficient. Figures 4.2.23 and 4.2.24 show the transmissivity and storage data respectively. Transmissivity data vary from 0.55 to 29 000 m^2/d, with a geometric mean of 1600 m^2/d and median of 2600 m^2/d. The 25 and 75 percentiles of the data are 840 and 6100 m^2/d respectively. Measurements of transmissivity for the area tend to be high chiefly because of the intensity of testing of high yielding sites for the river augmentation schemes. Measurements of the storage coefficient vary from 7×0^{-5} to 0.06 with a geometric mean of 0.008 and median of 0.009. The data show an approximately lognormal distribution; the 25 and 75 percentiles of the data are 0.005 and 0.017 respectively. Figure 4.2.25 illustrates the relation between transmissivity and specific capacity.

Vertical variations in aquifer properties

Several of the detailed studies in Hampshire have illustrated the variability of aquifer properties with depth. The first such study was the investigation of artesian boreholes at watercress farms at Alresford in east Hampshire. A narrow zone of 30 m near the top of the boreholes was found to constitute the majority of flow, with the rest of the aquifer providing upward leakage to this high transmissivity layer (Headworth, 1978).

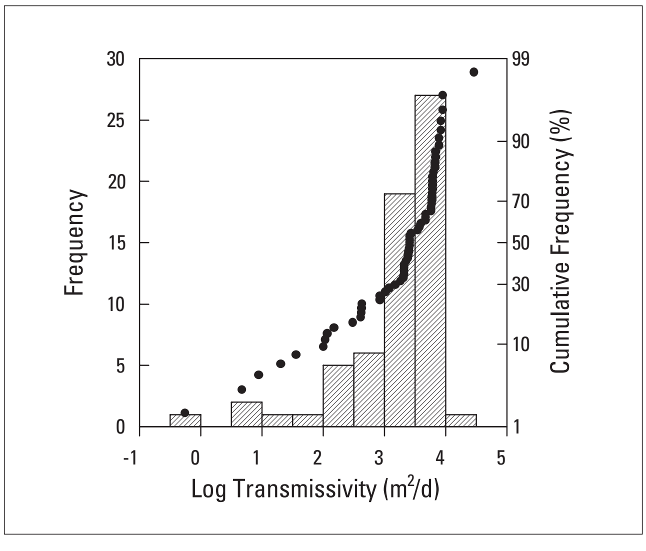


Figure 4.2.23 Distribution of transmissivity data from pumping tests in the Chalk of Hampshire.

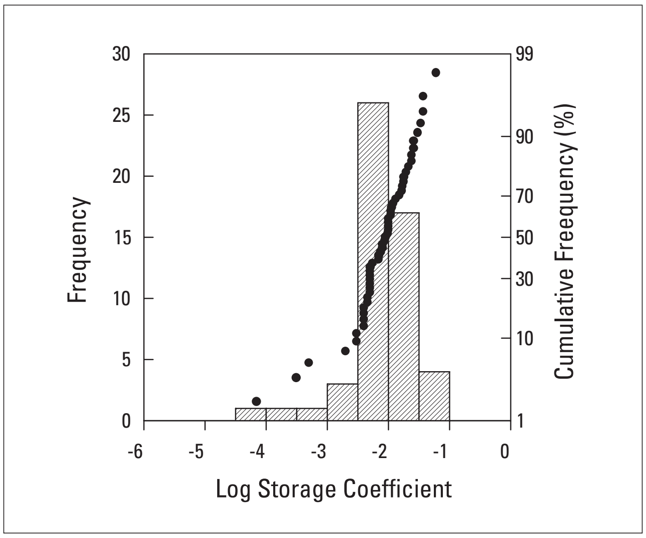


Figure 4.2.24 Distribution of storage coefficient data from pumping tests in the Chalk of Hampshire.

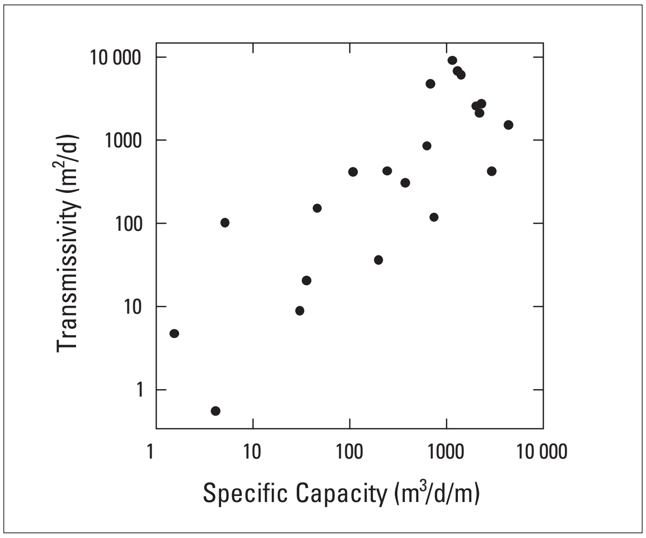


Figure 4.2.25 Plot of transmissivity against specific capacity (uncorrected) for the Chalk of Hampshire.

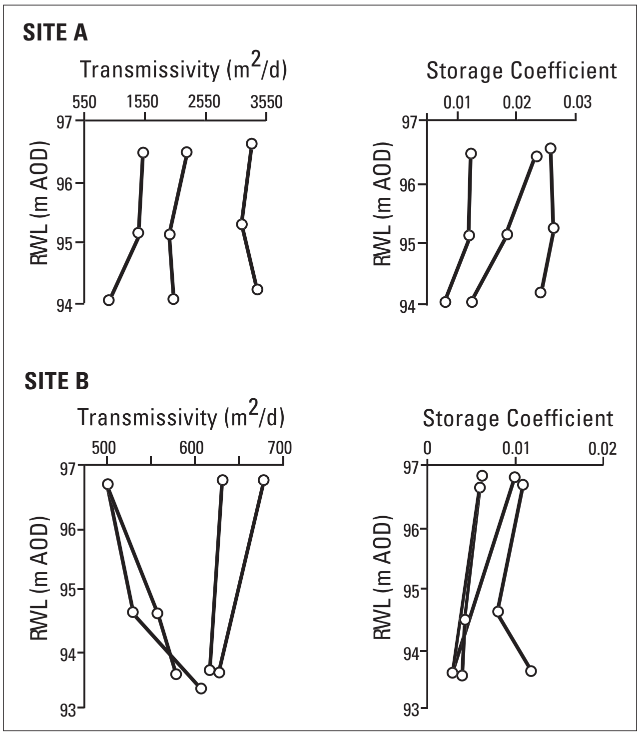


Figure 4.2.26 Measurements of transmissivity and storage coefficient from various pumping tests with different rest water levels at two sites. The figure illustrates the decrease in storage coefficient with rest water level (after Headworth, 1978).

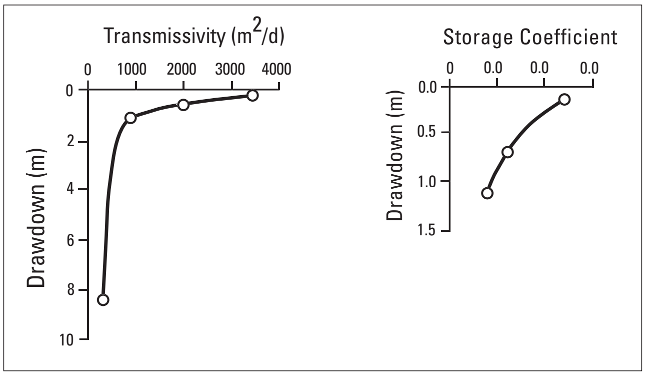


Figure 4.2.27 Non-linear decrease in transmissivity and storage coefficient observed during a group pumping test in the Candover catchment (after Southern Water Authority, 1979a).

The detailed investigations of the Itchen augmentation scheme have given further information on the variation of aquifer properties with depth. From individual pumping tests carried out at different rest water levels (1975 and 1976) the storage coefficient was observed to decrease with depth (Figure 4.2.26). No convincing trend, however, was observed for transmissivity. The scheme was further tested during a prolonged period of drought in 1976 when water levels were very low. A method of analysing drawdowns from a group pumping test was proposed (Keating, 1978) and transmissivity and storage coefficients calculated for each observation borehole. A non-linear decrease in both transmissivity and storage coefficient was found with drawdown (Figure 4.2.27) (Southern Water Authority, 1979a). Calculations made from the size and shape of the cone of depression inferred that in the Candover catchment the aquifer was multi-layered (Headworth et al., 1982). The top layer, just below the water table had high transmissivity and storage coefficient, and was probably about 6 m thick. Beneath that was a lower transmissivity and storage layer constituting the rest of the Upper Chalk.

In conjunction with the Candover investigations by Southern Water Authority, the IGS carried out detailed tests in three different boreholes: Abbotstone [SU 558 349], Itchen Down Farm [SU 546 334], and Totford [SU 569 380]. All three were located in dry valleys. Core permeability testing, along with geophysical logging and packer injection testing were carried out at each site (Figure 4.2.28). Several conclusions were drawn from the study:

- throughout the borehole, the permeabilities measured from packer tests were consistently one or two orders of magnitude greater than core permeability

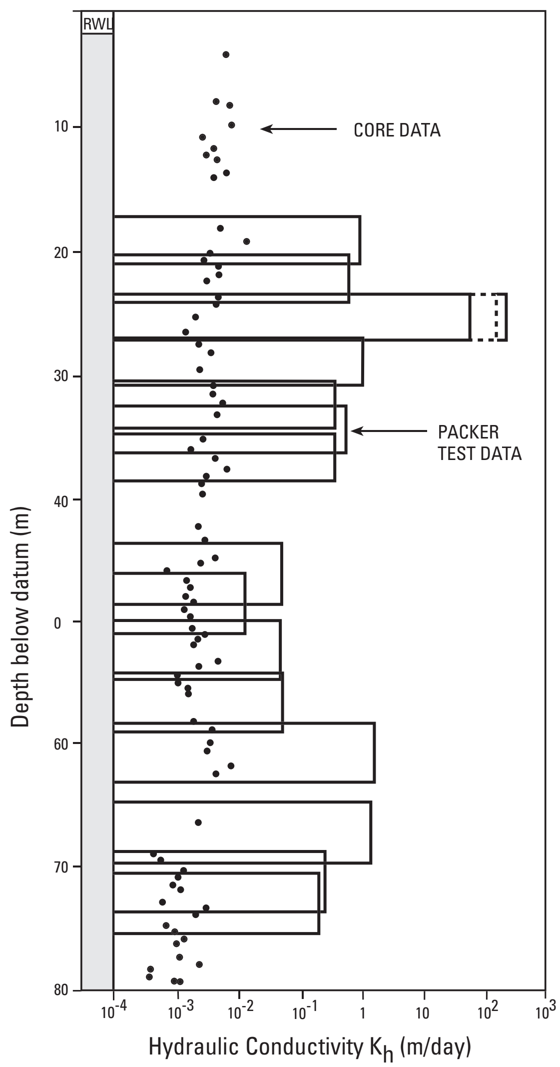


Figure 4.2.28 Variation of hydraulic conductivity with depth from packer tests (bars) and laboratory core measurements (dots) from a Chalk borehole in the Candover catchment. The figure illustrates the low values of intergranular hydraulic conductivity compared with the packer tests, and shows the concentration of high packer tests values in the upper section of the borehole (after Price et al., 1977).

- zones that had very high permeability corresponded to fracture locations
- most of the saturated thickness of the Chalk had very low permeability — only a few fractures were required to give the total transmissivity
- the most important flow horizons were near the top of the borehole, with very little flow below 40 or 50 m.

Recently, modelling work undertaken in the Wallop Brook catchment included discussions of vertical variations in permeability (Mott MacDonald, 1992). Observations, both from groundwater hydrographs and the calibration exercise, indicated that a two layered model was required. The top layer had a high transmissivity and varied in thickness from about 30 m near the interfluves to 1 or 2 m at the river. On the interfluves the hydraulic conductivity of the top layer was taken as twice that of the lower layer. Towards the river this ratio increased to 20:1.

In summary, various studies undertaken mainly in the Candover Valley have illustrated the vertical heterogeneity of the Chalk aquifer. The transmissivity is controlled by a few fractures which tend to be most developed towards the top of the borehole near the zone of water table fluctuation. There appears to be little correlation between the presence of high transmissivity layers and the stratigraphy of Upper Chalk (Headworth, 1978)

The conclusions of the above studies should be applied with caution to the rest of Hampshire. Detailed studies in the Alre catchment which is adjacent to the Candover Valley showed very different aquifer properties. The aquifer was not layered in the same manner as the Candover catchment. Rather, large diameter fractures were observed at various levels within the Upper and Middle Chalk.

Areal distribution of aquifer parameters

From detailed work it has become apparent that the areal distribution of aquifer properties is complex and does not adhere to any one particular pattern. For that reason several different techniques used to estimate aquifer properties are reviewed following a brief discussion on the various controls on aquifer properties development in Hampshire.

Controls on aquifer properties in Hampshire

Lithology has a significant effect on the aquifer properties of the region. In general the Upper Chalk exhibits the best aquifer properties at outcrop. The formation is highly fractured and has numerous flint and marl bands along which dissolution can occur. At the base of the Upper Chalk, the Chalk Rock can sometimes form a preferential flow horizon where it is close to the water table. It is not clear whether groundwater flow is through an increased density of fracturing within the layer or channelled above and below the hardground. Groundwater flow within the Middle Chalk is variable. In general, poorer aquifer properties have been observed and attributed to an increase in marl content at the top of the Middle Chalk (Southern Water Authority, 1979a). At other locations (e.g. the Alre catchment) karstic flow has developed, resulting in very high yielding boreholes for the Middle Chalk. The high marl content and less developed fracturing of the Lower Chalk hinder the development of a system of solution enhanced fractures and thus result in poor aquifer properties.

There is very little information about the aquifer properties of the Upper Greensand. A borehole drilled through the Upper Greensand by the oil industry, however, had such a large artesian flow, that the land owners had it licensed for their own use (Lowings, V, personal communication) There is evidence to suggest that the Chalk and Upper Greensand are not in hydraulic continuity (Giles and Lowings, 1990).

Secondly, as is typical of chalklands there is evidence that topography affects the aquifer properties, especially in the Test catchment. Pumping test data are limited, but information from the farmers in the area suggests that yields in interfluves are less reliable than those in the valleys (the Agency, Winchester, personal communication).

Thirdly, structure appears to have a significant control on aquifer properties. This control manifests itself in different ways — both directly and indirectly. The *indirect* effect is the result of structure having a role in the development of topography: some river and dry valleys have developed along the axes of synclines or faults (Southern Water Authority, 1979). Therefore higher transmissivity and storage can develop as in the typical topographic model. There is also evidence for structure having a *direct* effect on aquifer properties. Pumping test data indicate that higher yields are found along the axes of denuded synclines than anticlines (Giles and Lowings, 1990). When the structure of the Chalk and the water table surface are compared a pattern emerges (Figure 4.2.29). Many groundwater mounds, suggestive of poor transmissivity, are situated on the axes of anticlines. The calibration of a groundwater model of the Wallop Brook tributary catchment in the west of the area indicated a low permeability area (Mott MacDonald, 1992). This zone was discordant to the general topographic model but coincident to the axis of an anticline.

Finally, there is evidence that rapid groundwater flow is more likely near to the Eocene cover (Atkinson and Smith, 1974). Rapid groundwater flow has been detected at Bedhampton and Otterbourne which are both located at the feather edge of the Eocene cover.

Pumping tests

The distribution of pumping test data over Hampshire is variable. In the east where the groundwater schemes have been developed there are many pumping tests, while in the west relatively little data exist. However, the complex hydrogeology ensures that even where there is an abundance of pumping test information no clear pattern of the variation of aquifer properties emerges.

The few pumping tests that have been carried out in the catchment of the River Test have all been carried out in valleys, where the pumping stations are located. The majority of the sites are on Upper Chalk and indicate transmissivity values ranging from 50 to 3000 m^2/d. However,

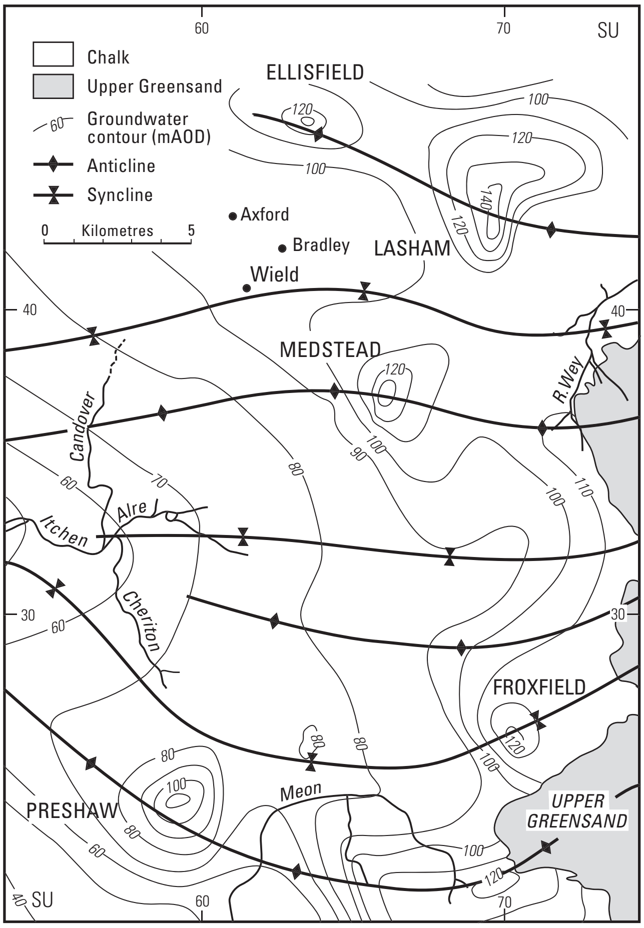


Figure 4.2.29 Groundwater levels and structure for the Upper Itchen catchment; many groundwater mounds, indicating poor transmissivity, are situated on the axes of anticlines (after Giles and Lowings, 1990).

more typically results are between 1000 and 2500 m^2/d. Further north where the Middle and Lower Chalk outcrops, transmissivity tends to be lower, probably less than 500 m^2/d. As the pumping test data are so biased towards valleys it is difficult to make any predictions about spatial variations. Farmers, however, have drilled on the interfluves and indicate that yields are variable and as many as one in three boreholes can be dry (EA, personal communication). Northwards on the escarpment, close to the Eocene deposits of the London Basin, the transmissivity recorded from pumping tests increases and is generally greater than 1000 m^2/d. This is probably due to the changing lithology and also topography and drainage.

As a preliminary to the river augmentation schemes both the Candover and Alre tributary catchments of the River Itchen have been studied in detail. The catchments are very dissimilar. In the Candover catchment, transmissivity values vary from about 1000 to 6000 m^2/d, with the majority of tests falling in the range 1000–3000 m^2/d. The storage coefficient was calculated as being between 0.01 and 0.03. Most of these tests were carried out in dry valleys. However, the shallow highly permeable zone inferred from group pumping tests, is believed to extend throughout the catchment. Drawdown curves actually show an apparent increase of transmissivity as the cone of depression moves outwards, away from valley sites. This is not thought to be real increase, but a spurious effect of the pumping tests. Whatever the reason, this illustrates the hydraulic complexity of the area and the difficulty in analysing pumping test data in the region.

In the neighbouring catchment, the Alre, the groundwater regime is very different. Rather than being governed by an extensive, but thin highly permeable zone, transmissivity in the Alre catchment is controlled by groundwater flow through a large diameter fracture network. Estimates of transmissivity from boreholes that have intersected this network are very high, 5000–30 000 m^2/d but more typically 5000–7000 m^2/d. The storage coefficient is correspondingly very low, 0.005. Conventional pumping test analysis, however, which assumes an approximation to homogeneous and isotropic conditions, is not really appropriate in such an area. Therefore the results should be treated qualitatively, rather than strictly quantitatively, indicating very rapid groundwater flow through discrete fractures.

There are some pumping test results from further east towards the Weald. Most of these boreholes are located on the outcrop of the Middle or Lower Chalk across the groundwater divide from the Higher Itchen tributaries. Transmissivity values are generally low. From the pumping tests located in the valleys values range from 5 to 500 m^2/d —typically less than 200 m^2/d.

The few pumping tests from the Meon catchment illustrate moderate transmissivity, generally less than 1000 m^2/d. The lower transmissivity values could be attributed to the presence of the anticline. Denudation has resulted in most of the Upper Chalk being removed from the upper reaches of the catchment. Therefore there is only a thin outcrop of Upper Chalk, with groundwater flow primarily through the Middle and Lower Chalk.

Water levels

Since structure has some control on the development of both transmissivity and the general topography, transmissivity can be said to loosely follow the topography in Hampshire. However, from the detailed studies of the Candover and Alre catchments, water levels, and in particular the gradient of the water table, have proved better estimators of transmissivity. Near-horizontal water tables are thought to indicate zones of high transmissivity and steep water tables, low transmissivity. The water table is very shallow over much of the Candover, Alre and Cheriton catchments. Pumping tests carried out in these zones have generally confirmed the high transmissivity.

There are many groundwater mounds throughout Hampshire. These mounds are generally located on the axes of anticlines for example at Ellisfield, Lasham, Medstead and Preshaw in east Hampshire (Giles and Lowings, 1990); and define the groundwater divides. The transmissivity of the Chalk under these mounds is thought to be low. Over three of the mounds in east Hampshire (Ellisfield, Lasham and Medstead) anomalously low groundwater fluctuations have been observed. This is thought not to indicate high transmissivity, but rather a reduction in recharge rate due to the low permeability of the overburden. The amount and rate of recharge must be in quasi-equilibrium with groundwater flow away from the mound, thus giving low fluctuations (Giles and Lowings, 1990).

Groundwater recession curves

Natural groundwater fluctuations have been used in Hampshire to estimate aquifer parameters (Headworth, 1972). Two different methods were applied. The first considered the fluctuations in individual boreholes and produced values of transmissivity and storage coefficient. These aquifer properties were then compared to 'real' pumping test data. The method was thought ambiguous, however, when applied to Dorset (Alexander, 1981).

The second method gave a regional value of the storage coefficient for a groundwater catchment by comparing the volume of groundwater flow (from river hydrographs) with the change in volume of the saturated aquifer. The technique was applied to the rivers Test and Itchen. For the Test a storage coefficient of 0.033 was calculated, and for the Itchen 0.034.

Further work (British Geological Survey, 1993) has suggested that estimates of storage coefficient from groundwater fluctuations (regional) are greater than those calculated by pumping tests (local).

Groundwater models

Several groundwater models have been developed for the area. These models have been associated with estimating the net gain of the river augmentation schemes of the Alre and Candover. A two-dimensional model was constructed for the Candover catchment in the mid seventies (Southern Water Authority, 1979a). However, the model did not give a good representation of the water levels or stream flows, so a lumped parameter model was developed (Keating, 1982). This assumes no lateral variations of parameters. The aquifer was assumed to have two layers: a shallow layer with transmissivity 10 000 m^2/d and storage coefficient 0.05 and the deeper layer transmissivity of 1000 m^2/d and storage coefficient of 0.01. The model gave good representations of winterbourne and groundwater hydrographs.

A model has recently been developed for the Alre and Cheriton catchments (Irving, 1993). Although the model requires refinement, it gave a good representation of groundwater levels and stream flow. Extremely high transmissivity values were required within the centre of the catchment (Figure 4.2.30) to give the observed stream response. Interestingly, a much higher storage coefficient was required than that indicated from pumping tests, 0.03 as opposed to 0.005.

A groundwater model was also constructed for Wallop Brook, a tributary catchment of the River Test (Mott MacDonald, 1992). The transmissivity distribution varied from greater than 5000 m^2/d in the valley bottom to less than 100 m^2/d over the interfluves (Figure 4.2.31). A low transmissivity zone was included discordant to the topography which followed the axes of an anticline. The storage coefficient was set to 0.01. The model gave a good representation of streamflow and water level data.

Tracer tests

Towards the south of the area, around Bedhampton [SU 707 064] rapid groundwater flow has been observed

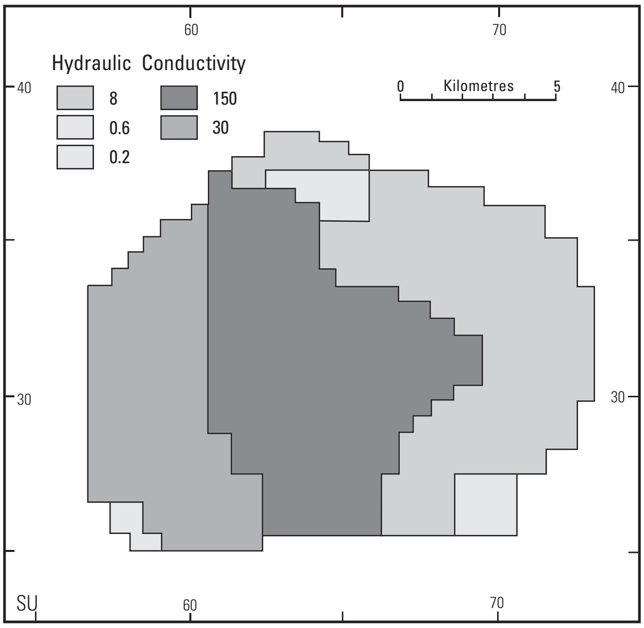


Figure 4.2.30 Transmissivity distribution for the Alre and Cheriton catchments used in a MODFLOW model of the area (after Irving, 1993).

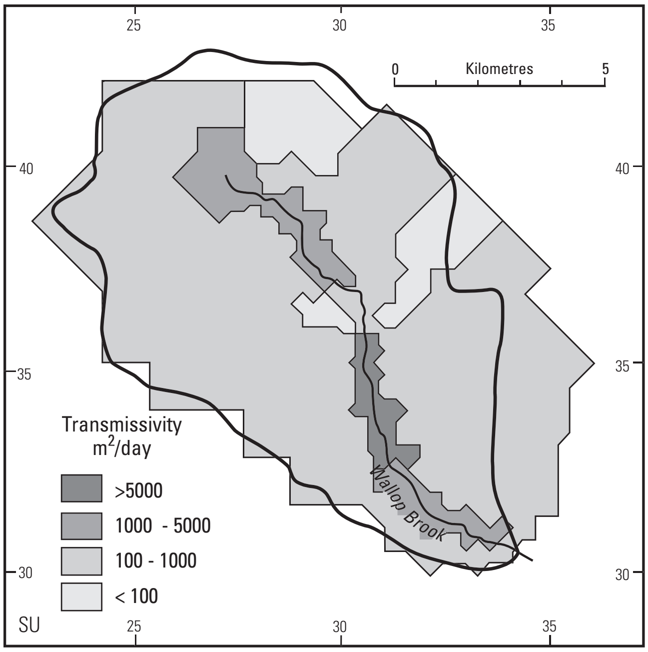


Figure 4.2.31 Transmissivity distribution for Wallop Brook; note the low transmissivity zone discordant with the general topographic distribution, this has been attributed to the presence of an anticline (after Mott MacDonald, 1992).

(Atkinson and Smith, 1974). A tracer study carried out between a series of sinkholes and springs 5 km apart proved a direct connection and turbulent flow through a discrete conduit system. The actual velocity of groundwater movement was calculated to be 2 km/d. This conduit system is located at the northern margin of the Eocene outcrop and it is thought that it has developed due to the increased solution potential of runoff from the Eocene sediments. More than 70% of the dye was recovered from the test, and the majority of it arrived at one spring, over a small period of time. This implies that flow was through a narrow set of conduits, rather than a diffuse network.

Rapid flow has also been detected at Otterbourne (EA, personal communication). High-turbidity water enters one of the adit systems after rainfall, implying rapid recharge or a connection with surface water. It is not known of any other examples in the area, but the likelihood of rapid transport at the feather boundary of the Eocene deposits is high.

CONCLUSION

Several pieces of evidence, including the collected data, have been examined to give an indication of the lateral variation of aquifer properties in the Hampshire area. It is thought that transmissivity values of 1000 m^2/d are common in the valleys, and that both transmissivity and storage coefficient decrease up the interfluves. East Hampshire has been studied in detail. A layered aquifer with an extensive high transmissivity zone is thought to exist in the Candover catchment, with typical transmissivity values of 1000–3000 m^2/d and storage coefficient 0.01–0.03. The neighbouring Alre catchment is thought to have a discrete set of large diameter conduits which if intersected will give extremely high transmissivity values (>5000 m^2/d). However if a borehole does not intersect the system, the yield is very low. Estimates of storage coefficient from pumping tests in the Alre are lower than those calculated from modelling or river hydrographs.

Along the axes of anticlines, aquifer properties are thought to be less well developed. Often anticline axes are associated with groundwater mounds which have low transmissivity, possibly less than 100 m^2/d.

In east Hampshire, across the groundwater divide towards the Weald the aquifer properties are much poorer (usually less than 500 m^2/d) This reflects the stratigraphy of the Chalk. Groundwater flow is primarily through the Lower Chalk, which is less fractured and therefore has low transmissivity and storage. In the north however, on the scarp slope towards the London Basin the aquifer properties improve. Tests within valleys illustrate transmissivity and storage coefficient comparable to valley sites on Upper Chalk on the dip slope (approximately 1000 m^2/d).

To the south of the area, near the feather edge of the Eocene deposits, extremely rapid groundwater flow is possible. Velocities of up to 2 km/d have been recorded from tracer tests.

4.2.6 The South Downs

Introduction

Geological and geographical setting

The Chalk of the South Downs outcrops in a narrow line from Eastbourne to the Hampshire county boundary. The outcrop is approximately 90 km in length and on average 12 km wide, with a total outcrop area of 770 km^2 (Headworth and Fox, 1986). In east Sussex, the Chalk forms a spectacular cliff line at Beachy Head and the Seven Sisters. A coastal plain, occurs in the west where the Chalk is overlain by superficial deposits. Inland, the Chalk produces the landscape of the South Downs whose escarpment trends east–west rising to a height of approximately 250 m AOD. The South Downs are split into five separate Chalk blocks defined by several north–south flowing rivers, the Arun, Adur, Ouse and Cuckmere (Figure 4.2.32).

Within the South Downs the boundary between the Upper and Middle Chalk has not been extensively mapped, although Mortimore (1986a) recognised several subdivisions (Table 4.1.2). Unfortunately at the present time it is difficult to ascertain any differences in the aquifer properties between

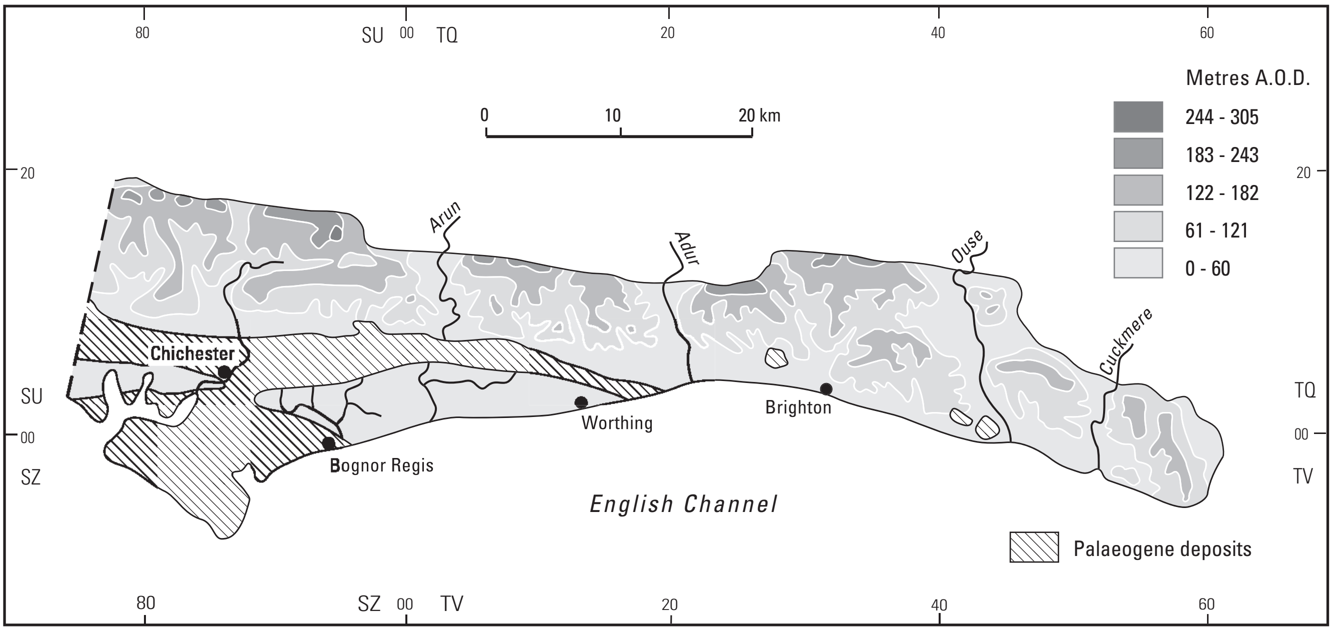


Figure 4.2.32 Location map of the Chalk and the South Downs, illustrating the Chalk outcrop and the river network.

these new subdivisions, since historical pumping tests do not make the distinction. In general the Upper and Middle Chalk is a soft white chalk with nodular and tabular flints, marl seams and layers of nodular chalk. The distribution of flint, marls and nodular chalk can vary laterally (Mortimore, 1986b). The Lower Chalk comprising the Plenus Marls, Grey Chalk and Chalk Marl has a high marl content and therefore generally low permeability. The Upper Greensand outcrops in a narrow band at the foot of the escarpment and is generally of little significance as an aquifer.

Clay-with-flints, comprising a stiff yellow and reddish brown clay with weathered flint nodules is found on the interfluves of the South Downs. Head Gravels, formed by solifluction (previously known as Coombe Rock and Valley Gravels) are found in the valleys.

Groundwater investigations

There have been many hydrogeological investigations and research programmes undertaken throughout the South Downs. The most important study for aquifer properties was the South Downs Groundwater Project which was started in 1971 and carried out by Sussex River Authority in conjunction with the Water Resources Board. Exploratory boreholes were drilled and tested. If the yields were promising, a larger, production borehole was drilled and the aquifer properties examined in detail. Several boreholes were drilled in each Chalk Block and a considerable amount of information was gathered on the behaviour of the Chalk aquifer. Several reports were written detailing the progress of the investigation (Sussex River Authority, 1972; Sussex River Authority, 1974; Southern Water Authority, 1979b; Southern Water Authority, 1984b). In the Chichester Block, the role of the Chichester syncline was examined by stream flow and chemical analysis of the Chichester Rifes (Harries, 1979).

In conjunction with the aquifer testing programme a groundwater model was created to help describe the transient effects of natural infiltration and abstraction and assist in the long term management of the aquifer. An automated method for calculating transmissivity and storage coefficient distributions was developed for the model but was hampered by the non-uniqueness of the solution (Nutbrown, 1975; Nutbrown et al., 1975). A numerical model was also created for the Chichester Chalk Block as part of an investigation of the groundwater resources of the aquifer (Southern Water Authority, 1984b).

The South Downs aquifer has to be carefully managed due to its long coastline and saline interface. Consequently many observation boreholes have been drilled and logged along the coast and routinely monitored for chloride levels. The logs can give much useful information about the depth and extent of fracturing. Recently many of the available logs have been digitised and combined into one report (Southern Science, 1992a) although the initial investigations took place much earlier (Monkhouse and Fleet, 1975).

More recently there have been several smaller studies which have given some indication of the aquifer properties of the Chalk of the South Downs; e.g. investigations at Mount Caburn (Southern Science, 1991b); study of the Warningcamp borehole (Southern Science, 1992b; Southern Science, 1992c; Southern Science, 1993); packer testing of the Chichester Chalk Block (National Rivers Authority, 1993); test pumping of boreholes at Tortington and Madehurst (Southern Science, 1994) and studies of the hydrogeological/hydrological balance between Swanbourne lake, springs, groundwater and surface streams (National Rivers Authority, 1990). A large modelling exercise recently has been undertaken of the Chichester Block to help predict the groundwater resources of the area (Halcrow, 1995). After the severe flooding at Chichester in 1993 an investigation of the cause was set up. Groundwater was thought to have played a crucial role (Posford Duvivie, 1994).

Aquifer properties

General statistics

Most of the pumping test information for the area was gathered during the South Downs Groundwater Investigations of the 1970s (Sussex River Authority, 1972; Sussex River Authority, 1974; Southern Water Authority, 1979b; Southern Water Authority, 1984b). The purpose of this study was the estimation of the overall yield of the Chalk and calculation of the optimum location of boreholes to maximise yield and minimise contamination of the groundwater resources by saline intrusion. During the 12 years of this investigation numerous boreholes were drilled and tested. Other pumping tests have been carried out in the South Downs for smaller investigations or licensing purposes. In total, data exist for 28 different locations, giving 45 estimates of transmissivity and 22 estimates of the storage coefficient (estimates of the storage coefficient >0.1 have been omitted from the analysis; see section 4.1.8 for further details).

The transmissivity distribution for pumping tests in the South Downs is approximately lognormally distributed (Figure 4.2.33). Values range from 16 to 9 500 m^2/d with a geometric mean of 500 m^2/d and median of 440 m^2/d. The 25 and 75 percentile values are 230 and 1600 m^2/d respectively. No clear regional trend in distribution of transmissivity emerges from the data due primarily to their bias towards valley sites. However, with the available data it was possible to infer an inverse relation between transmissivity and depth to water levels (Figure 4.2.34). Where water levels are shallow (for example in discharge areas and valleys) transmissivity tends to be high; in areas with deeper water levels (e.g. over interfluves) transmissivity values are generally low. There appeared very little relation between specific capacity and transmissivity from the available data.

The storage coefficient distribution is shown in Figure 4.2.35. Values range from $2 \times 10^{-4} - 0.032$ with a geometric

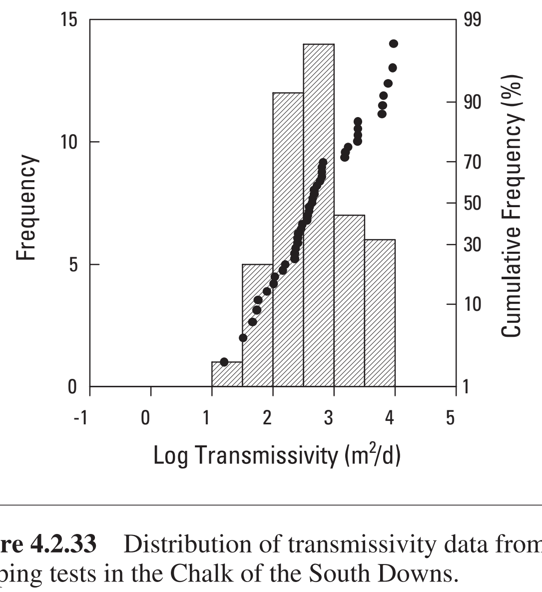


Figure 4.2.33 Distribution of transmissivity data from pumping tests in the Chalk of the South Downs.

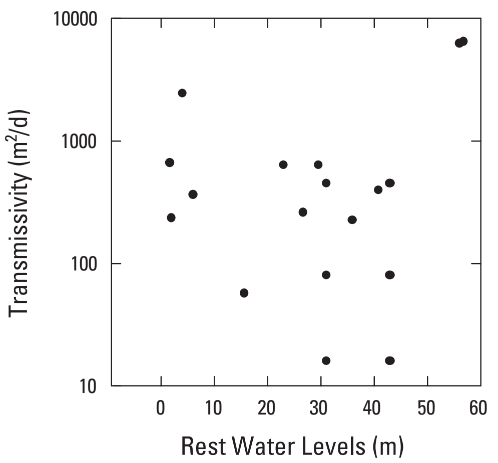


Figure 4.2.34 Plot of transmissivity against rest water level for the Chalk of the South Downs.

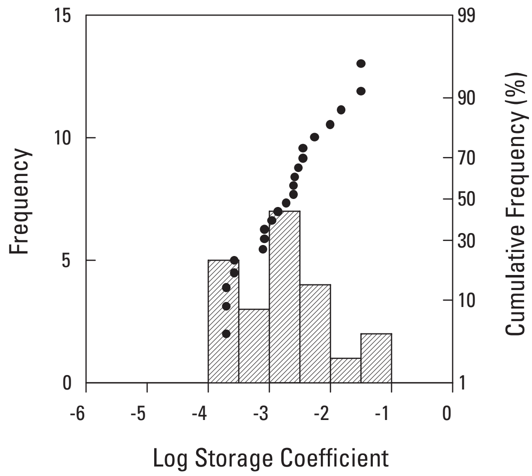


Figure 4.2.35 Distribution of storage coefficient data from pumping tests in the Chalk of the South Downs.

mean and median of 0.0018 and 0.0022 respectively. The 25 percentile is 6.1×10^{-4} and the 75 percentile 0.0040.

Vertical distribution of aquifer properties

As with most chalk aquifers it is the zone of water table fluctuation that is believed to be most important for groundwater flow in the South Downs. However, the situation is further complicated in this area. The large changes in sea level during the Pleistocene caused changes in the base levels within the aquifer and created active fractures at many different depths. Thus groundwater flow can occur at depths of 140 m below the surface (Southern Water Authority, 1979b) and active fracture systems exist above the normal water table.

Packer testing in the Chichester Block at three inland locations showed that the aquifer properties were best developed within about 40 m of the water table (NRA Southern Region, 1993). Permeability was very low at greater depths. High permeability values were measured above the water table, especially on the interfluve site (Colworth Farm, Figure 4.2.36). This suggests that if water levels rose to a sufficiently high level, groundwater flow could become very rapid, even over the interfluve. This mechanism could possibly help to explain the severe flooding experienced in Chichester in 1993 (Posford Duvivier, 1994).

Geophysical logging of boreholes closer to the sea, however, has identified groundwater flow at depths of up to 140 m below ground surface. It is therefore possible that the effective aquifer actually thickens towards the sea. This could be attributed to a change in base levels during the Pleistocene when sea levels were sometimes as much as 120 m below present sea level. Therefore, the discharge points within the aquifer would be much lower, and a conduit system could be developed deep within the aquifer. At the present time these fractures do not contribute significantly to the yield of the borehole although they can be important in determining the chemistry of the groundwater (Southern Science, 1992a) as many of the deeper fracture systems are connected to the sea. Therefore with seasonal and tidal variations in the groundwater head, sea water incursion can occur along the deep fractures and contaminate the aquifer. The mixing of saline and fresh water along these fracture zones may also promote dissolution and further enhance the permeability (Saniford and Konikow, 1989).

Areal distribution of aquifer properties

The limited pumping test data available from the South Downs indicates a general topographic trend with high transmissivity values recorded in areas of shallow water levels and low transmissivity values where the water levels are deep.

For example, testing on an interfluve in the Chichester block gave a transmissivity value of only 1 m^2/d while pumping tests in the Winterbourne valley at Houndean Farm [TQ 397 098] indicated transmissivity values of >1000 m^2/d (Sussex River Authority, 1974). Testing in dry valleys high up on the interfluves, e.g. Balmer Down on the Brighton block [TQ 369 103], Lychpole [TQ 155 083] and Annington [TQ 179 085] on the Worthing Block indicated very poor yields (Headworth, 1994).

However, topography is not the only control on the distribution of aquifer properties within the South Downs. Between neighbouring valleys, the aquifer properties can be quite different; and sometimes good yields are recorded in interfluves while boreholes drilled in valleys are dry.

One factor that can have a marked effect on the aquifer properties is lithology. Where the Chalk is softer and more marly, fracturing is less well developed and aquifer properties tend to be poorer. In general, the Middle and Upper Chalk has a low marl content and is easily fractured. The local geology is also very important for the development of fractures. Boreholes drilled in the Benfield Valley [TQ 262 083] have low yields which have been attributed to the fact that throughout the valley the Middle and Upper Chalk is compact, soft and marly with little fracture development (Sussex River Authority, 1974).

In the western section of the South Downs, within the Chichester Block, the properties of the Chalk aquifer are affected by its structure. A series of flexures, striking east-west are developed. The most significant from the point of view of the aquifer properties are the Singleton Anticline and the Chichester Syncline. The Lower Chalk is near to the surface in the core of the Singleton Anticline. This has the effect of reducing the values of the aquifer properties along the axis of the anticline and impeding groundwater flow to the south. However when water levels

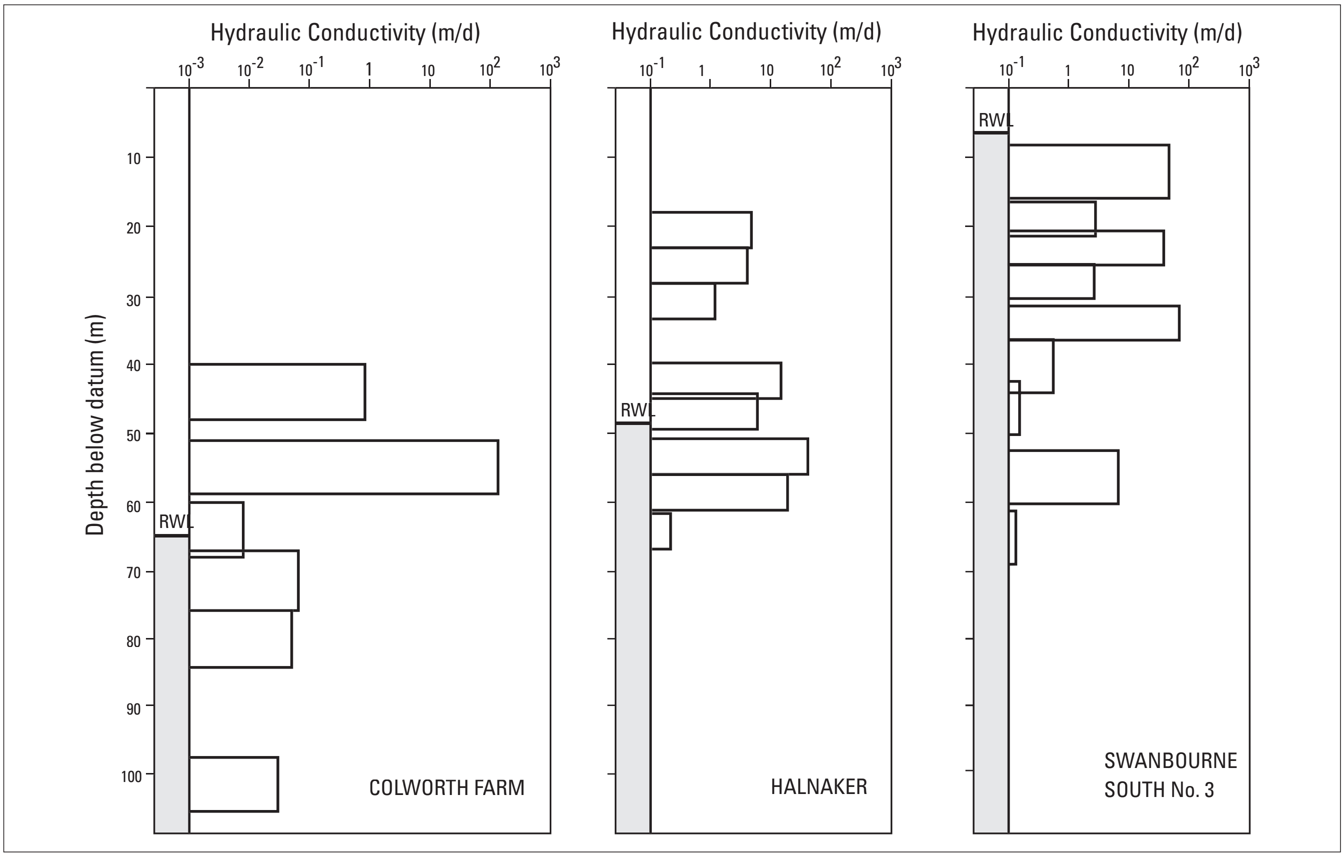


Figure 4.2.36 Hydraulic conductivity distribution from three packer tests in the Chichester Chalk block (after NRA, 1993).

rise above the Plenus Marls within the anticline groundwater flow can be rapid. This was illustrated during the Lavant floods of 1993.

The Chichester Syncline is infilled with over 100 m of Palaeogene deposits and acts as a barrier to groundwater flow southward to the sea. Groundwater is therefore focused to discharge at several discrete points throughout the Chalk block. The increased groundwater flux created at these discharge points has helped to create narrow zones of high transmissivity (Figure 4.2.37). One such point is Arundel on the River Rother where groundwater is discharged that originated far up the Chalk block and was deflected by the syncline. The other main discharge point is at Fishbourne. Here groundwater is focused under an arch in the syncline and discharges through a series of springs.

Although the Chalk comprises a fairly uniform and homogeneous rock, the small proportion of inhomogeneities are probably important in controlling the distribution of primary fractures and the extent of dissolution and consequent enlargement of the fractures (Price, 1987).

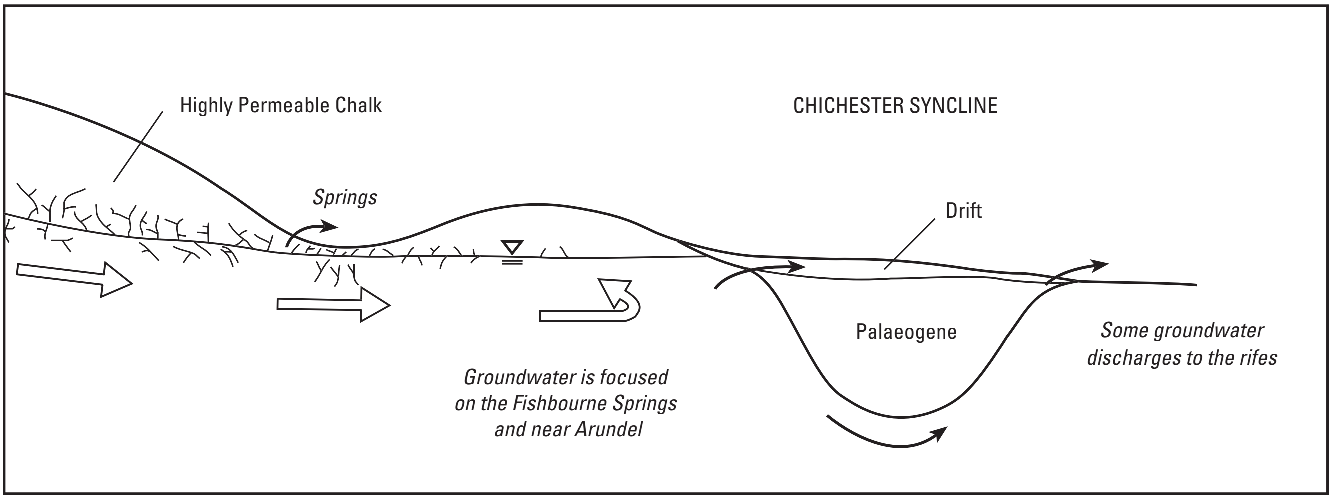


Figure 4.2.37 The role of the Chichester Syncline in controlling groundwater flow in the South Downs (after Jones and Robins, in press).

Continuous flint layers, marl seams and nodular chalks are common within the chalk of the South Downs (Mortimore, 1986b) and all influence the hydrogeology to some extent.

Harder nodular chalks, referred to as hardgrounds or Grade I chalks (Ward et al., 1968) usually fracture more cleanly than softer chalks. As a result of the greater density of open fractures, the permeability within hardgrounds is often higher than in the surrounding rocks (Price et al., 1977). Within the South Downs the Melbourn Rock usually illustrates higher permeabilities than surrounding chalk, especially when not deeply buried so that the fractures can remain open.

Model information

Several groundwater models have been developed for the Chalk of the South Downs (Nutbrown et al., 1975; Southern Water Authority, 1984b; Halcrow, 1995). The earliest model was developed for the Brighton block; high values of transmissivity were assigned to the valleys (2500 m^2/d) and lower values for the interfluves (100 m^2/d). The other two models were both developed for the Chichester Block. Considerable difficult has been experienced in modelling due to the complex groundwater flow in the Chichester block, for example the rapid flow towards Swanbourne Lake and Fishbourne, the Chichester floods, and the role of the Chichester Syncline. The distribution of transmissivity used in the most recent model is shown in Figure 4.2.38.

Rapid groundwater flow within the South Downs

The Chalk of the South Downs shows some evidence of karstic development. In several catchments groundwater flow is extremely rapid and associated with relatively few, large diameter fractures. These systems are generally developed close to the edge of the Palaeogene or superficial deposits and usually culminate in large springs.

At the feather edge of the Palaeogene deposits, on the Chichester Block, there are several examples of rapid groundwater flow. Pumping tests at a source in Madehurst had a rapid effect on outflows 4 km away around Arundel and Swanbourne Lake (Southern Water Authority, 1984b; Southern Science, 1994). Within 8 hours of the start of the pumping test the spring outflow was reduced. Therefore a highly connected network of fractures must exist. Springs at Fishbourne also appear to be fed by a network of large fractures. Groundwater flow is concentrated under an arch in the Chichester Syncline, to a series of springs at Fishbourne. A similar scenario was observed at the Havant and Bedhampton springs in Hampshire where tracer tests indicated flow velocities of 2 km/d (Atkinson and Smith, 1974).

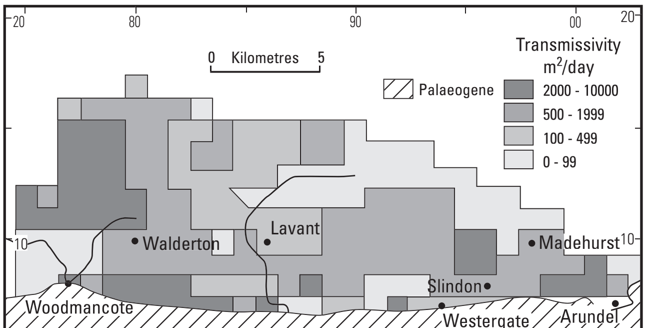


Figure 4.2.38 The distribution of transmissivity in the unconfined zone used in a groundwater flow model developed for the Chichester Block by Halcrow (1995).

Solution pipes and swallow holes are also observed in the South Downs and can have an important effect on the aquifer properties of the Chalk (Mortimore et al., 1990; Edmonds, 1983). As discussed in Section 4.1, swallow holes can concentrate large volumes of acidic recharge to certain points in the aquifer producing a discrete network of large diameter fractures which can transport recharge through the aquifer very rapidly (with potentially significant effects on contaminant transport predictions). Solution pipes are generally developed beneath superficial cover by the dissolution and removal of chalk and can extend downwards for many tens of metres linking in with existing fracture systems. Large amounts of aggressive recharge can then travel through the solution pipes and circulate deep within the aquifer enlarging the fracture network. Sands and gravels from the overlying Palaeogene and Quaternary deposits can be washed down through solution features clogging up the fracture network. Problems due to running sand in chalk fractures were experienced during groundwater abstraction from the Warningcamp borehole [TQ 058 067] (Southern Science, 1992c). Pumping tests combined with geophysical logging have demonstrated sand entering the borehole from fractures as deep as 70 m. Rapid groundwater flow induced by the abstraction disturbs the sand within the fractures and transport it into the borehole.

An extensive adit system was built within the Chalk aquifer during the second half of the nineteenth century and early part of the twentieth century (Mustchin, 1974). The notes made during their construction are extremely interesting and useful for understanding the aquifer properties of the Chalk. The yield of each adit is recorded as coming from only a very few fractures — possibly as little as one every 30 to 50 m. Sometimes no producing fractures were recorded. However, this information is highly subjective and depends on what the original engineer thought constituted a productive fracture. It is possible that only the very high yielding springs have been recorded. In addition, the adits are quite deep within the Chalk and are horizontal. Therefore, there is a possibility that the majority of the flow is in a more extensive fracture network higher up in the aquifer. Nonetheless, the adit systems provide useful additional data on the distribution of productive sub-vertical fractures within the Chalk aquifer.

A cave system has been identified and examined within the Chalk at Beachy Head (Reeve, 1981). The cave system is developed along a series of faults and joints and although generally sub-horizontal, has occasional vertical steps. The retreat of the cliff line at Beachy Head intersected and exposed the system allowing speleologists the opportunity to examine it. A tabular flint layer appeared to be associated with the cave development and was observed to be followed by the caves (including vertical displacements). It is possible that the perturbation in groundwater flow caused by the presence of the flint layer initiated the dissolution and enlargement of the fractures which were then further enlarged by the concentration of flow through the fractures. As the caves are now mainly above the water table they must have developed when water levels were higher, possibly during interglacial periods of Devensian time.

4.3 THE THAMES BASIN

4.3.1 Introduction

The Chalk of the Thames Basin has been highly exploited for groundwater since the eighteenth century. Early development of the aquifer depended on hand-dug shafts, some with horizontal adits extending laterally for up to 1000 m. In Victorian times the drilling rig superseded the well diggers, allowing exploitation to increase rapidly. Within the London Basin itself the Chalk is confined by Palaeogene deposits. Originally Chalk groundwater was artesian, but the heavy exploitation led to water levels being depressed by up to 75 m during the 1930s and 95 m by the 1950s; water levels are now rising rapidly in the centre of London, since the decline of water intensive industry, and threatening the foundations of high buildings and the underground system.

The area discussed in this section includes more than the confined Chalk aquifer directly below London (see Figure 4.3.1). The upper reaches of the Thames Basin, including the Kennet Valley and Chilterns are important aquifers both for local supply and via the Thames Groundwater Scheme for augmenting the Thames in times of drought. The Chalk of the North Downs is also included in this section; this aquifer is highly developed and as it is environmentally sensitive, a thorough knowledge of the aquifer properties can help plan its further management.

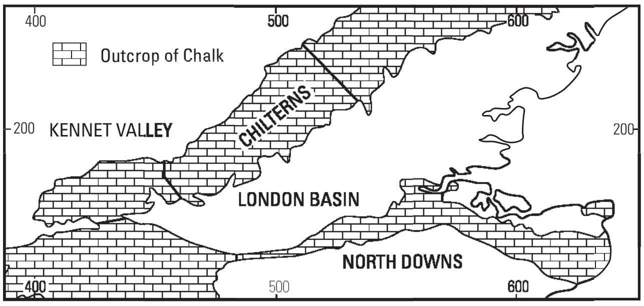


Figure 4.3.1 The Chalk of the Thames Basin and North Downs. For the purposes of examining the aquifer properties of the region, four sub-regions have been defined, these are: the Kennet Valley, Chilterns, London Basin and the North Downs.

The Chalk of the Thames Basin is gently folded into a broad syncline upon which are superimposed several small flexures, most of them in the south of the Basin. The majority of the Chalk outcrop within the region was not subject to glaciation. The area was, however, subject to long periods of periglacial activity, which led to many of the features characteristic of Chalk downland.

For the purpose of this report the Chalk of the Thames basin has been split into four subregions: Kennet Valley, Chilterns, London Basin and North Downs. Within each section, a general description of the geology and physiography is given along with an indication of the groundwater investigations that have been undertaken within the area. Then the data-holdings within the Aquifer Properties Database are described, with a summary of pertinent statistics. A discussion of the vertical and areal distribution of both transmissivity and the storage coefficient follow, and where appropriate a discussion of the various controls on aquifer properties or other additional information is included.

The Kennet Valley

Introduction

Geological and geographical setting

The Kennet Valley is the name given to the area of Chalk west of the Goring Gap on the edge of the London Basin and incorporates the Berkshire and Marlborough Downs (Figure 4.3.2). The northern edge of the Downs is defined by a prominent double escarpment which runs approximately east–west from Wallingford past the Vale of the White Horse to Swindon, with the highest points at Hackpen Hill (270 m) and Whitehorse Hill (261 m).

Two main rivers drain the outcrop area: the River Lambourn and the River Kennet. The River Kennet rises

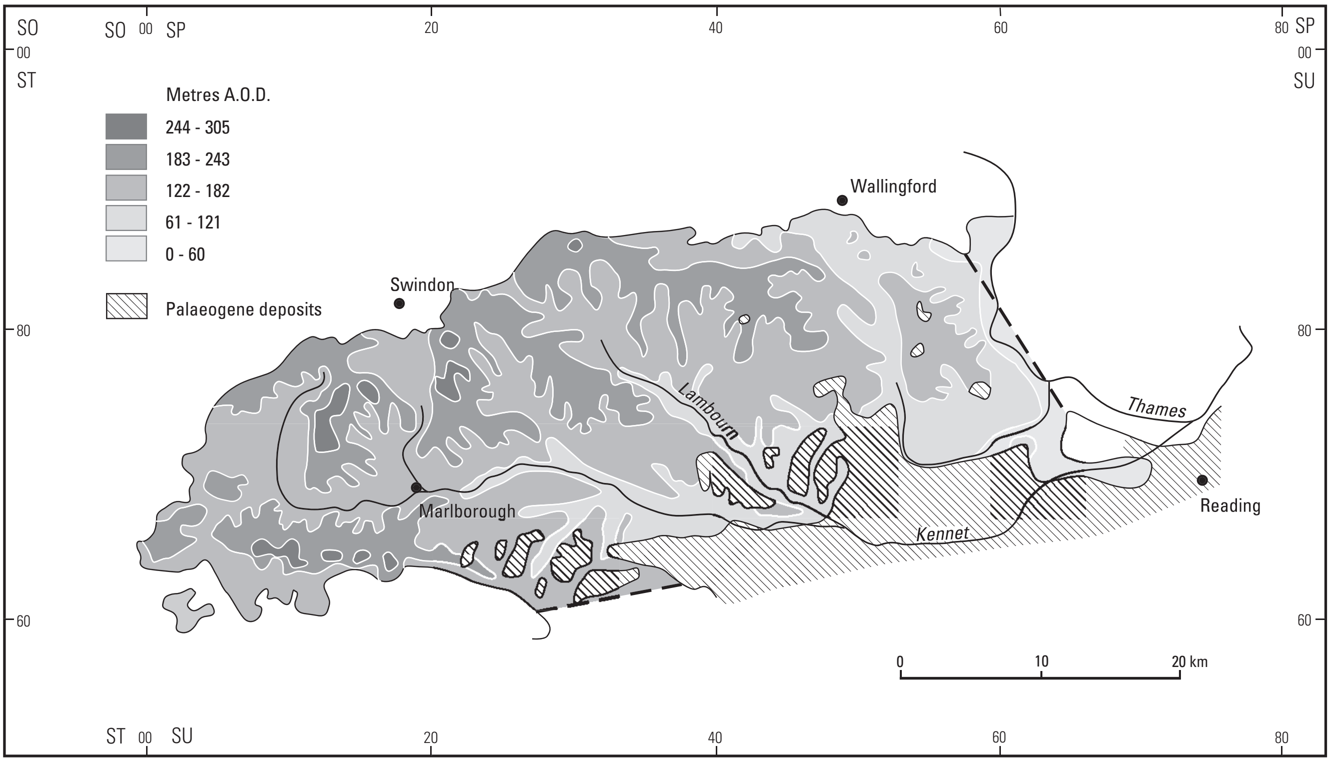


Figure 4.3.2 Location map of the Chalk of the Kennet Valley, illustrating the Chalk outcrop and drainage.

on the Chalk escarpment west of Marlborough and flows eastward joining the River Thames at Reading; while the River Lambourn (a tributary of the river Kennet) rises in the north-east of the Downs around the village of Lambourn and flows south-eastward joining the river Kennet to the east of Newbury.

Throughout most of the outcrop of the Kennet Valley the Chalk dips gently to the south-east and passes under Eocene deposits. The total thickness of the Chalk is probably about 220 m (Institute of Geological Sciences, 1960). The Upper Chalk is composed of soft white chalk with numerous flints. Middle Chalk forms the main mass of the escarpments flanking the Vale of the White Horse and the Vale of Pewsey, the Lower Chalk often forming a flat area beneath the main escarpment giving a characteristic double escarpment. The lower 30 m of the Lower Chalk comprises Chalk Marl which has low permeability. The Chalk Rock at the base of the Upper Chalk and the Melbourn Rock at the base of the Middle Chalk are the most significant hardgrounds within the area; other hardgrounds include the Totternhoe Stone (known locally as the Chilton Stone) at the top of the Chalk Marl found east of Letcombe Bassett [SU 37 85]; the Top Rock which is found in the south-east of the area a few metres above the Chalk Rock; and 20 m above the base of the Chalk Marl a very compact Chalk band known as Marl Rock is found.

Upper Greensand in the Kennet Valley varies from 10 to 50 m in thickness and can be divided into at least two facies, the upper one of glauconitic, micaceous, fine-grained sands and sandstones; and a lower one consisting of well-cemented siliceous rock known as malmstone.

The structure of the area is relatively simple, with the Chalk dipping south-east at about 1° toward the centre of the London Syncline. To the south of the area the Chalk is upfolded into the Pewsey Anticline where the dip is much greater. The location of some valleys on both dip and escarpment slopes are thought to be controlled be faults.

Eocene deposits are found on many of the interfluves in the south-east of the area (Figure 4.1.15). Clay-with-flints deposits are common on the summits of the Upper Chalk ridges, but are also found further down the slopes (Jarvis, 1973). Dry valley deposits occur in many of the valleys. They comprise gravels and coombe rock. Alluvium deposits are found along Chalk streams and bournes.

Groundwater investigations

During the 1970s the Chalk aquifer in the Kennet Valley was subject to a large investigation as part of the Thames groundwater scheme (Thames Water Authority, 1978). The purpose of this scheme was to augment the flow of the River Thames in times of drought by pumping groundwater from the aquifer and transferring it to the perennial sources of the Chalk streams. Downstream, the additional water could then be re-abstracted and used to meet high water demands.

Thirty-three abstraction boreholes were drilled as part of the scheme. Each of these was subjected to numerous tests and the aquifer response measured using purpose built observation boreholes (Owen et al., 1978). The observation boreholes were also test pumped for a limited period (Robinson, 1978). During the investigation, geophysical logging was carried out in the abstraction borehole and many of the observation boreholes giving much information on the vertical distribution of aquifer properties (Robinson, 1975; Owen and Robinson, 1978). Various numerical models have been created for the aquifer to help manage the groundwater resources and estimate the response of the system to extensive use of the augmentation boreholes (Rushton and Chan, 1976; Connorton and Reed, 1978; Morel, 1979; Morel, 1980). These models have been reviewed and updated as increased computing power has made it possible to create more sophisticated models including the non-linear response of the aquifer (Rushton and Tomlinson, 1985; Rushton et al., 1989).

A conceptual model of how transmissivity is developed within the Chalk has been suggested for the Kennet Valley (Robinson, 1976). This work was carried out using all the pumping test and geophysical logging information gathered from the Thames Groundwater Scheme investigations. With the advent of GIS, this work has been developed further at BGS.

The more esoteric nature of the aquifer has been investigated as part of a tracer experiment near Stanford Dingley, Berkshire (Banks, 1988; Banks et al., 1995). Recent work on turbidity and bacteriological occurrence in boreholes has also revealed rapid groundwater flow.

Aquifer properties

General statistics

For the Kennet Valley, data are available from 74 locations, with 117 pumping tests giving transmissivity values and 107 storage coefficient values. The transmissivity distribution is approximately lognormally distributed, with a slight negative skew (Figure 4.3.3). Transmissivity values range from 0.5 to 8000 m^2/d with a geometric mean of 620 m^2/d and a median value of 830 m^2/d. Twenty-five percent of the data are less than 380 m^2/d and 75% less than 1500 m^2/d. There is some evidence to suggest that the transmissivity within the Upper Chalk is greater than that within the Middle and Lower Chalk (the geometric mean from 58 pumping tests carried out in Upper Chalk is 680 m^2/d; the geometric mean of 59 pumping tests undertaken in the Middle or Lower Chalk is 570 m^2/d).

The storage coefficient distribution is also lognormally distributed with a slight negative skew and evidence of bimodality (Figure 4.3.4). Values range from 1×10^{-4} to 0.071 with a geometric mean of 0.006 and a median value of 0.0075. The Upper Chalk tends to give higher values of storage coefficient from pumping tests. This could be attributed to the large number of Upper Chalk sites that

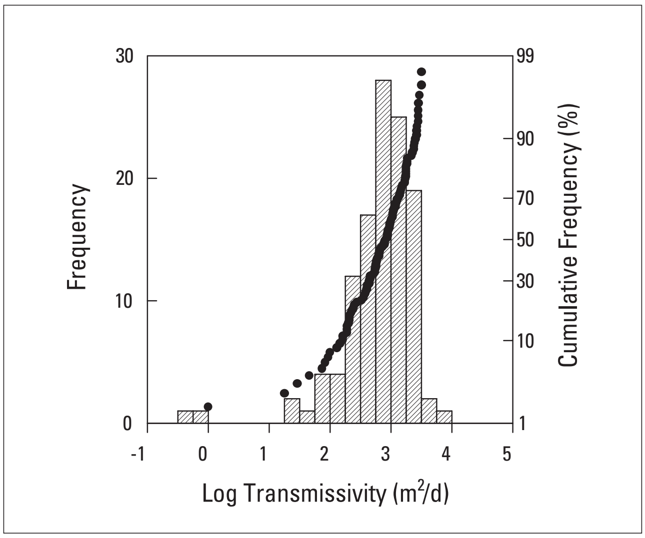


Figure 4.3.3 Distribution of transmissivity data from pumping tests in the Chalk and Upper Greensand of the Kennet Valley.

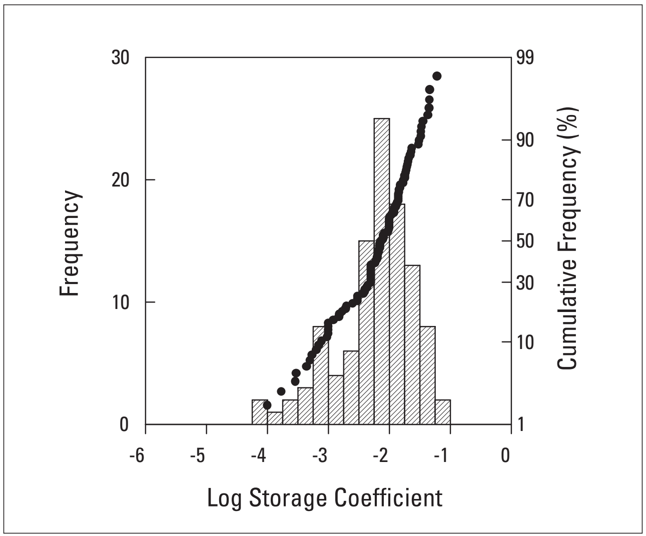


Figure 4.3.4 Distribution of storage coefficient data from pumping tests in the Chalk and Upper Greensand of the Kennet Valley.

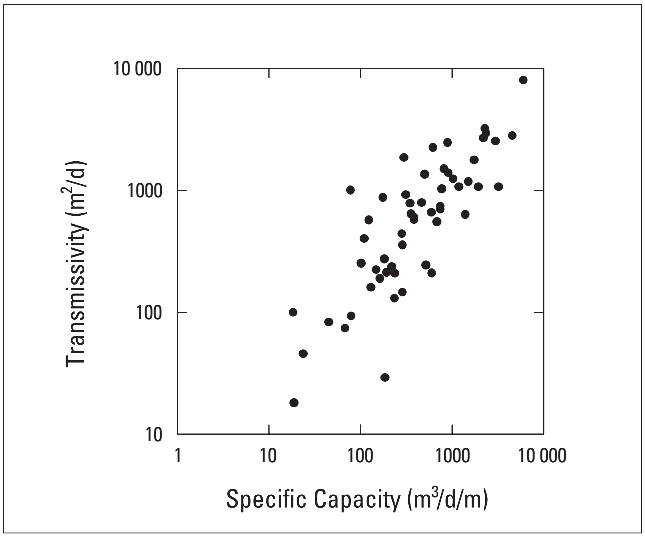


Figure 4.3.6 Plot of transmissivity against specific capacity (uncorrected) for the Chalk of the Kennet Valley.

are unconfined compared to the undifferentiated Chalk boreholes which are generally from confined sites. Alternatively, the trend might be due to greater fracture density within the Upper Chalk.

The data infer a degree of correlation between storage coefficient and transmissivity: boreholes with high transmissivity tend also to have high storage coefficient (Figure 4.3.5). (The observations above which illustrate high transmissivity and storage values in the Upper Chalk are in keeping with such a correlation). A correlation would be expected where the same mechanism is controlling both parameters — in this case fracture size and distribution. Figure 4.3.6 illustrates a good correlation between log transmissivity and specific capacity for the Kennet Valley.

Vertical variations in aquifer properties

The extensive investigations of the Thames Groundwater scheme during the mid 1970s led to a good understanding being developed of the vertical distribution of aquifer properties in the Chalk (Owen and Robinson, 1978; Rushton and Chan, 1976; Connorton and Reed, 1978). Since then, the detailed modelling of the area has corroborated the field evidence and helped to extend the findings over the whole area (Rushton et al., 1989).

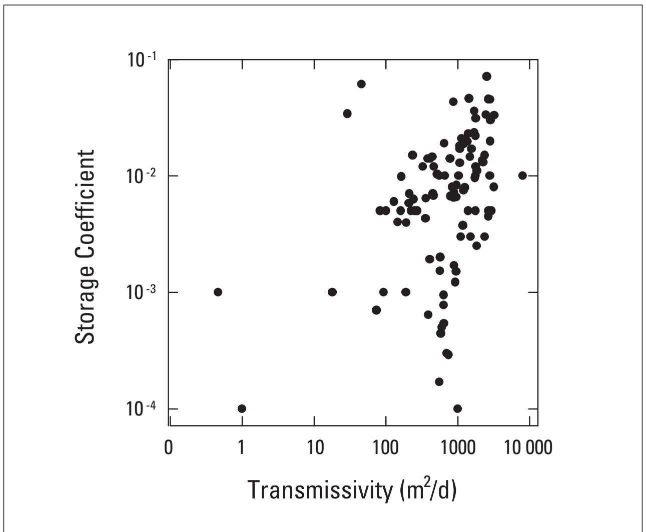


Figure 4.3.5 Plot of storage coefficient against transmissivity for the Chalk of the Kennet Valley.

A series of springs issue from the foot of the Chalk escarpment. Their location is largely controlled by the underlying geology and therefore gives some information on the hydraulic properties of the various units within the Chalk (Morel, 1979). West of Letcombe Bassett [SU 37 85] springs are numerous and tend to issue from the base of the malmstone or within the Upper Greensand, where groundwater is impeded by various impermeable layers. To the east of Letcombe Bassett the springs change slightly in character: they are larger and less frequent and tend to issue from within the Lower Chalk, frequently the from the Chilton Stone (Institute of Geological Sciences and Thames Water Authority, 1978). In the west, the malmstone is possibly less cemented and therefore more permeable, allowing the development of numerous springs along the boundary with the Gault. Some general patterns of the aquifer properties of the Chalk and Upper Greensand aquifer in the area can be deduced from the spring distribution: the aquifer properties tend to be less well developed within the Lower Chalk because of the marl layers, but hardgrounds can be important flow horizons; where the malmstone is well cemented it can act as a barrier to groundwater flow.

Hydraulic continuity between the Chalk and the Upper Greensand is thought to be limited over much of the Kennet Valley due to the clayey nature of the Lower Chalk. An exception to this is around Woodsend (Rushton et al., 1989).

Within the Upper and Middle Chalk, the vertical distribution of aquifer properties has developed with little regard for stratigraphy. A histogram of fracture distribution with depth has been produced for the Kennet Valley using geophysical logs from the valleys (Owen and Robinson, 1978). The fractures tend to be non-linearly distributed with the majority (90%) occurring within the top 60 m below ground level, or below the confining layer (Figure 4.3.7). Therefore with an average depth to rest water-level of 15 m, the aquifer thickness is roughly 45 m. Occasionally inflows

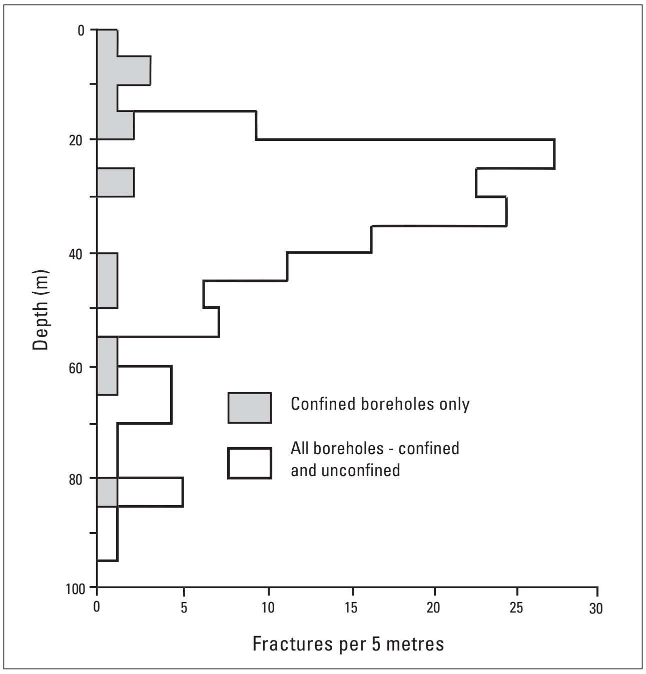


Figure 4.3.7 Distribution of flowing fractures with depth taken from geophysical logs in the Kennet Valley (after Owen and Robinson, 1978).

have been detected at greater depths (80 m) associated with the Chalk Rock. Inspection of television logs illustrated that the majority of fractures within the aquifer were parallel to bedding (although the data are naturally biased because vertical boreholes are more likely to intersect horizontal, than inclined, features).

In addition to the logging evidence, pumping tests also implied the importance of shallow fractures (Connorton and Reed, 1978; Owen and Robinson, 1978). During testing, a number of boreholes illustrated a sharp break in their time-drawdown curve as the test proceeded. This was attributed to the dewatering of important fractures (Figure 4.3.8). Multiple pumping tests have been carried

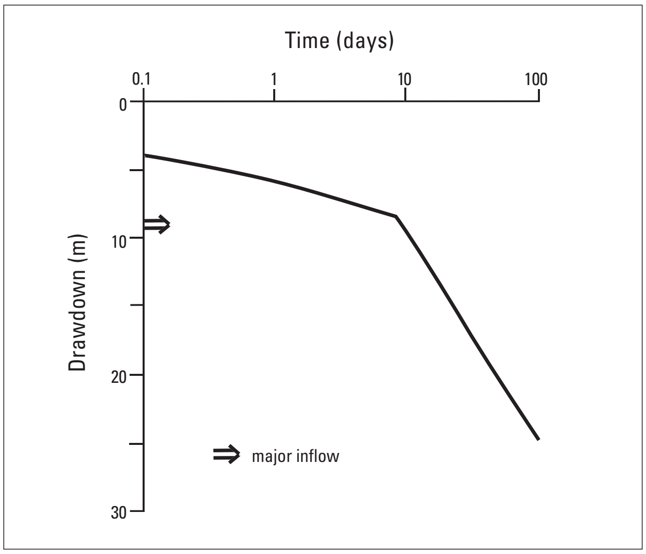


Figure 4.3.8 Typical drawdown curve in the Kennet Valley illustrating the dewatering of important fractures (after Owen and Robinson, 1978).

out at various locations giving a number of transmissivity and storage coefficient values for different water levels. Estimates of *both* parameters from these tests appear to decrease non-linearly with depth, (Figure 4.3.9). Therefore, like transmissivity, as important fractures near the top of the borehole are dewatered, the storage declines.

Modelling of the aquifer system reinforces the non-linear vertical distribution of transmissivity (Rushton and Tomlinson, 1985; Rushton et al., 1989). It was impossible to represent stream flow and groundwater levels using constant transmissivity: stream flows during low periods were too large and groundwater heads too high during times of recharge. To represent both these phenomena in the same model, a 'cocktail glass' vertical distribution of transmissivity had to be used (Figure 4.3.10). (This is

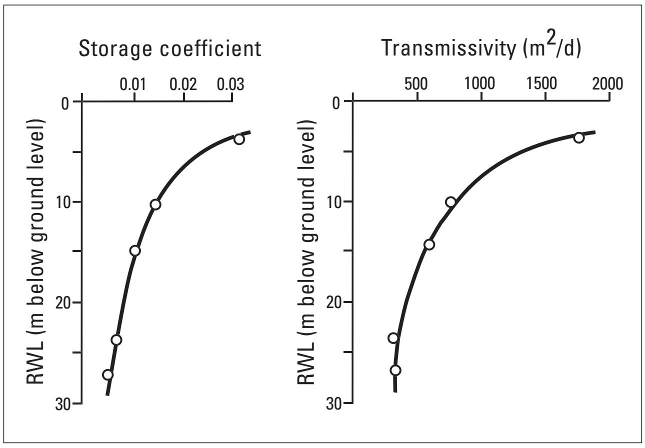


Figure 4.3.9 Non-linear decrease in transmissivity and storage coefficient measured from pumping test at progressively deeper rest water level (after Owen and Robinson, 1978).

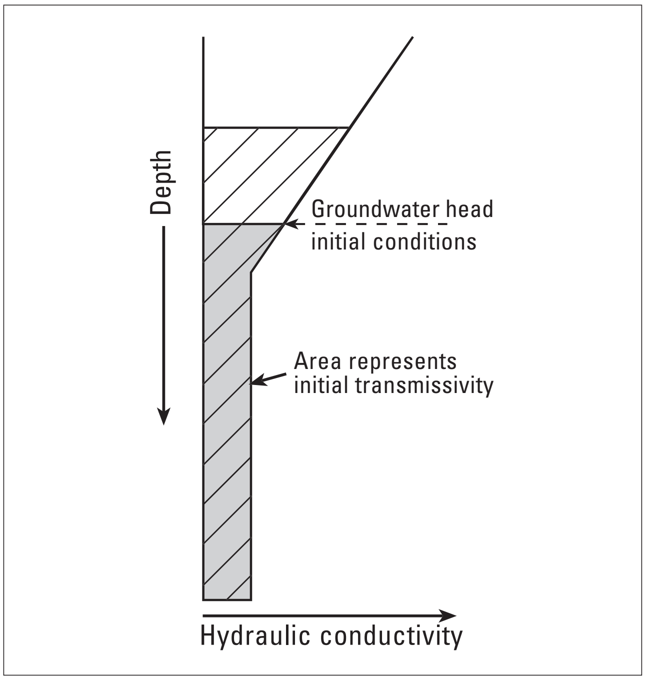


Figure 4.3.10 Vertical distribution of transmissivity used in a transient groundwater flow model of the Kennet Valley (after Rushton et al., 1989).

similar to those used by Birmingham University in many of their other Chalk models). Transmissivity is represented as being fairly constant throughout most of the thickness of the aquifer. However, in the top few metres, within the zone of water table fluctuation, transmissivity increases non-linearly. Using this vertical distribution significantly improves the model representation of both stream flow and groundwater levels throughout the year. This is achieved as follows: (1) high water levels cannot develop due to the ever increasing transmissivity, and during periods of low groundwater levels, groundwater flow is significantly reduced due to the low transmissivity of the basal layer. Evidence at various locations from borehole logging provides some physical basis for this vertical distribution, and therefore it is not unreasonable to extrapolate such a distribution to the rest of the aquifer. However, the rate of decrease of transmissivity with declining water levels may vary significantly (Morel, 1980).

There is little field evidence to describe the vertical distribution of the aquifer properties high up on the interfluves. The recent groundwater model, however, requires the same non-linear behaviour as is observed in the valleys (Rushton et al., 1989). The limited field evidence that does exist from flow logging in observation boreholes on the interfluves suggests a thin zone of fractured rock near to the water table (Robinson 1978) — thinner than the corresponding zones in the valley (Figure 4.3.11). This ties in quite well from evidence elsewhere (National Rivers Authority, 1993; Posford Duvivier, 1994). Therefore it is possible that a similar distribution is found over the interfluves as in the valleys, but at a much smaller scale due to the lack of flux to develop it.

The areal distribution of aquifer properties data

The Kennet Valley has perhaps experienced more physical hydrogeological investigation than any other area of Chalk downland in England. Aquifer properties data have been collected not only in the high yielding valley sites, but also in the more unpredictable lower yielding interfluves. In general, transmissivity values range between 50 and 2500 m^2/d with the higher values in the main valleys (valleys containing streams and principal dry valleys). Away from the head of the main valleys the transmissivity decreases rapidly. Pumping tests undertaken within valleys illustrate the reduction of transmissivity away from the valley (Figure 4.3.12). Initially the drawdown rate is very slow due to the high transmissivity of the valley. As the test continues, the cone of depression extends into areas with lower transmissivity, and the drawdown rate increases, giving a characteristic signature on the drawdown curve. Owen and Robinson (1978) observed that within the Kennet Valley they could distinguish such drawdown curves from the abrupt changes in slope characteristic of many Chalk pumping tests due to the dewatering of important fractures.

These initial observations led Thames Water Authority to create a model of the transmissivity distribution over the Kennet Valley using three easily measured parameters (Robinson, 1976):

- depth to minimum rest water level
- saturated thickness of the aquifer
- distance away from winter flowing streams

A map of each was produced and then the parameters weighted and combined to produce a distribution of the transmissivity variation over the Kennet Valley. By using a base value of transmissivity in the valleys of 1600 m^2/d a map could then be produced show transmissivity over the whole valley. With the advent of GIS techniques this methodology could be repeated, tested and manipulated. Using the same basic rules as Robinson (1976) the transmissivity distribution for the Kennet Valley was estimated (Figure 4.3.13). A similar variation for storage coefficient was suggested but was thought to be less consistent. Modified distributions of aquifer properties given by this

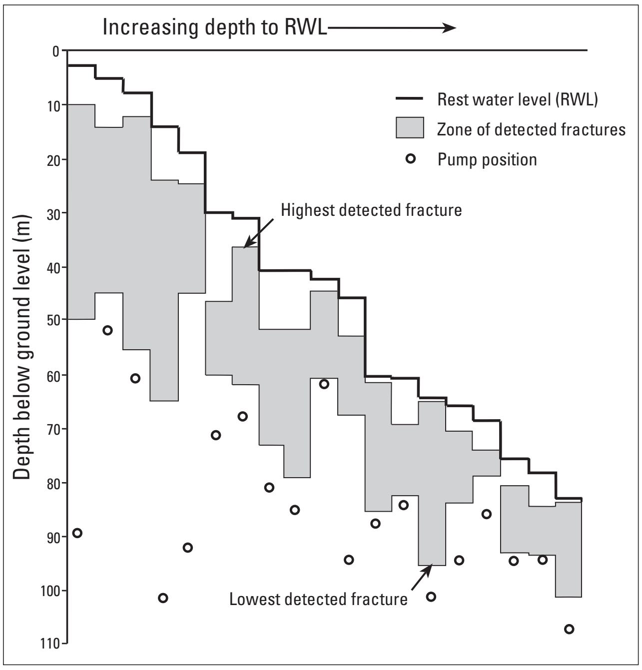


Figure 4.3.11 The change in fracture distribution (measured from geophysical logs) away from valley axes in the Kennet Valley area (after Robinson, 1978). The data suggest that the saturated fracture zone identified in the valleys thins away from the axes.

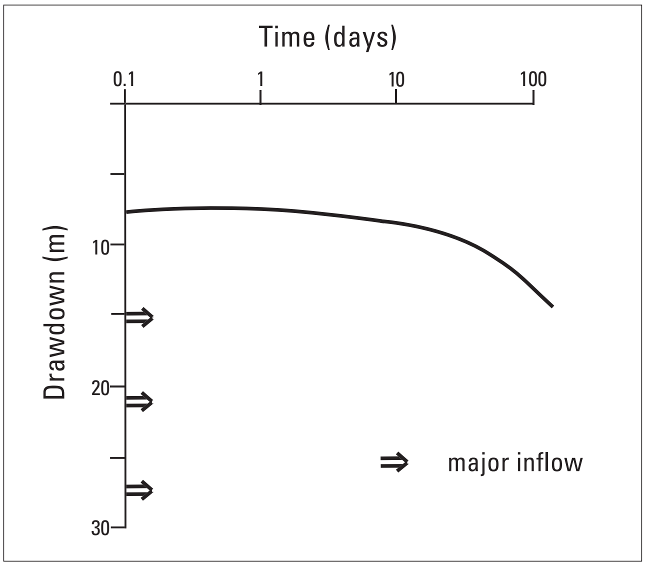


Figure 4.3.12 Typical drawdown curves in the Kennet Valley illustrating a general increase in drawdown due to the cone of depression moving away from the highly permeable valley to the interfluves (after Owen and Robinson, 1978).

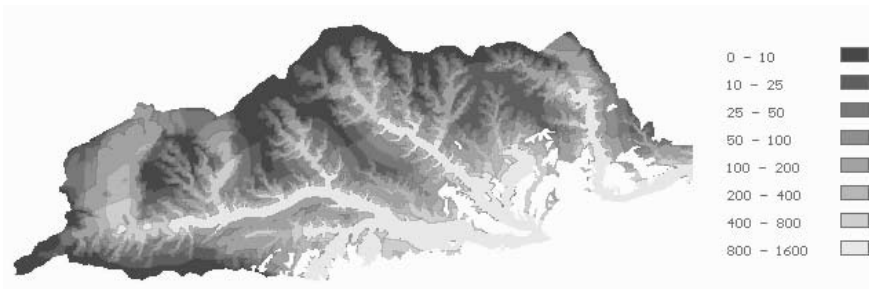


Figure 4.3.13 Transmissivity variation over the Kennet Valley calculated from three parameters: distance from rivers; thickness of unsaturated zone; thickness of aquifer (using data from Environment Agency, Thames Region).

conceptual model have been used as the basis for numerical groundwater modelling (see Figure 4.3.14) (Rushton et al., 1989).

There are two basic ideas behind the model: groundwater flux and aggressiveness. Near to valleys the volume of water flowing through the aquifer increases giving a large flux, therefore a higher transmissivity is required to enable the water to pass through. With a thick unsaturated zone on the interfluves groundwater has more chance to become fully saturated with calcium carbonate before reaching the water table, consequently, recharge that has had to travel a long way through the unsaturated zone will have less potential for dissolving and enlarging fractures.

This conceptual model was tested on the GIS by comparing the results with the real pumping test data. The three input parameters to the model were found to be co-correlated — as distance from the valleys increased, so the unsaturated zone increases and the thickness of the saturated aquifer decreases. By testing each parameter individually, the best correlation (significantly better than the three combined as above) was found with distance from main valleys only. However, all the variance is not explained by this model and other factors also play a significant role in developing the aquifer properties e.g. distance from the Eocene deposits.

In summary, transmissivity generally decreases away from the main valleys. Transmissivity values of 2000 m^2/d

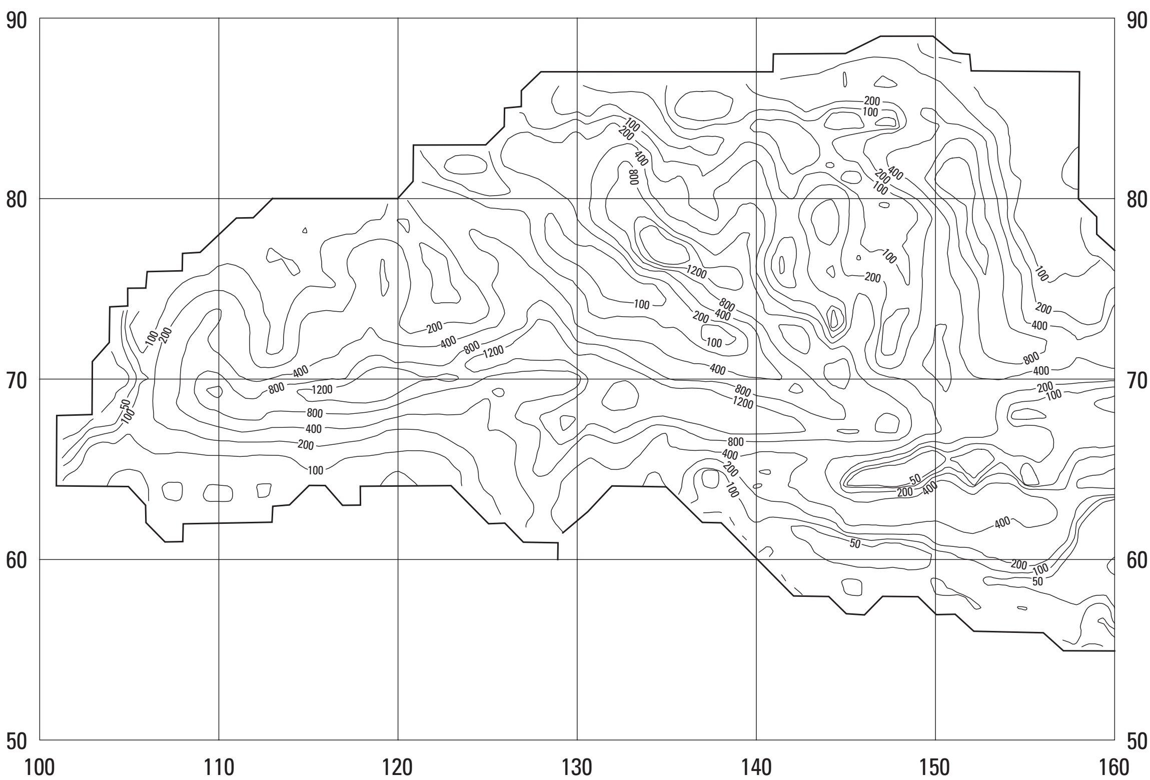


Figure 4.3.14 Transmissivity distribution used in a groundwater model of the Kennet Valley (after Rushton et al., 1989).

are common in the valleys e.g. along the Kennet and the Lambourn, and in the ephemeral streams of the Pang and the Winterbourne and Og. On the interfluves transmissivity can decrease to less than 50 m^2/d and even to less than 1 m^2/d. The storage coefficient follows a similar pattern with values of 0.015–0.03 in the valleys declining to 0.005 over the interfluves.

Rapid groundwater flow

In some parts of the aquifer rapid groundwater flow has been identified. Tracer studies near Stanford Dingley on the floodplain of the River Pang have revealed a connection between swallow holes and a Chalk spring known as the Blue Pool (Banks, 1988; Banks et al., 1995). Flow velocities of over 6 km/d were recorded between the swallow holes and spring 4.7 km away. Similarly, many swallow holes have been identified on the interfluves of the Berkshire and Marlborough Downs (Edmonds, 1983; Goudie, 1990). These tend to be associated with some sort of cover, either Eocene deposits or clay-with-flints and can be of significant size. During periods of heavy rainfall the swallow holes can be quite active allowing large quantities of surface water to recharge the aquifer.

A series of such swallow holes have been identified at Little Bedwyn [SU 306 650]. During the summer months of 1994, a surface stream on the Eocene deposits disappeared through the stream bed at several locations, associated with tree roots. During January 1995, after a prolonged period of heavy rainfall, sufficient water was passing through the system to activate swallow holes further downstream. In a neighbouring system the entire stream was captured by one large swallow hole. The importance of such rapid recharge should not be underestimated when considering contamination within the Kennet Valley. Features are common where the Chalk is covered by Eocene deposits or clay-with-flints.

4.3.3 The Chilterns

Introduction

Geological and geographical setting

The Chilterns is the name given to the chalk hills lying north-east of the Goring Gap. The hills run from Goring north-eastward to Luton (Figure 4.3.15). The Chilterns exhibit classic cuesta geomorphology, with a prominent escarpment rising to 256 m at Watlington and a series of distinctive dry valleys. Several rivers, (tributaries of the Thames) drain the outcrop: the Misbourne, Colne and Ver; the River Thames cuts through the Chalk outcrop at the Goring Gap before flowing eastward in a series of large meanders past Reading, Henley and Marlow before leaving the Chalk outcrop at Maidenhead.

Upper Chalk outcrops over the majority of the area of the Chilterns. In many of the valleys, however, Middle Chalk is exposed due to deep incision (Figure 4.3.15). Lower Chalk and Upper Greensand are exposed below the main escarpment where they form relatively flat platforms with sometimes a secondary smaller escarpment below. The Chalk Rock is present throughout the area at the base of the Upper Chalk and also the Melbourn Rock at the base of the Middle Chalk. Two hard bands are present within the Lower Chalk, the Risborough Rock and Totternhoe Stone.

Eocene deposits are found on many of the interfluves to the south-east of the area. Clay-with-flints deposits

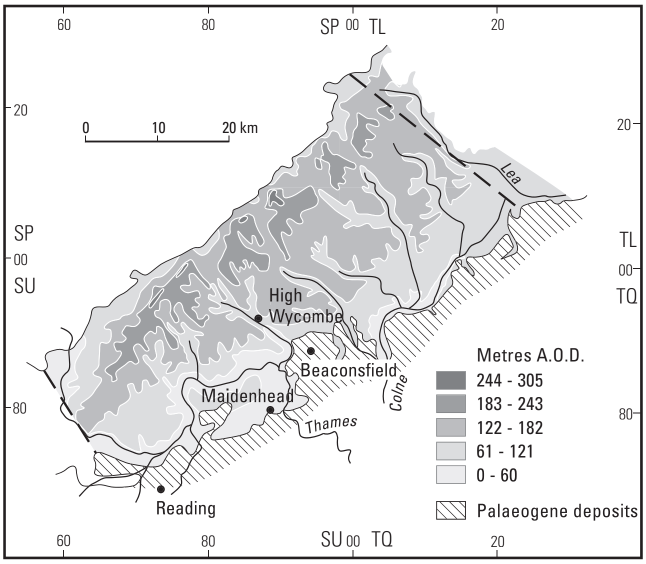


Figure 4.3.15 Location map of the Chalk of the Chilterns, illustrating the Chalk outcrop and drainage.

are common on the summits of the Upper Chalk (Figure 4.1.15). Dry valley deposits are found in many of the valleys. Alluvium deposits are found along streams and bournes.

The area is largely characterised by deep dry valleys extending far up the dip slope. However, there are some other physical features that are of note: some dry valleys cut right through the escarpment, for example at Wendover, Tring, Luton, and Hitchin; periglaciation has also had an important influence on the hydrogeology — especially within the larger flowing valleys, e.g. the Thames and the Colne (Younger, 1989).

Groundwater investigations

Compared with its neighbour, the Kennet Valley, there have been relatively few studies of the aquifer properties within the Chalk of the Chilterns. A short regional discussion of the eastern section of the area was provided by the Water Resources Board as part of their analysis of the hydrogeology of the London Basin (Water Resources Board, 1972). More recently Thames Environment Agency have been involved in creating a groundwater model for the whole of the Chilterns, and although detailed data on aquifer properties data were not collected, calibration of the model can give some insight to the aquifer system. Two tracer studies have been carried out within the area — one earlier on this century in South Mimms (Woolridge and Kirkaldy, 1937; Morris and Fowler, 1937), and another at the junction between the M1 and M25 in the late 1980s (Price et al., 1992).

A study of the influence of periglaciation on the development of permeability within the Chalk was carried out at Newcastle University in conjunction with Thames Water Authority during the late 1980s (Younger, 1989; Younger, 1990). Within this investigation an explanation was suggested for the different transmissivity values measured along the route of the Thames.

In conjunction with these larger studies, detailed pumping test reports are held within Thames Environment Agency for investigations of individual boreholes or spring surveys.

Aquifer properties

General statistics

Within the database, data are available from 44 locations within the Chilterns; there are 62 pumping tests with transmissivity values and 44 which gave values of storage coefficient. The transmissivity data approximated to a log-normal distribution (Figure 4.3.16). The data ranged from 38 to 25 000 m^2/d with a geometric mean of 820 m^2/d and median value 860 m^2/d (25% of the data are less than 270 m^2/d and 75% less than 2100 m^2/d).

The distribution of storage coefficient data is shown in Figure 4.3.17. Values (values of storage coefficient >0.1 have been omitted; see section 4.1.8 for further details) from different pumping tests ranged from 6.5×10^{-5} to 0.09 with a geometric mean of 0.0037 and median 0.0029; 25% of the data are less than 8×10^{-4} and 75% of the data less than 0.028. The data have a bimodal distribution with approximate modal values of 3×10^{-4} and 3×10^{-2}.

Nineteen sites within the Chilterns have estimates of both transmissivity and specific capacity — a scatter plot of the data is shown on Figure 4.3.18.

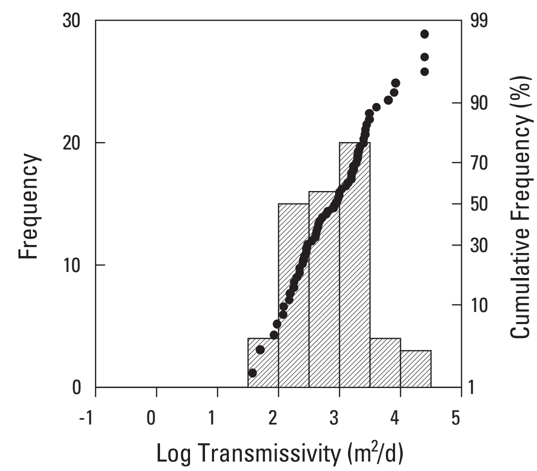


Figure 4.3.16 Distribution of transmissivity data from pumping tests in the Chalk and Upper Greensand of the Chilterns.

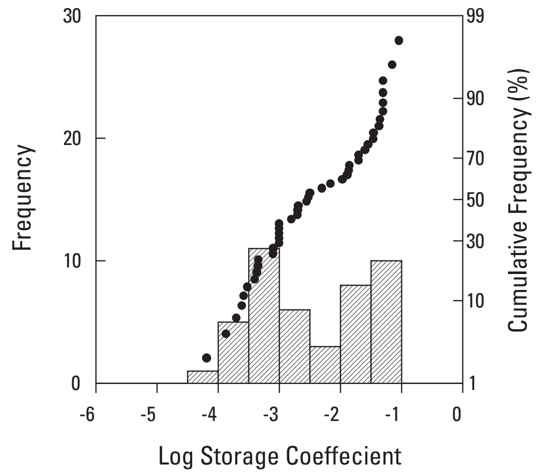


Figure 4.3.17 Distribution of storage coefficient data from pumping tests in the Chalk and Upper Greensand of the Chilterns.

The thickness of the aquifer

The total thickness of the Chalk over the Chiltern plateau is in the order of 200–250 m (British Geological Survey, 1993); the Upper Greensand achieves a thickness of about 10–50 m. There are few geophysical logs for the Chilterns and no packer tests, however in the absence of any contradictory data it appears reasonable to assume that the Chalk aquifer in the Chilterns behaves in roughly the same manner as the Berkshire Downs. Therefore the important flow horizons are probably within the upper 50 m of the saturated Chalk. It is also possible that as in other areas (cf. South Downs and Berkshire) significant fracture zones exist above the water table.

However, in some locations within the major valleys, putty Chalk has been detected at the top of the Chalk, especially where it is overlain by river gravels. The putty chalk as the name suggests is a very soft, clayey chalk — probably broken down form fresh chalk by the annual cycle of freezing and thawing during the cold periods of the Devensian (Younger, 1989). Putty chalk has low permeability and can therefore impede the flow of groundwater at the top of the Chalk, sometimes confining the aquifer below or restricting the flow of groundwater between the gravels and the Chalk.

There are two clear spring lines on the northern escarpment of the Chilterns, one within the Lower Chalk at the Risborough Rock or Totternhoe Stone and the other at the base of the Upper Greensand (Robinson, 1988). Also the heads measured within the Lower Chalk and the Upper Greensand at the same location can be significantly different (Institute of Geological Sciences and Thames Water Authority, 1978). Therefore it appears that the Chalk Marls within the Lower Chalk act as an effective aquiclude, splitting the Chalk and Upper Greensand into two distinct

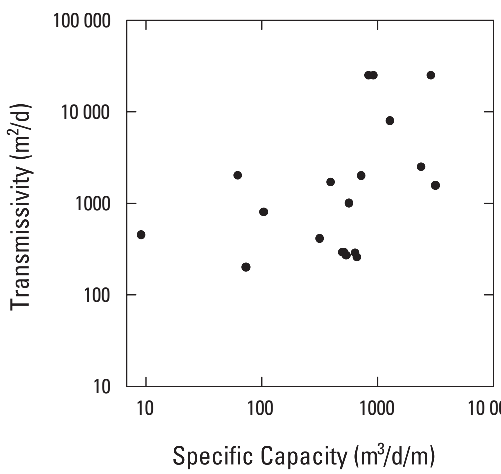


Figure 4.3.18 Plot of transmissivity against specific capacity (uncorrected) for the Chalk of the Chilterns.

aquifers. The majority of the springs issuing from the Upper Greensand do so at the boundary with the underlying Gault. This suggests that in this area, unlike some others, the Upper Greensand is permeable throughout its entire thickness with few low permeability layers to impede the flow of water.

The areal distribution of aquifer properties

There are insufficient aquifer properties data available for the Chilterns to support a detailed description of the change in aquifer properties from valley to valley. However, the Chilterns can be split into different geomorphological units which are likely to have their own unique range of aquifer properties due to the different processes involved in aquifer development. The following areas will be described: the major valleys; the dry valleys; the interfluves; at the foot of the main escarpment; close to the Eocene deposits; and deeply confined.

MAJOR VALLEYS (THAMES AND THE COLNE)

In general aquifer properties are favourable close to the River Thames and the River Colne. High yields are gained both from boreholes that penetrate the river gravels and also in many locations from those that penetrate the Chalk. Part of the reason for the large yields is the high degree of leakage to the aquifers from the River Thames; for example at Medmenham and Gatehampton water from the Thames leaks into the Chalk either directly or via the river gravels. The large component of leakage renders it quite difficult to calculate aquifer properties: e.g. the high transmissivity recorded at Medmenham of 25 000 m^2/d is probably more attributable to the leakage from the river than the aquifer properties. However, despite the difficulties in analysis, high transmissivity values are expected within the Chalk due to the high flux of groundwater that flows through the major valleys — enhancing the aperture of the existing fractures. From the data, transmissivity values within the Thames and Colne valleys are normally in the range of 1500–3000 m^2/d. Storage coefficient values are extremely uncertain due to the high leakage but are thought to be generally in excess of 0.02 (Thames EA, personal communication).

Within the valleys, however, putty chalk can reduce the permeability of the aquifer. Putty Chalk is present beneath wider sections of valley; it has been detected in the Thames at Wargrave, Hurley, West Marlow, Little Marlow and Spade Oak (Younger, 1989); and also in certain sections of the Colne (Thames EA, personal communication). During periglaciation in the Devensian, the repeated freezing and thawing of permafrost led to the shattering of the Chalk producing a putty; much of this was removed from the interfluves but not from within the wide sections of the valleys (Williams, 1987; Williams, 1980). Therefore, the freeze-thaw action underneath minor channels within the wider sections of the valley would produce the observed thick layer of putty chalk, and the persistence of permafrost would reduce the flux of groundwater leading to a reduction in dissolution and therefore transmissivity (Figure 4.1.14, Section 4.1). In the narrower sections of the valley however, e.g. Gatehampton and Medmenham, the surface water and groundwater flow was concentrated into a single channel, producing a perennial talik which remained unfrozen throughout the whole year. Therefore, dissolution would occur throughout the year, possibly at a higher rate than at present as a result of the low temperatures and higher groundwater flux.

DRY VALLEYS

The general topographic model of Chalk aquifer properties appears to apply to the Chilterns, although little data exist to test the assumption. Data from dry valleys near Chesham and High Wycombe indicate transmissivity valleys of between 400 and 1000 m^2/d, and storage coefficient values of 10^{-3} to 10^{-2}. In the absence of further aquifer properties data it is assumed that other dry valleys have similar properties. Although no data are available, most dry valleys have public supply boreholes within them (drilled before the advent of quantitative hydrogeology), therefore it is probably safe to assume that transmissivity will be quite high.

A recent model of the London Basin, including the Chilterns, created by Thames Environment Agency, used similar values for the dry valleys (Figure 4.3.19).

INTERFLUVES

No pumping test data exist for interfluve areas. However, from anecdotal evidence from Thames Environment Agency, yields are very poor. Extensive drilling on the interfluves in the neighbouring Kennet Valley revealed low transmissivity and storage coefficient, generally less than 50 m^2/d and 0.01 respectively. Therefore it can be suggested that in general aquifer properties will be low in high ground away from flowing or dry valleys.

AT THE FOOT OF THE ESCARPMENT

The Lower Chalk and especially the Upper Greensand form important aquifers in areas at the foot of the northern escarpment. Several public supply boreholes have been drilled around Princes Risborough and Watlington which

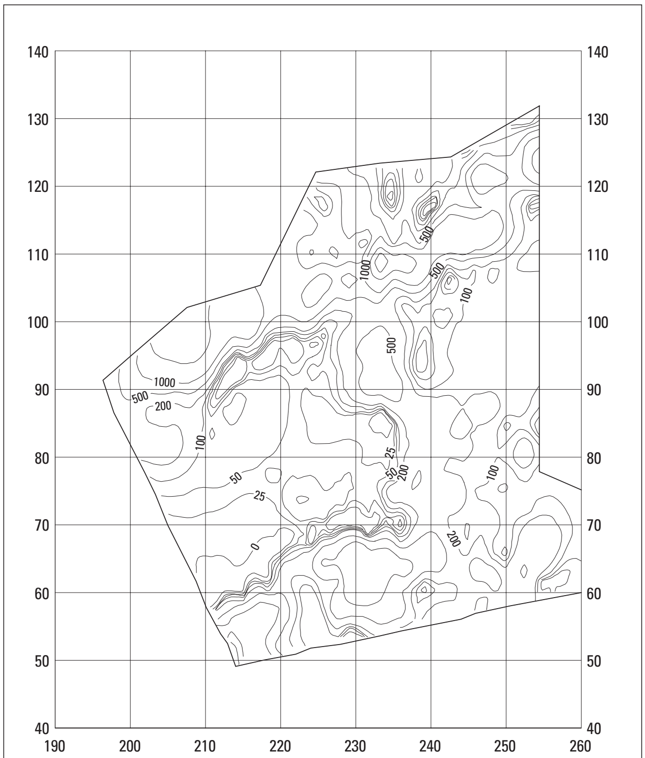


Figure 4.3.19 Transmissivity distribution for the London Basin in a groundwater model for the area (data from Environment Agency, Thames Region).

supply the local villages. Transmissivity values have been recorded of 500–2000 m^2/d, the storage coefficient is commonly 10^{-3}. The Chalk Marl within the Lower Chalk has a very low permeability, and therefore boreholes located within it tend to have low yields. However, it is possible that groundwater leaks downwards through the marl, therefore acting as a store of water for the more permeable Upper Greensand (Robinson, 1988).

THE CONFINED SECTION

Some pumping test data exist for the area of the Chalk south of the Thames where the Chalk becomes confined by Palaeogene strata. Here the best aquifer properties appear again to be associated with valleys, for example at Three Miles Cross, west of Reading. Transmissivity values of about 200 m^2/d are common with the storage coefficient less than 10^{-4}.

Rapid groundwater flow

There have been two tracer tests within the Chilterns testing different areas of the aquifer. The first study at South Mimms illustrated extremely rapid groundwater flow down a series of swallow holes in a tributary of the Colne. Evidence of the tracer was found in the neighbouring valley of the Lea indicating groundwater to move at 5.5 km/d in a different direction to the surface water. (Morris and Fowler, 1937). The swallow holes were found close to the edge of the Eocene deposits, where run off is intensified and recharge acidic. It is possible that the swallow holes are a relic of the bed of the proto-Thames which used to flow through the Vale of St Albans linking the Colne and the Lee (Walsh and Ockenden, 1982). A similar set of swallow holes have been identified in the River Mole in the North Downs.

A more recent tracer study was carried out at the intersection between the M25 and M1, on an interfluve only 2 km away from the Eocene outcrop (Price et al., 1992). On this occasion the tracer was not introduced into a swallow hole, but arbitrarily into the Chalk aquifer via a soakaway. Again the travel time were found to be very fast (2 km/d), but the tracer was highly dispersed. The Chilterns show much evidence of swallow holes and other geomorphological karstic features in association with Eocene deposits (Higginbottom and Fookes, 1971; West and Dumbleton, 1972; Edmonds, 1983; Goudie, 1990). Therefore it is likely that rapid conduit flow is common, both through interfluve features associated with Eocene or clay-with-flints deposits or in the floor of dry or flowing valleys.

4.3.4 The London Basin

Introduction

Geological and geographical background

The Chalk aquifer in this area differs from those discussed previously in that it is overlain by a thick layer of Palaeogene deposits. Originally, boreholes drilled through the cover into the Chalk were artesian, and groundwater naturally discharged through the overlying deposits to the River Thames. However, in the nineteenth and early twentieth century the aquifer was pumped extensively to meet London's high water demand, and eventually, by the late 1960s, the water table was depressed by some 90 m. From this date, as a result of a change in the patterns of pumping and the relocation of heavy industry from the centre of London, the water levels rose. Recovery over the last 30 years has exceeded 30 m in places and current rates are as much as 2.5 m per year in some central locations (Lucas and Robinson, 1995).

The confined section of the aquifer occurs within the centre of the London Basin (Figure 4.3.20). To the north, the area is bounded by the Chilterns, and to the south by the North Downs. The aquifer is most productive within eastern London, whereas to the east and west, where the Chalk becomes deeply buried it is only rarely used for water supply. The less productive areas are not discussed in detail in this account.

The full thickness of the Chalk is about 180–245 m. It is thickest at the base of the dip slope of the North Downs and thins northward to a general thickness of 200–215 m in most of the London Basin (Institute of Geological Sciences 1960). The Upper Chalk is the thickest division of Chalk and up to 100 m thick. The boundary between the Upper and Middle Chalk has sometimes been misinterpreted leading to the Upper Chalk being reported too thin. Boreholes drilled through the Palaeogene into the Chalk for water supply, rarely penetrate the Middle or Lower Chalk. The Upper Chalk is generally soft with numerous flint bands. The lower part is greyish and the Chalk Rock (approximately 1 m thick) marks the base. The Middle Chalk is soft, greyish white chalk with relatively few flints and is usually 45–80 m thick. The bottom 3 m is composed of hard bands, which together are known as the Melbourn Rock.

The top of the Lower Chalk is marked by the Plenus Marl. The bulk of the Lower Chalk consists of greyish chalks with marly partings which pass down into the Chalk Marl, blue-grey chalky marls. The basal unit is a green sandy marl known as the Glauconitic Marl. Few boreholes in the London Basin prove the base of the Chalk. The Upper Greensand has negligible contribution to the Chalk aquifer.

The Chalk is overlain by deposits of Palaeogene age. These consist mainly of the Thanet Sand, Lambeth Group

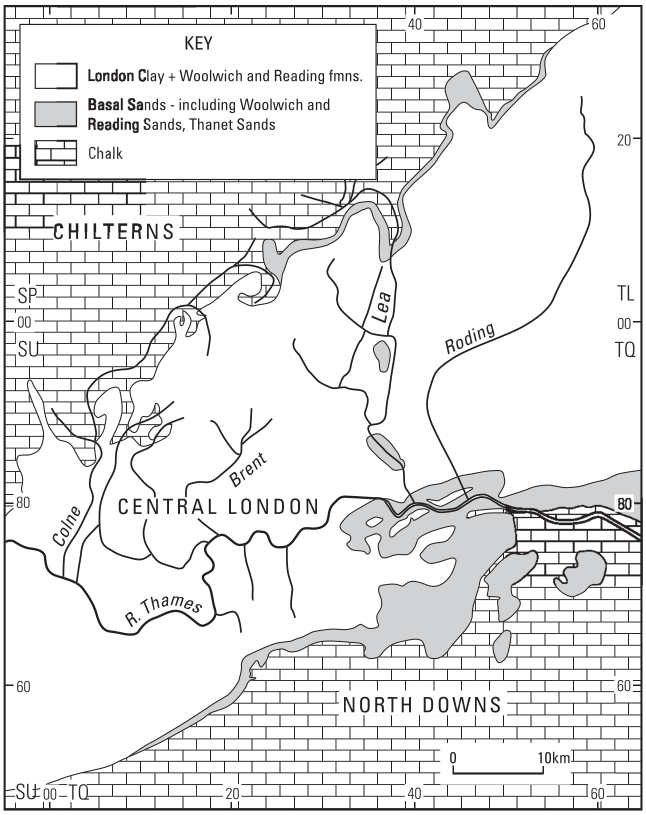


Figure 4.3.20 Location map of the Chalk aquifer of the London Basin.

(formally Woolwich and Reading beds) (Ellison, Knox, Jolley and King, 1994) and London Clay.

From a hydrogeological point of view, a unit known as the 'Basal Sands' that in general includes the Thanet Sand and the lower part of the Lambeth Group is in hydraulic continuity with the Chalk aquifer beneath London. The top of this unit is defined non-stratigraphically as the lowest clay greater than 3 m thick in the Palaeogene succession (Water Resources Board, 1972).

The London Clay consists of up to 130 m of stiff blue clay, where it is eroded away in the Thames Valley in the London area the Thames River gravels may be in direct hydraulic continuity with the 'Basal Sands' and the Chalk aquifer.

The structure of the London Basin has traditionally been considered to be dominated by a major asymmetrical syncline that runs from Savernake forest in Wiltshire, eastward to the North Sea. Dips on the northern limb are generally less than 1°. The beds of the southern limb dip more steeply, up to 3–5°. A few strike faults had been identified and dome like structures were attributed to crossing of two sets of anticlinal axes

Recent work by BGS, Thames Water Utilities Limited (TWUL) and Reading University has led to a greater understanding of the structure of the London Basin. Using the considerable amount of recent drilling information generated by the TWUL and other studies, re-interpretation of the top of the Chalk and base of the London Clay surfaces was undertaken. This revealed the detail several en echelon NNE–SSW-trending folds within the main London Basin syncline and zones of rapid changes in elevation of the modelled surfaces from a metre to over 30 m. These zones are interpreted as NW–SE-trending faults which divide the London Basin into a series of blocks bounded also by roughly NE–SW-trending faults such as the Greenwich Fault.

Groundwater investigations

Due to the importance of Chalk groundwater to the water supply of London, this section of the aquifer has been investigated at various times in detail. A comprehensive report was produced by the Water Resources Board in 1972, which collated much of the geology, aquifer properties and hydrogeochemistry of the Chalk. The primary objective of the study was to assess the potential of the aquifer for artificial recharge. Also during the 1970s the hydrochemistry of the groundwaters within the London Basin was examined (Smith et al., 1976; Downing et al., 1979). A large component of this programme was a study of the age of groundwaters and consequently to estimate the flow patterns within the basin. This information can help to indicate zones of high transmissivity or storage.

The investigations into artificial recharge within the London Basin have given useful information on aquifer properties. Three areas have been investigated within London. The first was the Lee Valley, where the additional storage within the Chalk aquifer created by falling water levels was utilised by a network of recharge and abstraction boreholes. The newly drilled boreholes were acidised, developed and then pump tested using both multiple rate and longer constant rate tests to give information on the well efficiency and aquifer parameters (Boniface, 1959; Flavin and Joseph, 1983). The second area to be investigated was again in north London, along the route of the New River in Enfield–Haringey. Fourteen new boreholes were drilled and test pumped as part of the scheme (Baxter and O'Shea, 1994), and in conjunction with existing boreholes and the New River form a recharge and abstraction scheme. Currently, the potential of South London for an artificial recharge/abstraction scheme is being investigated by TWUL.

The rising groundwater levels within London have recently come under scrutiny (CIRIA, 1989; Lucas and Robinson, 1995). As part of the investigations and forecasts a groundwater flow model has been created for the confined section of the London Basin. Other recent work includes the remapping of the geology of the London Basin by the British Geological Survey as part of the LOCUS (London Computerized Underground and Surface) project. Much new information from boreholes has been incorporated to produce an updated model of the structure of the Basin.

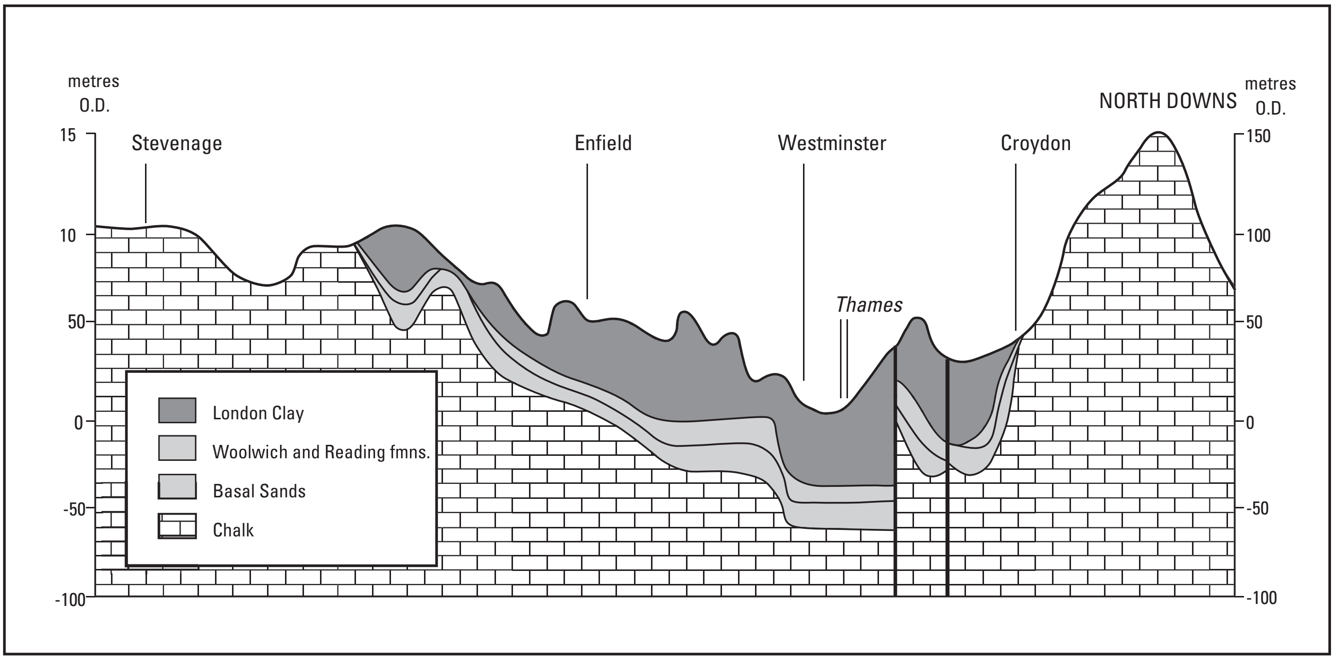


Figure 4.3.21 Cross-section through the London Basin (after CIRIA, 1989).

A major research programme into the hydrogeology of the London Basin has recently been undertaken by TWUL. Part of the work has been undertaken in conjunction with the University of Reading. Other work has involved detailed site investigations in conjunction with numerical modelling. Many interesting phenomena have come to light indicating that the hydrogeology of the London Basin is highly dependent on the structure within the Chalk.

In addition to these larger investigations there have been many smaller investigations centring on individual boreholes. Numerous pumping tests have been carried out and many boreholes geophysically logged.

Aquifer properties

General statistics

Within the database there are 88 pumping tests available from 81 locations within the London Basin. From these pumping tests transmissivity values are available for 88 of the tests and storage coefficient for 41 tests.

The transmissivity distribution shown in Figure 4.3.22 is approximately lognormal. The data range from 1 to 4300 m^2/d with a geometric mean of 160 m^2/d and median of 230 m^2/d; 25% of the data are less than 44 m^2/d and 75% less than 990 m^2/d. The storage coefficient distribution taken from 41 pumping tests is also approximately lognormally distributed (Figure 4.3.23). Data (measurements of storage coefficient greater than 0.1 have been omitted; see section 4.1.8 for further details) range from 3.5×10^{-5} to 0.05 with a geometric mean of 0.0016 and median of 0.0024. The 25 and 75 percentiles are 4×10^{-4} and 0.0047 respectively.

A direct relationship is observed between the logarithms of transmissivity and the specific capacity (Figure 4.3.24). This can be used to generate further estimates of transmissivity from boreholes which only have specific capacity data (Ineson, 1962; Water Resources Board, 1972).

Vertical distribution of aquifer properties

The Chalk reaches a maximum thickness of about 250 m within the London Basin, but as in the unconfined areas of the Chalk only the top sections of the aquifer contribute to the groundwater flow. This is illustrated by the lack of correlation between measured transmissivity and depth of penetration of the borehole within the Chalk. The majority of the boreholes are completed within the Upper Chalk with relatively few that prove the Middle and Lower Chalk. No increase in transmissivity is observed from boreholes that continue to the Middle or Lower Chalk, which implies that neither of the formations (including the Chalk rock which defines the boundary) have significant fracturing.

There are no packer tests within the area but a substantial number of geophysical logs indicate the majority of the inflows to be from the top 30 m (Thames EA, personal communication). The majority of the important fractures are believed to be within the top 10–15 m of the Chalk (Greenwood, 1990). As in the unconfined sections of the Chalk, the aquifer is therefore multi-layered. Groundwater flow is primarily through the upper layers with little flow deeper within the Chalk. The degree of hydraulic connec-

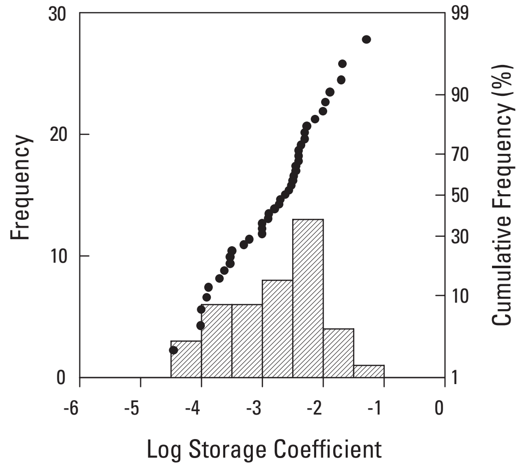


Figure 4.3.23 Distribution of storage coefficient data from pumping tests in the Chalk of the London Basin.

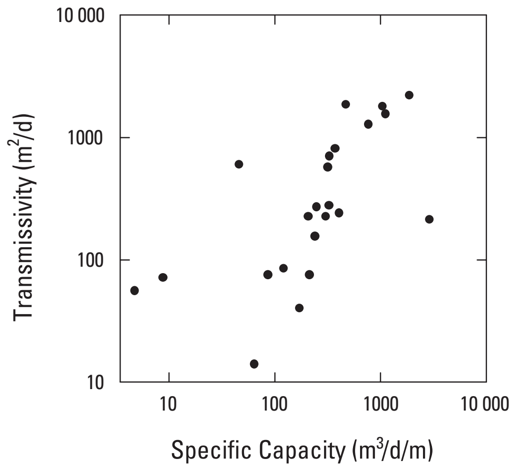


Figure 4.3.24 Plot of transmissivity against specific capacity (uncorrected) for the Chalk of the Chilterns.

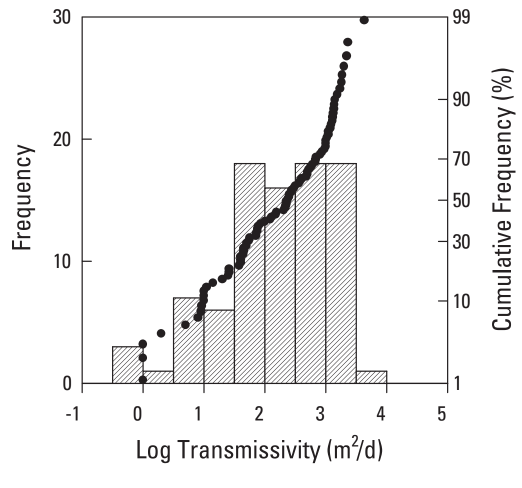


Figure 4.3.22 Distribution of transmissivity data from pumping tests in the Chalk of the London Basin.

tion between the two layers is uncertain; measurements of groundwater potential at various depths by TWUL (Sage, R, personal communication) have indicated that it is poor.

The Basal Sands above the Chalk are significant in providing leakage into the Chalk. They are present throughout most of the London area but thicken towards the east (e.g. 70–80 m around Chigwell, Leyton and Enfield). It is possible that they can significantly increase the storage capacity of the aquifer, although recent water level data have been ambiguous. Some water level hydrographs have recovered more rapidly within the Basal Sands than the Chalk, implying the storage within the sands is *less* than that of the Chalk. However, it is possible that the hydrographs in question are unique or spurious — more data would be required to indicate a general pattern. Recent research suggests that the thickness of the sands depends on faulting within the Chalk.

Since the highest permeability is found within the upper sections of the Chalk, the change in groundwater levels will significantly alter the aquifer's properties and groundwater flow. As groundwater levels rise, more of the high permeability zones will become saturated and groundwater flow is likely to become more rapid.

Areal distribution of aquifer properties

INTRODUCTION

The Water Resources Board produced a transmissivity map for the London Basin in the early 1970s using specific capacity data (Water Resources Board, 1972). Since that time their have been several revisions of this map as new data has become available or fresh insight into the aquifer has been gained (Greenwood, 1990; Lucas and Robinson, 1995; TWUL, personal communication). The WRB and similar maps are useful for giving general outline of the various main features that characterise the aquifer properties distribution and are therefore used as a basis for discussing the areal distribution of aquifer properties of the London Basin (Figure 4.3.25). Measured aquifer properties data are used to illustrate trends and undertake some simple analysis. In a recent analysis of specific capacity data from Chalk boreholes in the London Basin, Monkhouse (1995) identified three different zones, which generally correspond to the transmissivity variation (see Figure 4.3.26).

The Chalk is upwarped along the line of the London–Birmingham Ridge and London Platform. In these areas fractures are numerous and the aquifer is relatively shallow, therefore transmissivity can be quite high. To the north-east and west of this plateau, the Palaeogene cover becomes much thicker and the transmissivity reduces, giving very low-yielding areas, e.g. below Richmond and Essex. The thickness of the overburden appears to strongly influence the transmissivity distribution. This relation between depth of overburden and aquifer properties is illustrated by the pumping test data; boreholes that had deep casing tended to have low transmissivity (Figure 4.3.27). The small outcrop area along the Hog's back to the south of the London Basin also contributes to the low transmissivity observed in the western section of the basin. The very small outcrop area reduces the recharge and therefore the flux of groundwater through that section of the aquifer. To the south-west, beneath Aldershot, Brentford and Richmond, transmissivity is generally less than 15 m^2/d and often less than 5 m^2/d. Likewise to the north-east of the River Lea, beneath Essex, transmissivity declines rapidly due to the thickening of the cover.

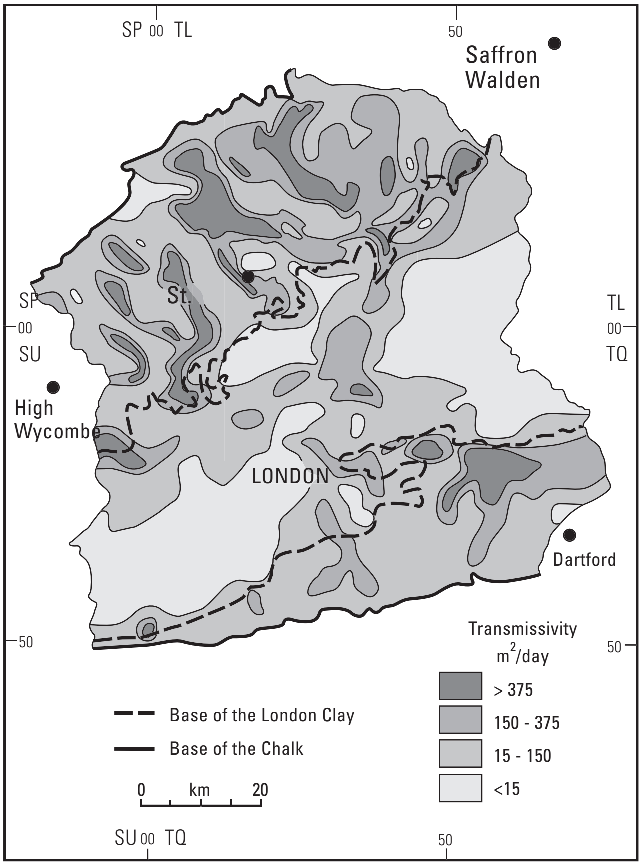


Figure 4.3.25 Schematic representation of the transmissivity distribution in the London Basin (based on Water Resources Board, 1972).

NORTH LONDON

High transmissivity appears to be developed in areas of highest fracturing, lower overburden and largest groundwater flux, which in north London appear to be along the lines of the Rivers Colne and Lea. Groundwater associated with these valleys tends to be young, (Downing et al., 1979, Smith et al., 1976) indicating preferential flow along these routes. Recent investigations and modelling by TWUL have identified high transmissivity zones within north London (Figure 4.3.19). High transmissivity has been identified under parts of the Lee Valley and to the west under parts of the New River. Typical transmissivity values range from 250–1000 m^2/d. Of major importance to the model was the presence of low permeability barriers crossing the zones of higher transmissivity. Without the introduction of such barriers to flow, the observed piezometry could not be simulated. These barriers approximate to lineations associated with the conjugate set of faults identified in other studies, but an exact correlation has not been identified. The lack of correlation reflects in part the lack of suitable data points (TWUL, personal communication). In some areas pumping tests within a few hundred metres illustrate radically different aquifer properties.

There are few pumping test data for the confined section of the Colne valley, however, there appear to be similarities to the Lee, with young groundwater within the valley and high-yielding boreholes. Therefore favourable aquifer properties are likely to have developed along its length.

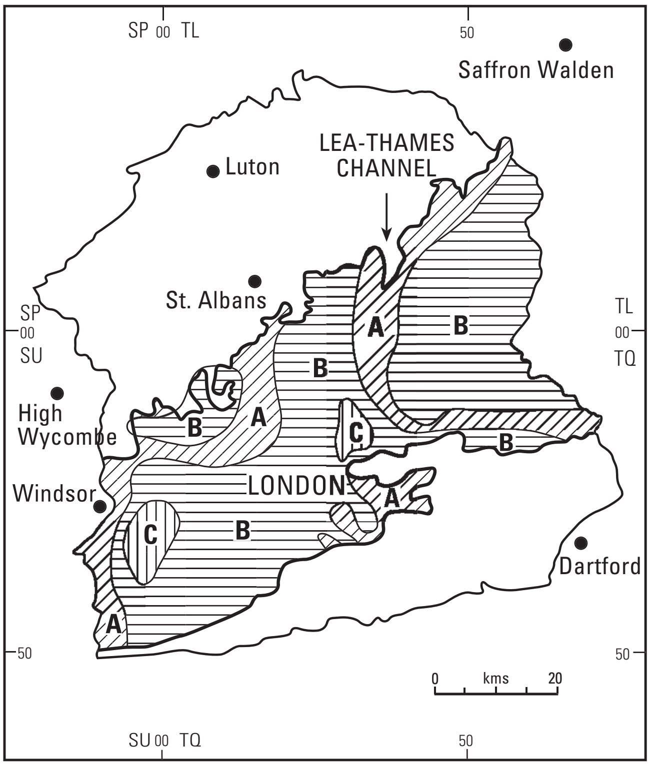


Figure 4.3.26 Schematic map showing zones of standardised specific capacity in the London Basin (after Monkhouse, 1995): Zone A > 1 m^3/d/m, Zone B ² 1 but > 0.1 m^3/d/m, Zone C ² 0.1 m^3/d/m. Values of specific capacity are divided by aquifer thickness to standardise.

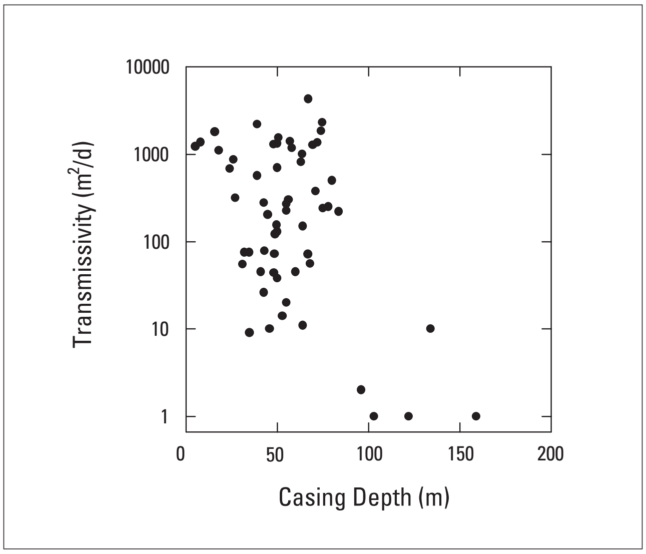


Figure 4.3.27 Plot of transmissivity against depth of casing for Chalk boreholes within the London Basin area.

Central London

There is another zone of moderate transmissivity within central London. This area used to be the part of the discharge zone for groundwater within the basin before large scale abstraction lowered the water levels. Groundwater would discharge through more permeable sections of the London Clay, or where it was absent, via gravels to the River Thames. This throughflow helped to enlarge fractures within the Chalk therefore increasing the transmissivity. It is often quoted that prior to development the artesian flow into the Thames was so powerful that ships sitting at the seaward end of Limehouse reach could bail fresh water straight from the estuary! Solution features have been noted near to the Thames and the Chalk inliers and it is possible that these were formed by pingos, in some places enlarged by scouring (Hutchinson, 1980; Gibbard, 1985). The presence of pingos is evidence of groundwater flow during periglacial conditions. Within the London Basin the pingo remnants are generally on the outcrop of the London Clay where groundwater seepage would have been slow enough to enable the pingos to develop (Hutchinson, 1980). Groundwater discharge through the Chalk and gravels was probably too rapid for pingos to form. The sub-permafrost groundwater flow during the Devensian would have helped to form the observed zones of enhanced transmissivity, by increased flux and dissolution.

Quaternary sea-level changes might have lead to the development of 'blow holes' within the Chalk. The changing sea levels would have increased the pressure of groundwater within the Chalk aquifer. There is now some evidence that suggests that the increased pressure was released in a dramatic fashion resulting in zones of greatly disturbed Chalk — this again would lead to the enhancement of Chalk aquifer properties (TWUL, personal communication).

South London

In south London the Chalk has been broken up into different blocks by numerous faults. This has had a significant effect on aquifer properties. Groundwater levels across faults can change significantly, sometimes as much as 40 m over a distance of 1 km. This implies low permeability perpendicular to the faults (e.g. faulting at Dulwich). Transfer between blocks occurs in some places, particularly at the node points of some scissor faults. Along the line of the faults, however, transmissivity can be very high. Some faults appear to act as drains taking groundwater away from the blocks to discharge further down the basin; the Deptford fault is thought to behave in this way, with evidence of flooded cellars close to the fault, a very large yield at Deptford pumping station, and large solution features of up to a metre in diameter observed in geophysical logging. Therefore transmissivity is fairly anisotropic with high values along the lines of faults and low values perpendicular to them. However, it is not apparent which fracture sets are more transmissive, the main NE–SW-trending set or the set trending NW–SE; rather, it is the blocky structure of the Chalk that is of primary importance.

As in north London, high transmissivity is often associated with valleys. Therefore the confined sections of the Rivers Mole and Wandle exhibit high transmissivity, in excess of 1000 m^2/d. It is quite probable that these valleys follow fault zones within the Chalk.

Variations in storage coefficient

Due to the historically lowered groundwater levels throughout the basin, many of the pumping tests were conducted with the aquifer in an unconfined condition. At the present time, however, water levels have risen and the majority of the aquifer is confined; storage values recorded from the original pumping tests give an estimate of specific yield rather than the confined storage coefficient. The aquifer properties data have been split up according to the state of the aquifer (Figure 4.3.28) It is immediately apparent that the confined pumping tests give a significantly lower estimate of storage coefficient than the unconfined or semi-confined tests. This gives the expected result that elastic storage within the Chalk when deeply confined is low compared to the storage from drainage (specific yield). The usual confined/unconfined split in storage data is exacerbated in the London Basin: the deeply confined areas have very little fracturing within them (as illustrated by the poor transmissivity data), therefore specific yield is less than for other well-fractured parts of the aquifer; when confined the elastic storage will therefore be even smaller.

The distribution of specific yield probably follows similarly the transmissivity distribution. Higher values are found where the Chalk is fractured — in the Colne and Lee valleys, in central London associated with old discharge areas, and to the south along faults.

In a recent model of the London Basin a storage coefficient of 0.02 was used for the unconfined Chalk, 0.1 for the Basal Sands and 0.0001 for the confined Chalk (Lucas and Robinson, 1995).

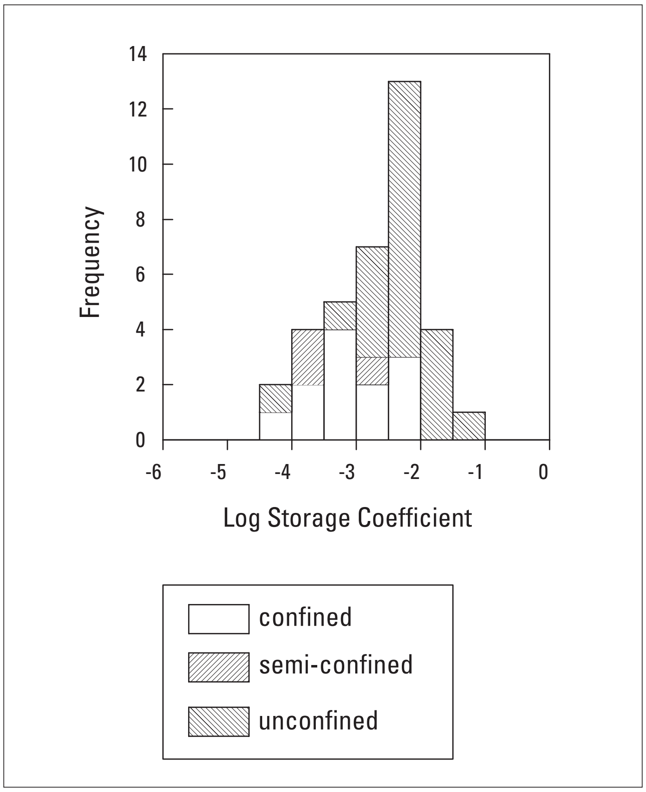


Figure 4.3.28 Distribution of the storage coefficient within the London Basin for data that indicate the condition of the aquifer.

4.3.5 The North Downs

Introduction

Geographical and geological setting

The North Downs is the name given to the Chalk hills to the south of London. They make up the northern limb of the Wealden anticline (Figure 4.3.29). This area, which is quite environmentally sensitive also supports some densely populated centres and locally some large industries, giving rise to a conflict of interest between development and conservation. Communications between the coast and London also lead to important protection issues in regard to the aquifer.

The scarp slope of the downs forms a prominent feature rising to about 200 m OD. Upper Chalk outcrops over much of the North Downs (Figure 4.3.29). However, Middle and Lower Chalk outcrop at the foot of the escarpment and in the dip slope valleys. The Upper Greensand is a few metres thick in the south-east of the region, thins rapidly to the north and in the east is overlapped by the Gault. Clay-with-flints occurs on many of the interfluves, and there are head deposits and alluvium in the valleys.

The Chalk dips to the north at an average of about 2°, although, in the west, the Hog's Back structure is more pronounced and the dip can be as much as 55° north. The general dip is modified by gentle folding parallel to strike, and some fractures and minor displacements perpendicular to strike. The area is heavily dissected by a network of interconnected dry valleys which are thought to be structurally controlled.

Several rivers cut across the Chalk outcrop: the rivers Mole, Darent, Medway and Stour. They originate on Lower Cretaceous strata and flow northward across the Chalk outcrop, often flowing perennially. Other rivers within the area are ephemeral and more typical of Chalk streams, e.g. the rivers Dour, Cray etc.

Drift deposits in the area comprise clay-with-flints on the interfluves and alluvium and dry valley deposits in the valleys. Outliers of Palaeogene deposits are found on interfluves close to where the Chalk becomes confined.

Groundwater investigations

There are several early publications regarding the hydrogeology of the North Downs (Reynolds, 1947; Stilgoe, 1907–08; Reynolds, 1970). During the 1980s, Southern Water Authority and Mid-Kent Water Company undertook an investigation of the groundwater resources of the north Kent Chalk and the Lower Greensand (including some modelling) which was documented in a final report (Southern Water and Mid-Kent Water Company; 1989). Contamination of the aquifer by mine drainage was investigated at Tilmanstone (Headworth et al., 1980). Recently, a model has been completed of the east Kent Chalk by the University of Birmingham and Folkstone and Dover Water Services (Cross et al., 1995).

The karstic nature of the Chalk has been investigated for many years in the North Downs and especially around the Mole Gap. In particular an eminent geomorphologist C C Fagg undertook a lot of his fieldwork in this area (Fagg, 1923; Fagg, 1958; Docherty, 1971).

In addition to published material and large-scale investigations there have also been many smaller studies. These are usually undertaken in connection with individual borehole licence applications. Currently there are several investigations that are being undertaken for environmental reasons — e.g. the effect of groundwater abstraction on flows in the River Darent; and the hydrogeological implications of the Channel Tunnel rail link.

The Mid-Kent Water Company has created some groundwater models of the Chalk for the area. This information, however, is treated as commercial-in-confidence and was not made available to the study.

Aquifer properties

General statistics

Within the North Downs there are 41 locations with aquifer properties data. Fifty-seven pumping tests have been

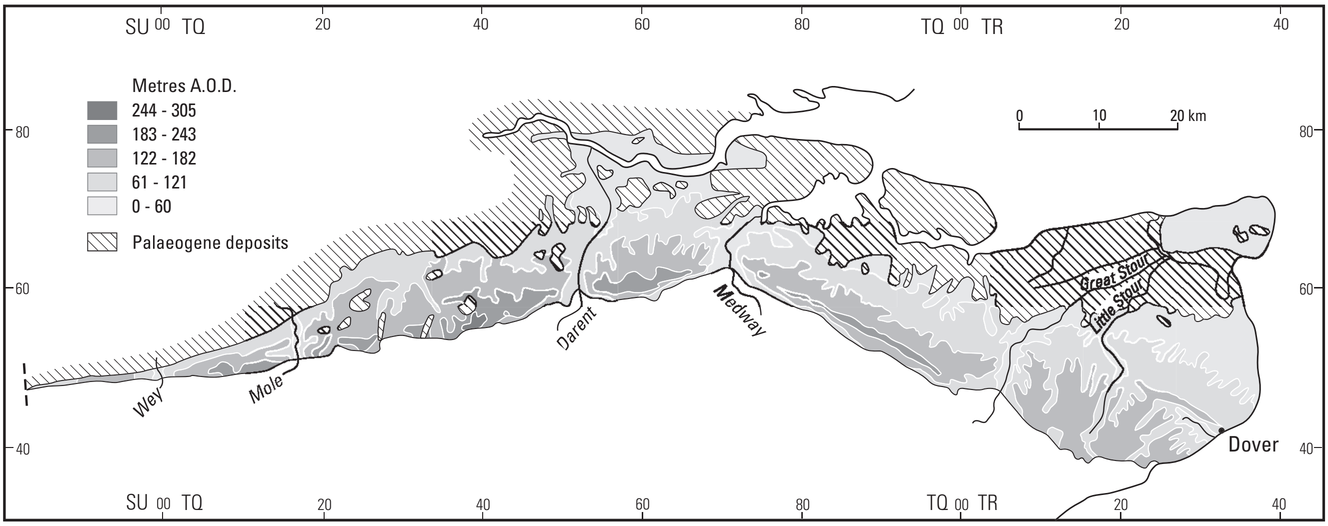


Figure 4.3.29 Location map of the Chalk of the North Downs, illustrating the Chalk outcrop and drainage.

undertaken giving 35 values of storage coefficient and 57 estimates of transmissivity.

Transmissivity data are approximately lognormally distributed (Figure 4.3.30). Values range from 52 to 7400 m^2/d with a geometric mean of 720 m^2/d and median value of 670 m^2/d. However, the data available for the North Downs is probably unrepresentative of the true aquifer properties due to a significant lack of low transmissivity values. Twenty-five percent of the data are less than 350 m^2/d and 75% less than 1600 m^2/d.

The storage coefficient data are shown in Figure 4.3.31. Values range from 1×10^{-5} to 0.060 with a geometric mean of 0.0031 and median of 0.0036. The 25 and 75 percentiles of the data are 0.001 and 0.015 respectively.

Forty of the pumping tests had information on specific capacity in addition to aquifer properties data (Figure 4.3.32).

Vertical variations

The North Downs follow the general pattern of all other southern Chalk areas — the most productive fractures are found in the upper sections of the aquifer, in the zone of water table fluctuation. Modelling of the aquifer (Cross et al., 1995) indicated that over the interfluves, a narrow band of high transmissivity, approximately 10 m thick was required to represent water levels and river hydrographs (Figure 4.3.33). Within the zone of water table fluctuation transmissivity increased non-linearly with increasing water level, while below this zone the transmissivity was constant. Towards the valleys a thicker zone of high transmissivity was required which again increased non-linearly within the zone of water table fluctuation. Over the interfluves these conceptual models were not proved by drilling, but information from other sources suggests a

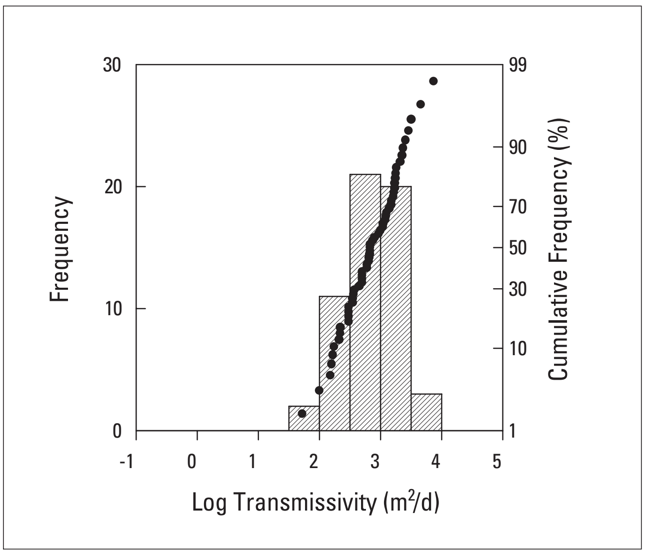


Figure 4.3.30 Distribution of transmissivity data from pumping tests in the Chalk and Upper Greensand of the North Downs.

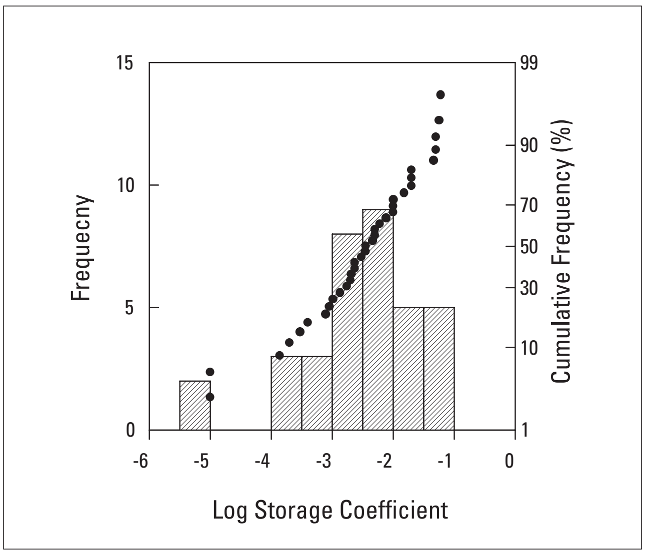


Figure 4.3.31 Distribution of storage coefficient data from pumping tests in the Chalk and Upper Greensand of the North Downs.

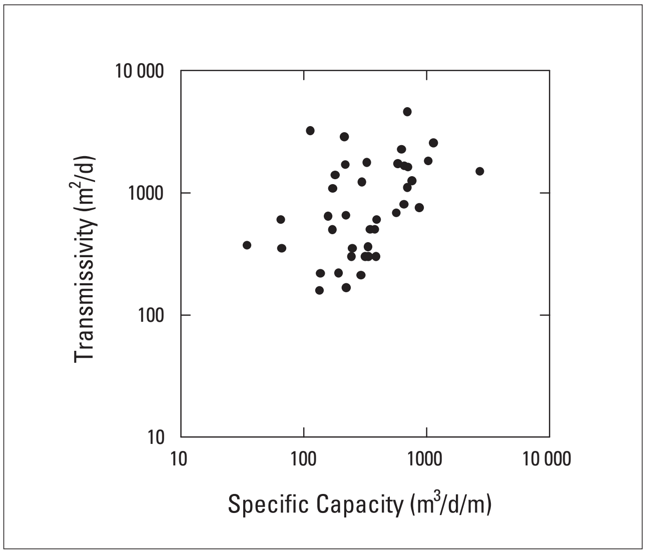


Figure 4.3.32 Plot of transmissivity against specific capacity (uncorrected) for the Chalk of the North Downs.

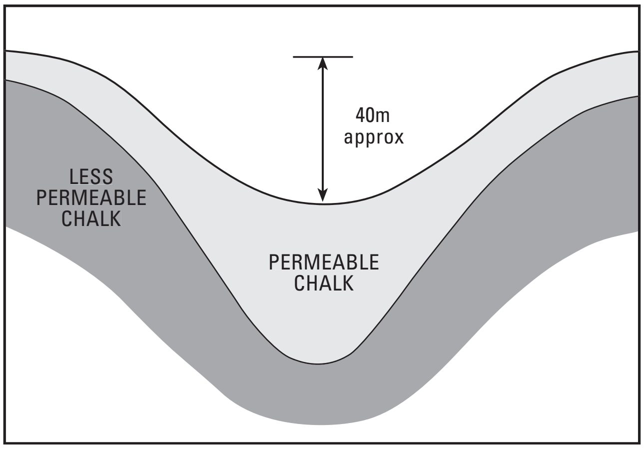


Figure 4.3.33 A schematic representation of the vertical distribution of transmissivity used in a groundwater model of the North Downs (after Cross et al., 1995).

similar distribution of transmissivity within the interfluves (Robinson, 1978; National Rivers Authority, 1993; Posford Duvivier, 1994).

The non-linear decrease of transmissivity with depth was illustrated by the recent droughts. Yields of major boreholes reduced dramatically in response to only a slight change of water levels: as the water level fell, important fractures were de-watered reducing observed transmissivity.

Geological variation between the different Chalk formations also has an impact on the vertical distribution of the aquifer properties. Boreholes within the Upper Chalk appear to give the highest transmissivity values, with the Middle Chalk also being a good aquifer. The Lower Chalk however is quite marly and therefore, especially within the Chalk Marl, aquifer properties are poor. This is illustrated by the large number of springs that issue within the Lower Chalk as vertical groundwater flow is impeded by the marl layers. Hardgrounds within the Chalk e.g. the Melbourn Rock and Chalk Rock can also alter the vertical distribution of aquifer properties — where they are near to the ground surface they can be more fractured than the surrounding rock and therefore increase the transmissivity.

Areal distribution

Introduction

The valley-interfluve model of Chalk transmissivity appears to be well developed within the North Downs. Along the valley floors, aquifer properties are generally very favourable and transmissivity and storage coefficient can be quite high; away from the valleys, however, the aquifer properties are significantly reduced. As in other areas this general pattern is modified by other effects, for example: rapid groundwater flow associated with Palaeogene deposits; local structure either increasing or reducing transmissivity; solution features within the beds of streams; and also locally, by artificial features like tunnels and adits. As the Chalk becomes confined the aquifer properties rapidly decline.

General distribution

The valley network within the North Downs appears to be controlled by structure, with a large number of dry valleys developing parallel to the dominant fracture set (Reynolds, 1970; Southern Water, 1989; Docherty, 1970). This relationship is particularly striking towards the east in the Dover/Deal area (Figure 4.3.34). Transmissivity and storage coefficient values within the valleys, both dry and flowing, are generally high. As a result of this trend most of the public supply boreholes are located in main valleys and therefore good pumping test data are biased towards the valleys with little investigation of the interfluves. However, modelling data coupled with local hydrogeologists expertise can help to extrapolate the existing pumping test data.

The eastern area

In the Dour catchment the aquifer mainly comprises Middle and Lower Chalk. As a consequence the regional transmissivity values are fairly low, especially as the water levels fall. For example, when modelling the aquifer, Birmingham University allowed the transmissivity values in the valley to reduce to less than 300 m^2/d (Cross et al., 1995). More typical transmissivity values

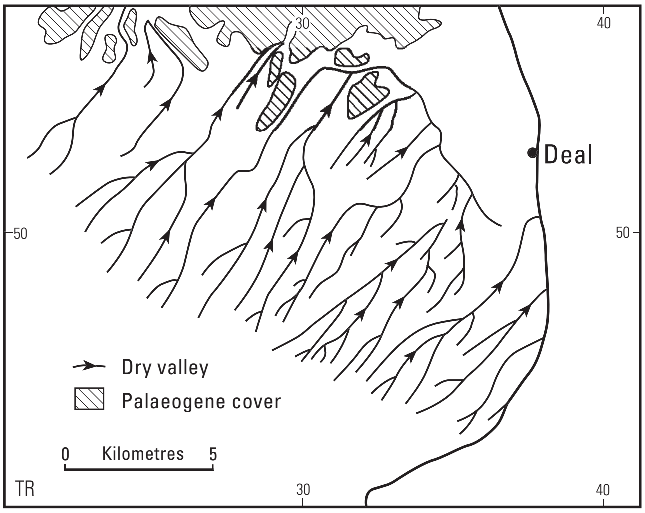


Figure 4.3.34 The direction of dry valleys in the Dover/Deal area.

from the database, were around 1500 m^2/d. Reynolds (1970) discusses conduit flow in the valleys of the Dour catchment, which have developed along bedding planes and fractures allowing rapid transport of groundwater. In support of this, large productive cavities and fractures have been identified within the valleys when constructing adits (Cross et al., 1995). The modelling suggested transmissivity values on the interfluves of around 30 m^2/d, increasing non-linearly as water levels increased. Rapid flow in the interfluves in times of high water levels might be possible, but no data exist to corroborate this.

Reliable storage coefficient values are harder to gain, but modelling suggested specific yields of about 0.015 for the valleys and 0.01 for the interfluves. Data from pumping tests tended to be slightly lower — possibly due to incomplete drainage during the test period.

Further north in the Dover/Deal area, transmissivity tends not to vary greatly with time. This is a consequence of relatively stable water levels throughout the year which characterise the area, setting it apart from the rest of the North Downs.

Investigations at the Tilmanstone Mine highlighted the importance of marl layers in focusing groundwater flow, and inhibiting vertical leakage. Borehole logging in the late 1960s identified important flow from above the Plenus Marl (Tate et al., 1970). The striking pattern of the dry valleys, and possibly fracture sets, is also reflected in the regional transmissivity giving an anisotropic distribution, with values for groundwater flow in a NNE–SSW direction five times those for flow in a WNW–ESE direction (Cross et al., 1995). Locally this can be interpreted as valleys having transmissivity five times that on the interfluves; from modelling, 1500 m^2/d was found to be appropriate for the valleys and 300 m^2/d for the interfluves. The value of storage coefficient used to model this area is quite high, 0.03.

The Acrise-Denton, Upper Nailbourne area again illustrates a marked change in aquifer properties from the valleys to the interfluves. Test pumping (Southern Water Authority, 1975) lead to average valley aquifer properties: transmissivity 1500 m^2/d and storage coefficient of 0.005 (Modelling implied a similar transmissivity but higher storage coefficient, 0.015) In the interfluves transmissivity is thought to decline rapidly, reducing the interaction between different valleys; Cross et al. (1995) attributed a transmissivity of 30 m^2/d and storage coefficient of 0.01 to the interfluves.

No aquifer properties data exist for the Isle of Thanet. However the aquifer properties are thought to be generally quite good across the outcrop of the Chalk (Environment Agency, personal communication). The relief is generally quite low and valley systems have not fully developed, therefore there is not a great difference between transmissivity and storage coefficient values from the valleys to the interfluves. Tunnels and adits are common within the Isle of Thanet. They constitute artificial conduits and therefore will significantly modify the aquifer properties.

Western area

There are insufficient data to describe the rest of the North Downs in as much detail as the eastern section. However the general pattern is very similar. High transmissivity and storage values are associated with dry valleys especially within the outcrop of the Upper and Middle Chalk. Away from the fracture sets of the valleys, favourable aquifer properties can be found in the zone of water table fluctuation where solution has enhanced the aperture of fractures and bedding planes; due to the high clay content of the Lower Chalk there are less fractures and therefore poorer aquifer properties (Southern Water and Mid-Kent Water Company, 1989).

Public supply boreholes are located within the principal river valleys e.g. the River Stour, Darent and Cray and also within the dry valleys. Not many of the large supply boreholes within the main valleys have been tested, but the licensed values are high, indicating good yields. During the groundwater investigation of the 1980s the dry valleys between the Stour and the Medway were tested for aquifer properties and reliable yields. Transmissivity values of between 300 and 600 m^2/d were most common. Similar values are probably found within the dry valleys further to the west between the Darent and the Medway and also near the Mole (near Leatherhead).

On the Hog’s Back, the Chalk is folded significantly, therefore the outcrop is quite narrow and the relief high. This has resulted in poor development of aquifer properties in the area. At the western edge of the Hog’s Back, in the Wey Valley around Guildford the aquifer properties improve (Water Resources Board, 1972).

As the Chalk dips north below the Palaeogene strata, the transmissivity and storage decrease significantly as the aquifer becomes increasingly confined. (This is explained in more detail in the section on the London Basin).

At the feather edge of the Palaeogene deposits transmissivity values can be quite high. For example pumping tests at Faversham and Littlebourne gave transmissivity values of several thousand (approximately 5000 and 3000 m^2/d respectively) Increased aggressive recharge causing the enlargement of fractures by dissolution is thought to account for these high values.

Rapid groundwater flow

Karstic features have been identified in the Mole Valley (Fagg, 1958). A series of 25 active swallow holes have been identified in the valley. The River Mole only rarely dries up sufficiently to allow examination of the swallow hole system; one such period was in successive years from 1948–50 when Fagg conducted his survey. Four different classes of swallow hole have been identified:

- in the bottom of depressions in river bed
- higher up the river bed near the river bank (i.e. can be bypassed at low flows)
- on the vertical sides of river valleys
- in depressions on the flood plains

Many obsolete swallow holes have been identified both in the river bed and also in the river terraces. Some of the holes have been modified by fishermen: clay has been used to plug the depressions to let the river flow longer, preserving the fish (and thus fishing). New holes can develop very quickly: one of the swallow holes increased remarkably in size from 1948 to 1949; while another swallow hole in the river bed floor (type 1) collapsed overnight. It has been suggested by later workers that such features could be common in Chalk valleys but obscured by glacial and periglacial deposits (Docherty, 1970). This might provided a mechanism by which rapid recharge could occur within dry valleys and explain why ephemeral streams often dry up in distinct stages.

4.4 EAST ANGLIA

4.4.1 Introduction and overview

Background

The Chalk of East Anglia has been subject to similar controls throughout the area, therefore the aquifer is often discussed in its entirety rather than being subdivided into several smaller sub-aquifers, as in the Thames or Hampshire Basins. For this reason, more emphasis is placed in this section on the general description of the whole region, with only brief descriptions of the data for individual sub-regions. The sub-regions used to explain the areal distribution of aquifer properties are shown in Figure 4.4.1. These are described in Sections 4.4.2 to 4.4.7. The divisions are generally based on groundwater divides. The areas have been given the name of the counties which dominate the area; however, as the divisions follow groundwater divides rather than county boundaries, parts of other counties may be included.

East Anglia is generally an area of low relief, with most of the ground being below 65 m AOD. Ground elevations reach their highest point in Hertfordshire, where small areas of the Chalk escarpment near Hitchin and Royston are above 130 m AOD. South-eastward from the Chalk scarp the ground slopes gradually seaward, and much of Norfolk, Suffolk and Essex undulate gently between 30 and 60 m AOD. The highest ground in Norfolk is the West Norfolk Heights and the Cromer Ridge, and can be up to 90 m AOD in some places. The West Norfolk Heights are a few kilometres to the east of the Chalk escarpment and are formed by glacial deposits lying on the dip slope of the Chalk. The Cromer Ridge runs from Syderstone to Cromer, and is composed of sand and gravel with large areas of chalk.

Throughout East Anglia, the Chalk has been subject to similar glacial influences. The area was covered by ice during the Anglian glaciation producing similar features over the outcrop. Much of the topography has been removed, therefore the typical chalk downland of the south is absent; also the area is largely covered by glacial deposits, and glacial features such as buried channels are present.

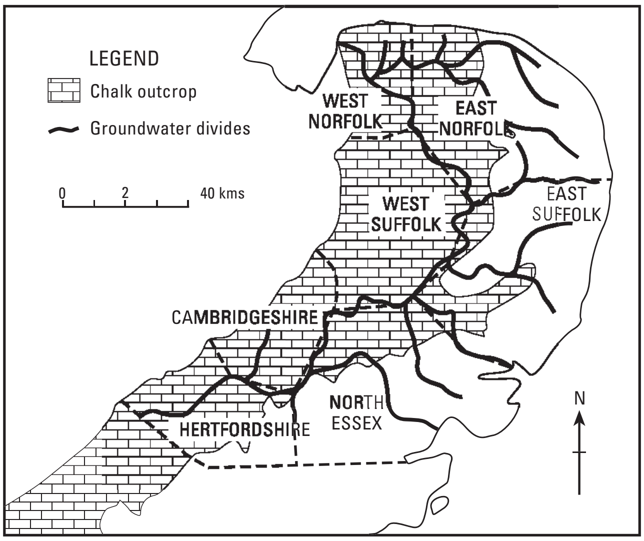


Figure 4.4.1 Regional subdivisions of East Anglia used in the text.

A major groundwater divide generally follows the surface water divide which trends south-west to north-east along the crest of the Chalk escarpment. To the west of this are the rivers of the Great Ouse system, including the Great Ouse itself, the Cam, Rhee and Granta, the Lark and Kennett, the Little Ouse, Thet and Sapiston, the Wissey, the Nar and the Babingly. These flow in a north-westerly direction to the Wash. East of the escarpment the rivers flow to the Thames or the North Sea. They include the Lea and its tributaries (the Mimram, Beane, Rib and Stort); the Roding; the Essex rivers, including the Chelmer, Brain, Blackwater and Colne; the Stour; the east Suffolk rivers, including the Gipping-Orwell, Deben, Alde and Blyth; and the east Norfolk rivers, including the Waveney, the Yare and its tributaries, and the Bure. In north Norfolk rivers rising on the Cromer Ridge or the Chalk flow northward to the North Sea; for example the Burn, the Glaven and the Stiffkey (Figure 4.4.2).

The position of the water table in the Chalk closely reflects the topography; it is high beneath the high ground of the Chalk scarp and dips in the valleys. The groundwater divides closely reflect the surface water divides except in the Suffolk coastal area — the Blyth and Alde catchments. The groundwater head falls beneath the Palaeogene cover; it has shown serious decline here historically. North of the edge of the London Clay, groundwater levels have declined little.

In the east and south-east of the area, the Chalk aquifer is confined by the London Clay. Elsewhere, where the Chalk is covered extensively with drift deposits, the Chalk piezometric surface is often found in the overlying deposits. However, the Chalk is considered to be semi-confined rather than truly confined, as leakage, sometimes considerable, occurs through the drift deposits, and rapid responses to pumping have been seen in the water levels in the drift.

The hydrogeology of the area was first described in the Water Supply Memoirs for Suffolk (Whitaker, 1906), Bedfordshire and Northamptonshire (Woodward and Thompson, 1909), Essex (Whitaker and Thresh, 1916), Norfolk (Whitaker, 1921a), Buckinghamshire and Hertfordshire (Whitaker, 1921b), and Cambridgeshire, Huntingdonshire and Rutland (Whitaker, 1922). Woodland (1946) gave a detailed account of the hydrogeology of the area between Cambridge and Ipswich. He compiled a map of the availability of water in the Chalk (Figure 4.4.3), based on borehole yields, corrected to a standard diameter of 300 mm. Ineson (1962) compiled a map of transmissivity variations for the whole of East Anglia, also based on yield-drawdown curves (Figure 4.4.4). The north Essex aquifer investigation (see also Lloyd et al., 1981) produced a map of transmissivity variations based on the original work by Woodland, refined and quantified by pumping test analyses (Figure 4.4.5).

Geological sequence and lithology

Figure 4.4.6 shows the pre-drift outcrop of the Chalk in East Anglia. The Chalk dips very gently to the south-east, as do the Palaeogene strata which overlie it. In the east of the area, the Pliocene and Pleistocene Crag deposits dip eastward. A simplified stratigraphy is shown in Table 4.4.1.

The East Anglian Chalk is lithologically transitional between the northern and southern Chalk provinces, but is more usually included in the southern province, with which it shares the characteristics of common hardgrounds and lack of tabular flints. The principal regional hardgrounds are the Totternhoe Stone, Melbourn Rock, Chalk Rock and Top Rock; other hard bands occur locally. The Upper

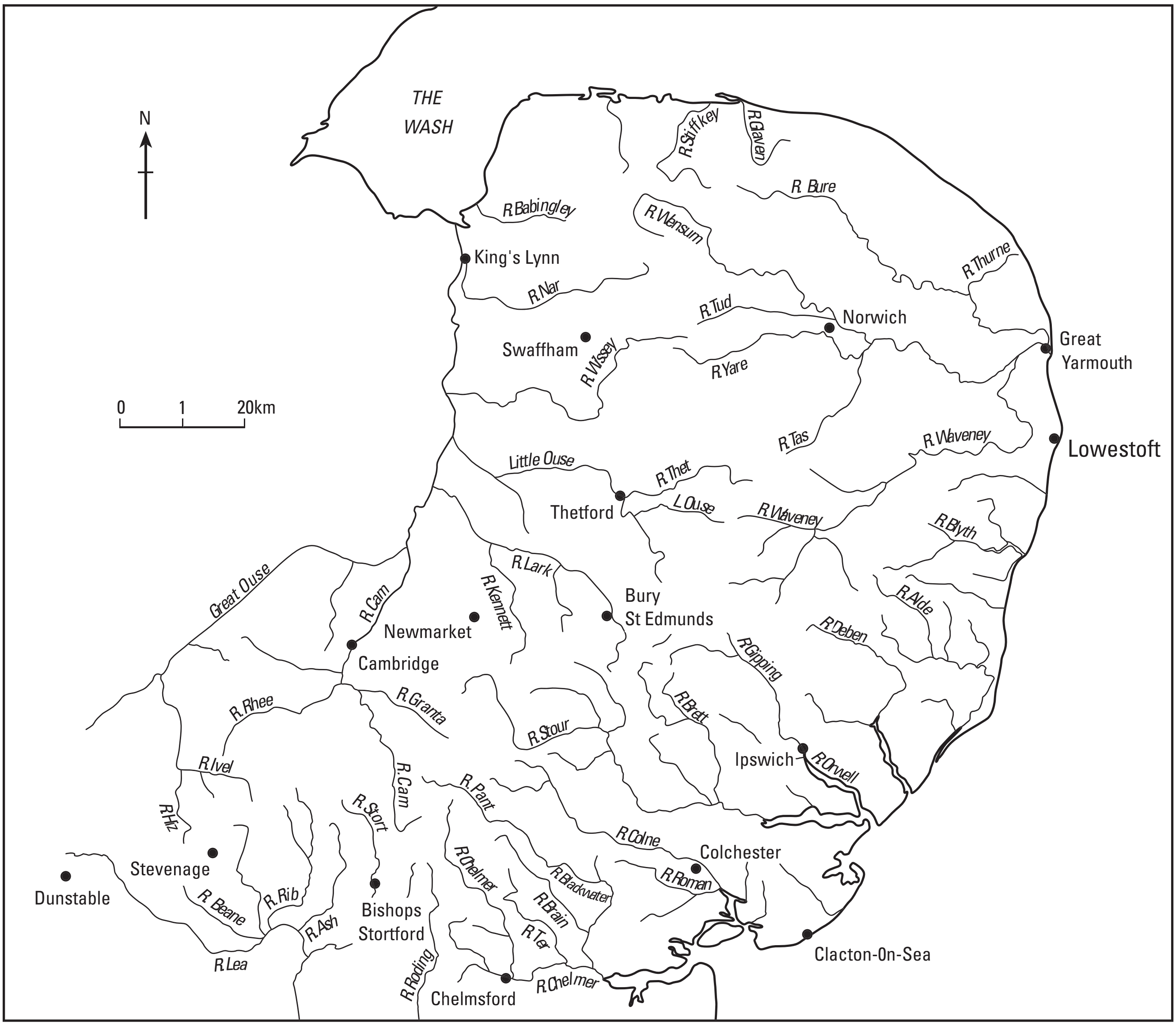


Figure 4.4.2 Major rivers of East Anglia.

Greensand is mostly absent in East Anglia, rather, the Chalk is underlain by the Gault, a soft mudstone which acts as an aquiclude.

The Lower Chalk includes at its base the Cambridge Greensand, a thin bed of glauconitic sandy marl rich in phosphate nodules. This rests unconformably on the Gault. The lower part of the Lower Chalk, below the Totternhoe Stone, is known as the Chalk Marl; it comprises a succession of relatively fossiliferous marls, coarse bioclastic shell-detrital chalks, and fine-grained chalks. The Totternhoe Stone is a compact, brownish, well jointed chalk rock, containing phosphatic nodules. Numerous springs issue from this rock. The Lower Chalk above the Totternhoe Stone is grey in its lower part and becomes cream to white towards the top; it is often known as the Grey Chalk. It commonly shows a characteristic nearly horizontal curvilinear jointing. At the top of the Lower Chalk are the Plenus Marls, comprising alternating greenish marls and chalks less than 1 m thick.

The Melbourn Rock marks the base of the Middle Chalk. A shelly nodular chalk overlies the Melbourn Rock succeeded by more marly chalks. The succession includes several persistent marl bands. Flints first appear about a third of the way up the division, becoming more abundant towards the top.

The boundary between the Middle and Upper Chalk is usually mapped at the base of the Chalk Rock, although in the geological sheet memoirs for Bury St Edmunds (Bristow, 1990) and Diss (Mathers et al., 1993) it has been placed at the base of the Brandon Flint Series. The Chalk Rock consists of hard nodular chalk, with large flints, less than 0.3 m thick, interbedded with more normal chalk. The Chalk above the Chalk Rock is blocky but rather soft and white with well-defined flint bands. Above this is another rock band, the Top Rock: a very hard fossiliferous yellow chalk up to about 0.4 m thick. The beds above the Top Rock consist of white chalk with flints. They are usually concealed beneath glacial drift in this region.

In many borehole logs a bed of 'soft chalk' or 'putty chalk' (soft, low permeability Chalk) is recorded at the top of the Chalk. This occurs both beneath valleys and higher ground, and is present beneath both drift and Crag deposits. In the west where Chalk is at the surface, the putty chalk is absent.

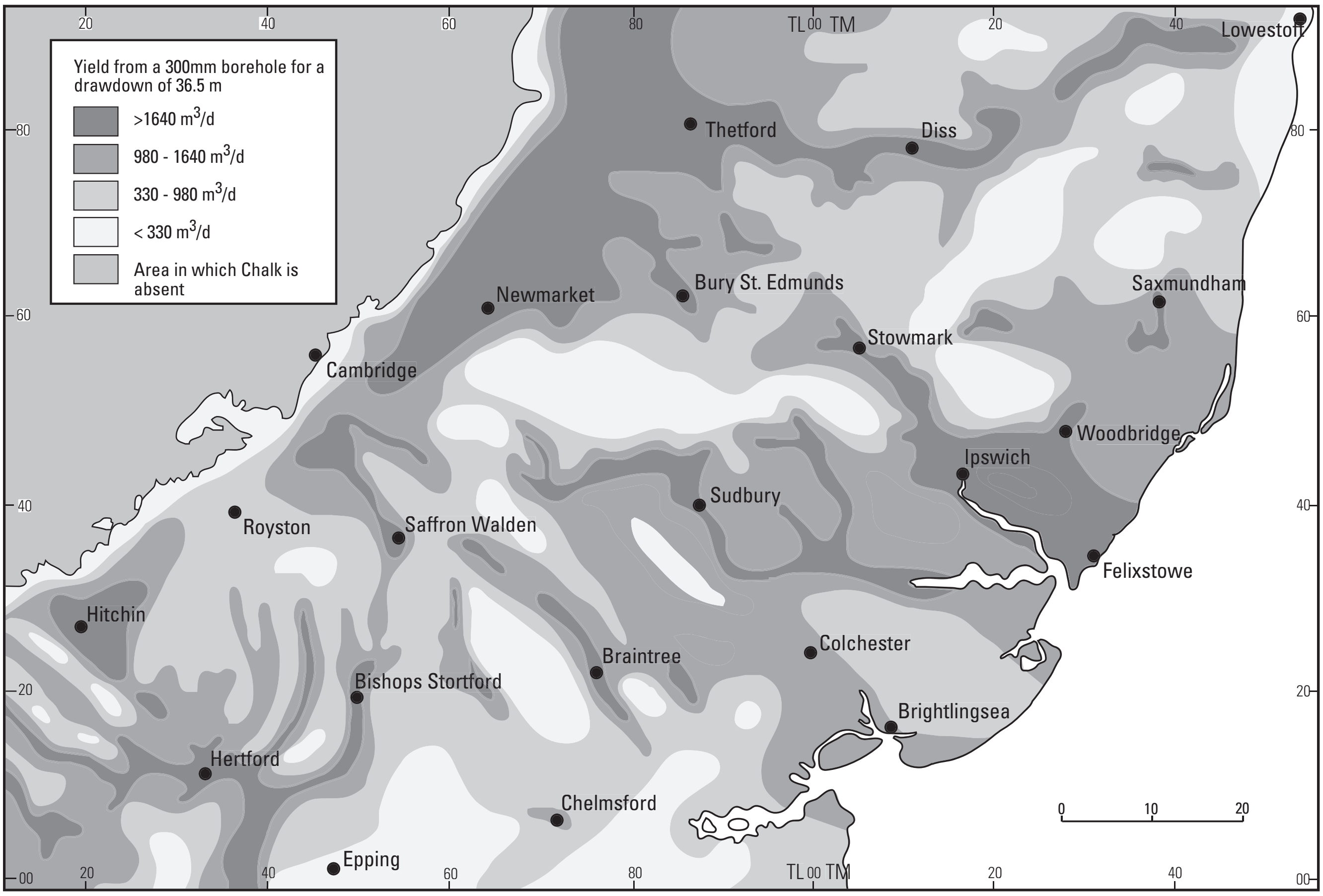


Figure 4.4.3 Distribution of type groundwater yields in East Anglia (after Woodland, 1946).

The younger deposits which overlie the Chalk in East Anglia have a marked effect on the hydrogeology of the region. Palaeogene deposits, including the Lambeth Group and the London Clay, unconformably overlie the Chalk south-east of a line which runs from Hertford to Ipswich and then northwards from Saxmundham to the north-east Norfolk coast. The Lambeth Group is sandy and may contribute to the water resources of the Chalk. The London Clay has low permeability and confines the Chalk aquifer. In the southern part of East Anglia, the Thanet Sand Formation is also present below the Lambeth Group, and is usually in hydraulic continuity with the Chalk aquifer. In the main valleys, such as the Stour and Colne, Palaeogene deposits have been removed by erosion. In south-east Essex, as the depth to Chalk beneath the Palaeogene cover increases, its yield and water quality, and hence its use as an aquifer, decreases.

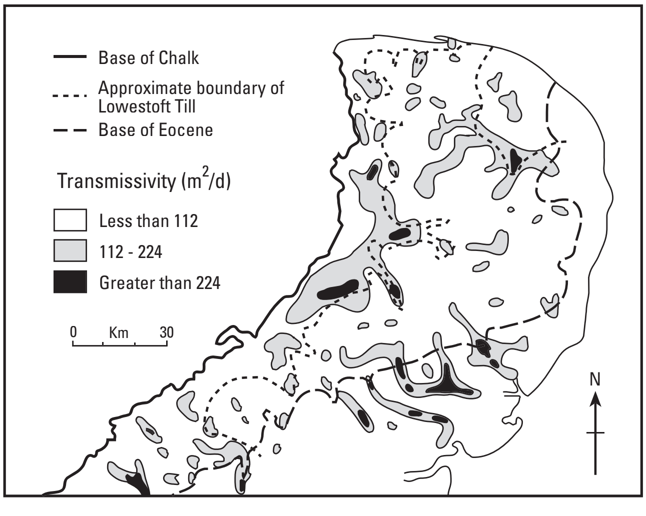


Figure 4.4.4 Distribution of transmissivity in East Anglia (after Ineson, 1962).

To the east of the area lie Pliocene–Pleistocene Crag deposits, resting either on the Chalk or on the London Clay. The oldest of these deposits, the Coralline Crag, is a calcarenite and is preserved only locally near Aldeburgh. The overlying Crag Group is a marine sand with some clay and gravels. The Crag is a minor aquifer; and where it overlies the Chalk directly, the two may be in hydraulic continuity. In the very eastern part of Norfolk and Suffolk, the Chalk water below the London Clay is highly saline and potable supplies are taken only from the Crag.

A detailed description of the stratigraphy and lithology of drift deposits is not appropriate here, but a brief resume is included. In East Anglia, drift deposits are variable, including pebbly sands, gravels, silts, and clays. A chalky till, known as the Lowestoft Till covers much of the area. The unweathered till is generally grey, sandy, silty clay with lithic clasts and has low permeability. Where weathered, the till is rust brown and is generally more permeable than the unweathered till. It is generally agreed that the most widespread deposits, belonging to the Corton Formation and the Lowestoft Till Formation, are from a single glaciation, of Anglian age, but from separate ice sheets. Figure 4.1.3 shows the extent of the different glaciations.

The total thickness of the Chalk varies from less than 100 m in the west, thickening to over 400 m on the coast.

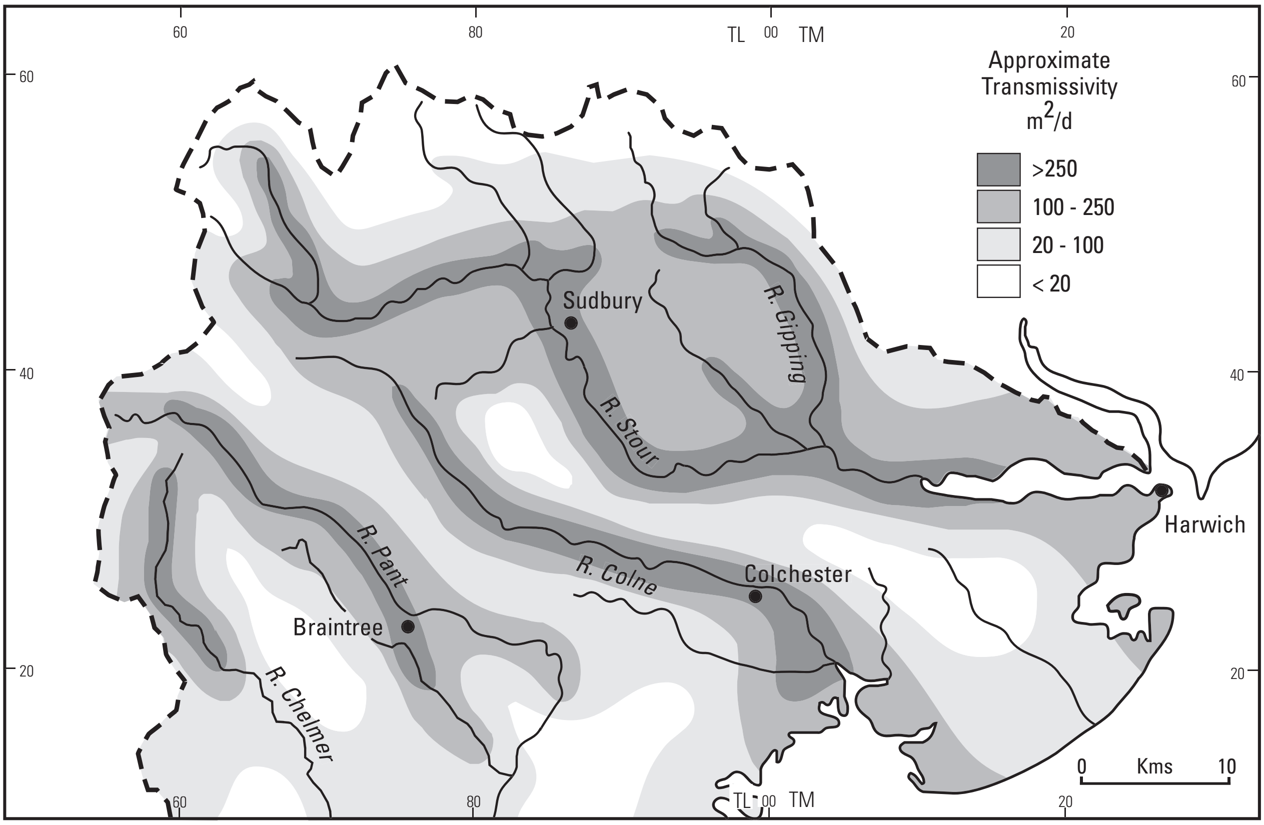


Figure 4.4.5 Distribution of transmissivity in the Chalk of north Essex and south Suffolk (after Anglian Water Authority, 1980).

As shown in Figure 4.4.6, the Lower and Middle Chalk outcrop on the north-westward facing scarp slope in a band which varies in width from up to 8 km in Hertfordshire and Cambridgeshire, to less than 1 km in north-west Norfolk. North-east of Royston, the relief becomes lower and less varied, and the scarp feature gradually diminishes, until it practically disappears around the Thetford area.

The Chalk in East Anglia tends to lack major structural features, excepting the Eye depressions, which may have a structural origin. Lines of disturbance have little surface expression, and are only easily seen in quarry exposures. The structure of the area around Cambridge has been inferred in some detail, partly from boreholes and partly on the level of beds at outcrop (Worssam and Taylor, 1969). The nature of the Chalk surface beneath the glacial deposits is not well known; where glacial erosion has taken place it is fairly irregular. Beneath the Palaeogene deposits the Chalk surface is more regular.

The Chalk surface is complicated by the existence of buried channels (Figure 4.4.7). These are old deeply eroded valleys left filled with glacial deposits after the disappearance of the Anglian ice sheet. These are very steep and narrow, and were probably scoured out in a very short time by powerful torrents below the ice sheet causing high Chalk dissolution (Woodland, 1946). However, there is some disagreement about their formation: Cox (1985) suggested that they were ancient, preglacial valleys, locally modified by glacial or subglacial means. The nature of the drift which fills the channels varies considerably. The channels have been described in detail by Woodland (1970).

As well as the buried channels, two parallel, south-west–north-east-trending depressions occur in the Chalk surface around Eye, in Suffolk. Woodland (1946) considered them to be synclines with an intervening anticline, and reported low yields from the depressions with high yields from the ridge between. However, Notcutt (1978), referring to them as the western and eastern Eye depressions, considered that they could equally have been formed by faulting or erosional scour. Bristow (1983), referring to them as the Kettlebaston Basin and the Debenham Basin, assumed that the linearity of the basins and intervening ridge, and the steepness of their sides, indicated that they are fault controlled. Mathers and Zalasiewicz (1988), referring to the Debenham basin as the Stradbroke–Sudbury basin, disputed this idea due to the lack of any significant Quaternary faulting in the adjacent southern North Sea Basin, and the existence of comparably steep slopes where no evidence of displacement within the bedrock strata exists. They suggested sea-bed scour as a more likely method of formation, as the topography of the top surface of the Chalk is similar to the present sea floor of the English Channel (but see Cornwell et al., 1996).

Summary of aquifer properties

A large amount of pumping test data exists for East Anglia. However, much of it is of low quality and poorly constrained, making evaluation and analysis of the data difficult. In addition, the aquifer properties of the Chalk can vary significantly over a small distance. For example, at Brandon in Norfolk, two boreholes drilled close together show completely different properties; one borehole intercepts a fractured zone and penetrates blocky, high-yielding chalk, whilst the other penetrates smooth chalk and yields very little. In the Ipswich area, transmissivity values can change from 20 m^2/d to greater than 600 m^2/d over distances of less than 20 m.

Transmissivity values greater than 2000–3000 m^2/d are less common in East Anglia than in the South Downs

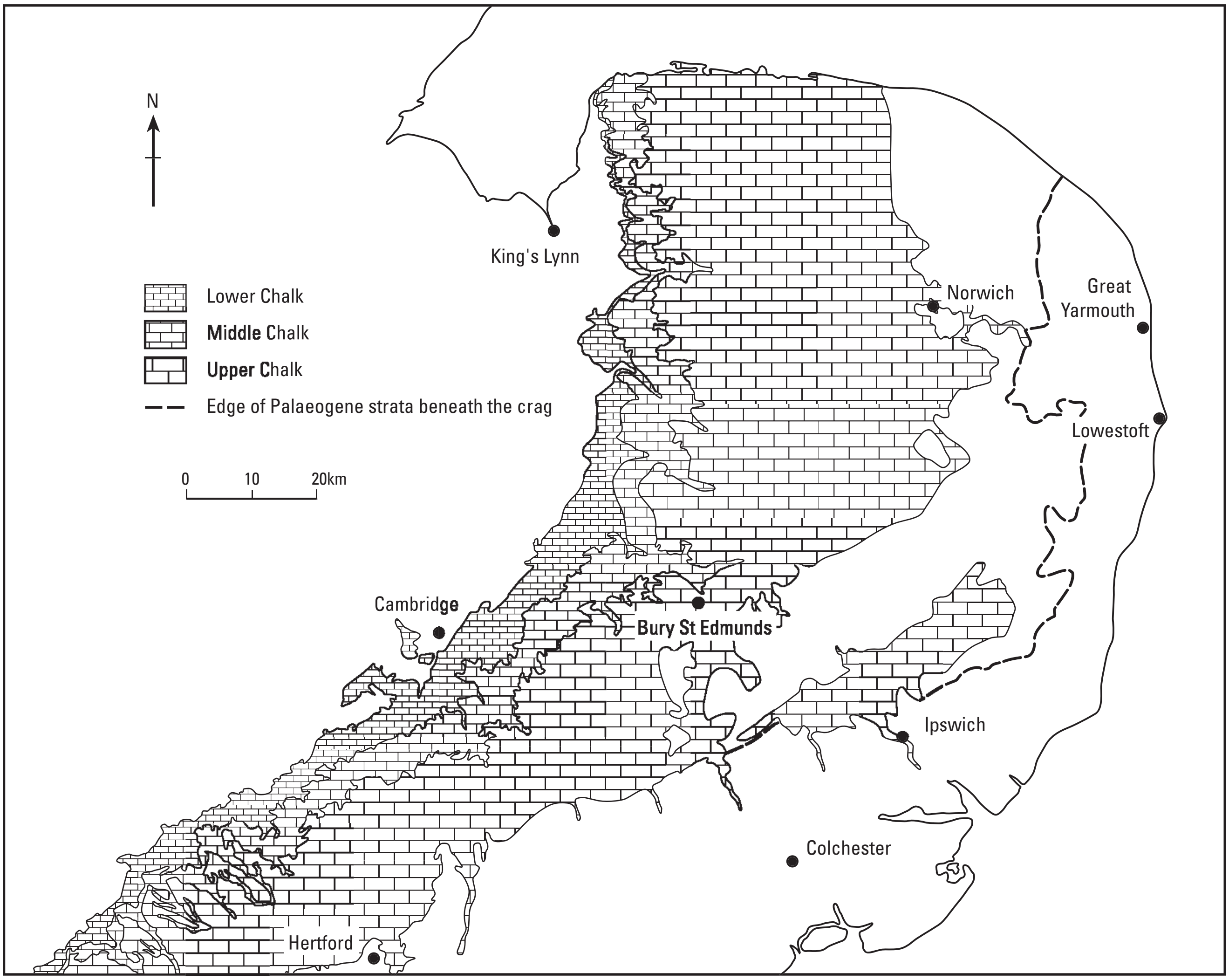


Figure 4.4.6 Pre-drift outcrop of the Chalk in East Anglia.

and the Northern Province of the Chalk. The histogram of transmissivity values for East Anglia (Figure 4.1.20c) shows that the majority of values are between 100 and 1000 m^2/d. Storage coefficients are commonly between 10^{-4} and 0.1 (Figure 4.1.21c).

Toynton (1983) obtained directional values of transmissivity from pumping tests by considering the angle of the observational borehole from the pumped borehole. He compared these with the angle of joints measured in quarry outcrops, and found a reasonably good correlation when considering high values of transmissivity. This may explain some apparently anomalously high values, for example, a directional transmissivity value of 10 000 m^2/d would not be unusual in an area where the average transmissivity is 2000 m^2/d. For lower transmissivity values there was little correlation.

Examination of the aquifer properties in individual areas shows that transmissivity values tend to be higher on the western side of the groundwater divide which runs through East Anglia. Mean transmissivity values in west Norfolk, west Suffolk, Cambridgeshire and Hertfordshire are significantly higher than those in east Norfolk and east Suffolk. The aquifer in these higher transmissivity regions is largely free of low permeability drift deposits, encouraging greater solution of the Chalk and development of fractures. In addition, the hardgrounds are at a sufficiently shallow depth to contribute flow to boreholes. The mean transmissivity value for north Essex is anomalously higher than would be expected given that the aquifer is confined or covered with thick drift deposits throughout most of the area. This value may reflect the bias of data towards higher transmissivity valley sites, in which most of the centres of population are found.

A clear correlation was indicated between pumping test transmissivity values and the specific capacity of a borehole (Figure 4.4.8). For areas where few pumping tests have been carried out, specific capacity data can provide useful information on the properties of the aquifer. However, the specific capacity also depends on other factors such as the diameter of the borehole, well efficiency and the position of the pump intake, and should be treated with caution.

The distribution of storage coefficients tends to reflect the distribution of transmissivity values, with higher mean values being found on the western side of the groundwater divide. No clear correlation could be found between the storage coefficient and the presence of permeable deposits overlying the Chalk. Comparison between pumping tests length and storage coefficient in west Norfolk indicates that delayed yield appears to be a factor affecting the measured storage coefficient. However, elsewhere in East Anglia, there was no clear indication of delayed yield affecting the storage coefficient of the aquifer.

The distribution of mean storage coefficients for Norfolk produced by Toynton (1983) (Figure 4.4.9) shows variation

Table 4.4.1 Simplified stratigraphy of East Anglia.

System	Chronostratigraphy		Lithostratigraphy		
Quaternary	Holocene	Flandrian	Blown sand		
			Peat		
			Alluvium		
			Breydon Formation (Waveney catchment only)		
			Marine (and estuarine) deposits		
	Pleistocene	Devensian	River terrace deposits		
			Head and Head gravel		
		Ipswichian	Interglacial silts		
		(Wolstonian)			
		Hoxnian	Interglacial silts		
		Anglian	Lowestoft Till Formation		
			Corton Formation		
		Cromerian 'complex'	Cromer Forest Bed Formation		
		Beestonian	Kesgrave Group		
			Bytham Sands and Gravels (probably down into Pastonian)		
		Pastonian Baventian/Pre-Pastonian Bramertonian/Antian Thurnian Ludhamian Pre-Ludhamian	Norwich Crag Formation Red Crag Formation	Crag Group	
Neogene	Pliocene		Coralline Crag Formation		
Palaeogene	Eocene	Ypresian	Thames Group (includes London Clay)		
	Paleocene	Thanetian	Lambeth Group (Woolwich and Reading Beds)		
			Thanet Sand Formation/Ormesby Clay Formation		
Upper Cretaceous		Maastrichtian Campanian Santonian Coniacian Turonian Cenomanian	Upper Middle & Lower Chalk	Chalk Group	includes: Top Rock Chalk Rock Melbourn Rock Plenus Marls Grey Chalk Totternhoe Stone Chalk Marl Cambridge Greensand
Lower Cretaceous		Albian	Gault Clay Formation		

from 0.011 to 0.077. The method used, of analysing baseflow and groundwater recessions, gives a storage coefficient for the whole aquifer system, and does not allow separation of the Chalk and drift components. There is no obvious distribution pattern to the values, although it may be significant that the Babingly catchment which shows the lowest storage coefficient is largely drift-free. Toynton's work has not been repeated using data after 1983.

Controls on aquifer properties of the Chalk of East Anglia

Within East Anglia, the aquifer properties of the Chalk appear to be related to topography. In addition, buried channels and the presence of some sort of cover also have a marked effect on the development of the Chalk as an aquifer. Although the influence of these factors have been described in Section 4.1, it is appropriate at this point to describe which processes are dominant in East Anglia.

Valleys and interfluves

The spatial variation in yield and transmissivity described by Woodland (1946) and Ineson (1962) show clear variation between valleys and interfluves, with higher transmissivity occurring in the valleys (Figures 4.4.3, 4.4.4 and 4.4.5). The enhancement of transmissivity along river valleys is particularly dominant where the Chalk is covered by low permeability deposits, such as along the valleys of the Stour, Wensum, Little Ouse and Waveney. In these valleys the overlying low-permeability deposits have been eroded, allowing penetration and solution of the aquifer by rainwater, which is restricted in the interfluve areas. Ineson (1962) found that the zone of increased transmissivity in these valleys appears to extend further away from the valley axis than in river valleys in the exposed Chalk. There are some exceptions to the rule that better yields are found in valleys than in interfluves; for example south of Swaffham a group of good boreholes lies to the south of a small valley, while boreholes in the valley are poorer. Scattered over the area are isolated good boreholes and these have probably intersected favourable fracture systems. The group south of Swaffham is probably situated on a major fracture system in the Chalk.

Correlation was attempted between pumping test transmissivity values and the depth to rest water level (RWL)

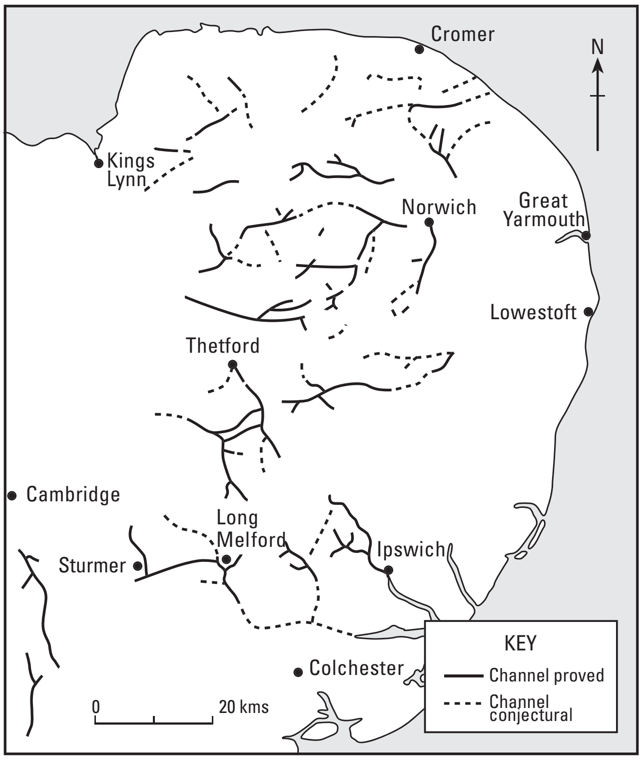


Figure 4.4.7 Location of buried channels in East Anglia (after Woodland, 1970).

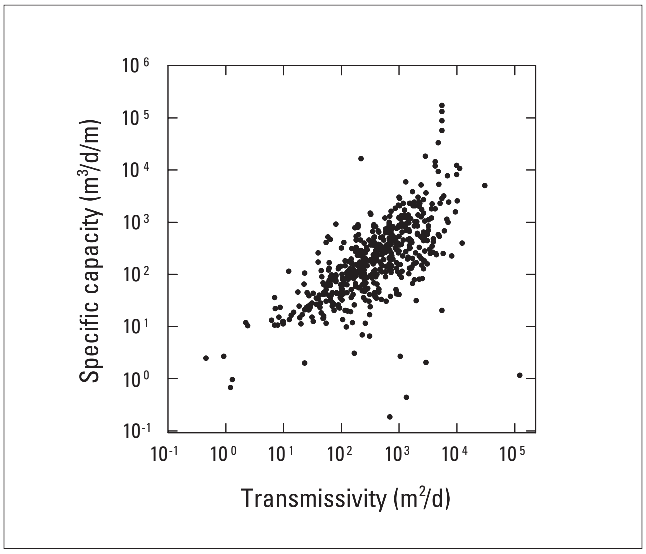


Figure 4.4.8 Plot of specific capacity (uncorrected) against transmissivity for the Chalk of East Anglia.

before pumping, in order to obtain a distinction between transmissivity values for valley sites (shallow RWL) and interfluves (deep RWL). However, no clear correlation was seen for any of the areas. This is probably due to the biased distribution of the data.

Buried channels

The effect of buried channels on aquifer properties is unclear. Woodland (1946) reported incidences of high transmissivity below buried channels but did not recommend them as sites for groundwater development due to the cost and difficulty of drilling through them. However, Foster and Robertson (1977), in their study of a buried

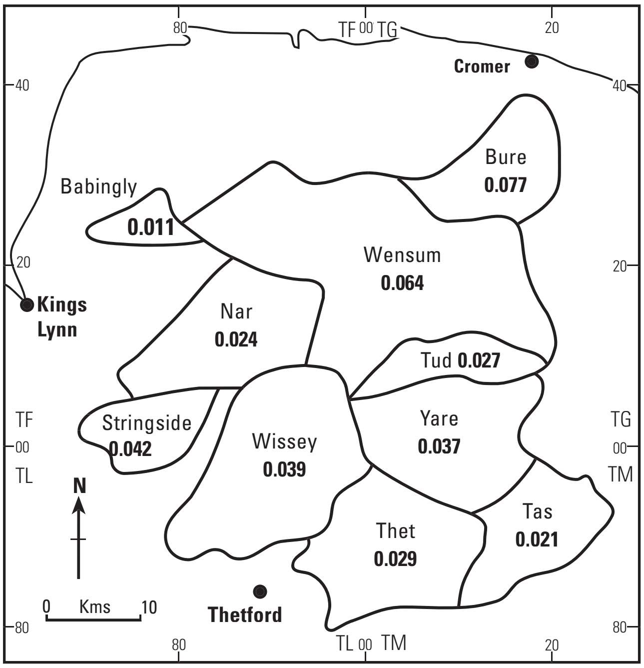


Figure 4.4.9 Distribution of storage coefficients in the Chalk of Norfolk (after Toynton, 1983).

channel at Rushall in Norfolk, concluded that buried channels were likely to be poor sites for groundwater development as the zone of enhanced Chalk permeability had been eroded. Forson (1987) suggested that where buried channels are in the same location as present day valleys, high transmissivity can be expected, but where there is no connection with modern drainage, as at Rushall, the transmissivity of the Chalk below the buried channels is low. In the Great Ouse Groundwater Study (Great Ouse River Authority, 1970), it was found that transmissivity is above average in the vicinity of buried channels where these cross the higher ground.

It is uncertain whether buried channels act as barriers to groundwater flow. Forson (1987) analysed pumping tests close to buried channels and found no evidence that they act as barriers. However, no pumping tests are available in which there is an observation borehole on the opposite side of the valley to the pumped borehole. The buried channels in the north of the area studied for the Great Ouse Groundwater Scheme were not considered to act as a barrier to groundwater flow. It is generally considered that buried channels act as barriers to flow if infilled with clay but not if infilled with sand and gravel deposits. It has been suggested that the development of the Chalk beneath buried channels is due to the barrier effect of the clay deposits forcing groundwater to flow beneath the channels. Where buried channels are infilled with sand and gravel, this can yield considerable water supplies; however, hydraulic continuity with the Chalk is usually prevented by a layer of putty chalk.

Differences between Chalk divisions

Many of the boreholes which showed the highest transmissivity penetrated the Middle and Lower Chalk rather than the Upper Chalk. This throws into dispute the often-held idea that the Upper Chalk forms a better aquifer than the other divisions. The superiority of the Middle and Lower Chalk as aquifers may be due to the presence of hardgrounds: the Totternhoe Stone and the Melbourn Rock.

Woodland (1942) suggested that in Hertfordshire yields from the Upper Chalk are lower, due to its low thickness, and that better supplies are obtained from the Middle Chalk which outcrops more extensively. Downing (1955) also reported that in Norfolk better yields are obtained in the west, where the Middle and Lower Chalk outcrop, than from the softer Upper Chalk. This was mirrored by the East Suffolk and Norfolk River Authority (1971) and confirmed by Toynton (1983) who prepared maps of transmissivity and storage coefficient for 10 stream catchments in Norfolk by baseflow and groundwater recessions averaged over a 10 year period (Figures 4.4.10 and 4.4.9). The transmissivity values show a range from 122 m^2/d for the Tas up to 735 m^2/d for the Stringside catchment, with a general increase in values towards the west. It is likely, then, that the greater use of the Upper Chalk as an aquifer is due to its greater extent, rather than any superiority in aquifer properties of this division.

Overlying deposits

Where the Chalk is covered by low permeability till, infiltration to the aquifer is reduced. This reduces the potential for enlargement of fractures by recharge water, which is likely to result in lower transmissivity and storage coefficient.

In East Anglia, major contributions to storage can be made by permeable deposits (sand and gravel, Lambeth Group, Crag) overlying the Chalk. Lloyd and Hiscock (1990) showed that baseflow discharges from Chalk under drift indicate significant additional storage in the drift deposits and the Chalk Storage Project (BGS, 1993) also concluded that was much dynamic storage in the drift deposits as there was in the Chalk. The storage available in these overlying deposits can be important in determining the sustainability of the Chalk as an aquifer. In pumping test analysis, it can be difficult to separate the contributions to storage made by the Chalk and by overlying deposits, as leakage may be rapid and good fits to type curves may be difficult to achieve. In general, it has been found that overlying sand and gravel deposits result in a storage coefficient for the aquifer system of around 10^{-2}, whereas the storage coefficient of confined Chalk is generally in the order of 10^{-4}. Great Ouse River Authority (1970) found that storage contributions were also made from less permeable Lowestoft Till, increasing the storage coefficient to around 10^{-3}. Storage coefficients (measurements of storage coefficient greater than 0.1 have been omitted; see Section 4.1.8 for further details) from pumping tests for the region (Figure 4.1.21c) are commonly between 10^{-4} and 0.1, showing variable degrees of confinement and contribution from drift.

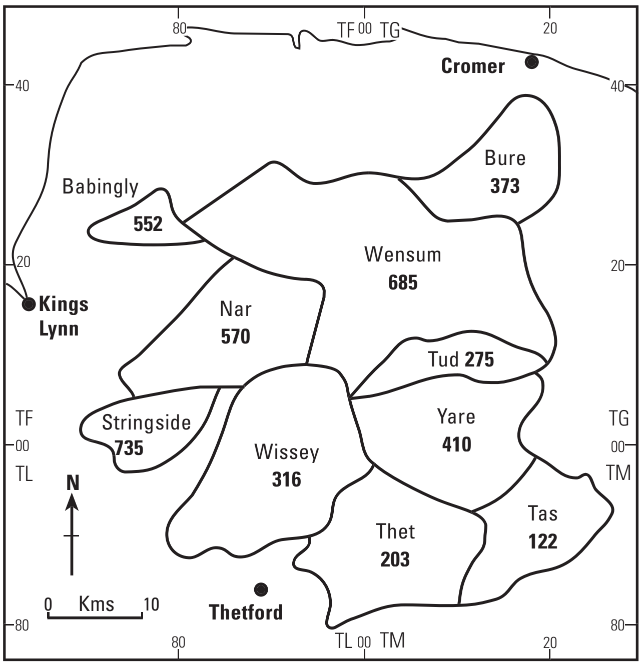


Figure 4.4.10 Distribution of transmissivity (in m^2/d) in the Chalk of Norfolk (after Toynton, 1983).

4.4.2 Hertfordshire

Geological and geographical setting

The area covers the catchments of the upper river Lea and its tributaries — the Mimram, Beane, Rib, Ash and Stort, which all drain south-eastward. It also covers a small part of the catchments of the Ouzel and the Ivel, which rise on the Chalk and flow north-westward towards the Great Ouse. The area is underlain entirely by Chalk, with drift deposits being present in the east and south. South-east of Hertford the Chalk is covered by London Clay and is included in the London Basin area. The Hertfordshire area falls mainly within Thames Region of the Agency, although part lies within Anglian Region. Public water supply is managed by Three Valleys Water Company. The aquifer is fully committed to licensed abstractions; many licences are for spray irrigation, sometimes resulting in seasonal over-abstraction of the aquifer.

The topography of the area is more pronounced than elsewhere in East Anglia. The Lea originates in the Chilterns, which form the highest points of the area. North-east of the Chilterns is the Hitchin–Stevenage Gap, an open valley through the Chalk escarpment which separates the Chilterns from the East Anglian Heights. The gap is about 4 miles wide and reaches a maximum height of about 120 m AOD at the south-eastern end. The East Anglian Heights form a belt, about five miles wide, of Chalk hills, masked by Lowestoft Till. The relief is subdued; mostly over 120 m AOD but rarely rising to greater than 160 m AOD. Valleys are mostly drift-filled with flowing streams. Seasonal springs are also common. The East Anglian Heights fade southwards into a dissected plateau, the East Hertfordshire Plateau, at a lower average elevation (around 100 m AOD is the height of the interfluves). This is part of the Chalk dip slope and is thickly drift-covered. The plateau covers the area between the valleys of the middle Lea and the Stort.

Most of the area is underlain by Upper Chalk, which reaches a maximum thickness of around 90 m in the south-east. The Lower and Middle Chalk also outcrop in narrow bands; the bands are narrower here than elsewhere in East Anglia as the scarp slope is steeper. The higher relief in this area causes greater dissection and the lower divisions outcrop along the valleys as long arms or elongated inliers surrounded by the upper beds.

A narrow, steep-sided buried channel exists in the Stort valley between Elsenham and Sawbridgeworth, filled with alternations of sand and gravels with marly clays. Another, very deep, channel lies in the Hitchin-Stevenage gap; in the vicinity of Hitchin it appears to be split into two sub-parallel channels. The fill is mainly bedded deposits of sands, gravels, loams and clays.

Groundwater investigations

The hydrogeology of the area has been described by Woodland (1942, 1946). He suggested that, in the west of the area, the Middle and Lower Chalk (above the Chalk

Marl) provide better yields than the Upper Chalk in this area, although this may be due to the fact that the Upper Chalk is mostly found on the higher ground, whereas it is the lower divisions which outcrop in the valleys where the majority of the abstractions occur.

Aquifer properties

Pumping test data in this area are less abundant than elsewhere in East Anglia. The database contains 23 pumping tests from 19 sites. Transmissivity values range from 26 m^2/d to 1407 m^2/d, with a geometric mean of around 320 m^2/d (Figure 4.4.11) 25% of the values are less than 160 m^2/d and 75% are less than 1000 m^2/d. The storage coefficient is also generally high, the geometric mean being 4.7×10^{-3} (Figure 4.4.12). The interquartile range is 1.6×10^{-3} to 0.023. Woodland (1946) reported high yield categories in the Hitchin–Letchworth area, and in the valleys of the Ash, Stort and Lea. The paucity of the pumping test data in the area makes confirmation of this distribution impossible, although high transmissivity values of around 1000 m^2/d have been recorded at Marsh Road, Cheshunt, in the Lea valley [TL 372 022], and at St Ippollitts, near Hitchin [183 255].

The highest yields tend to be found where high transmissivity occurs; at Marsh Road, a yield of 17300 m^3/d was obtained during a 14 day pumping test.

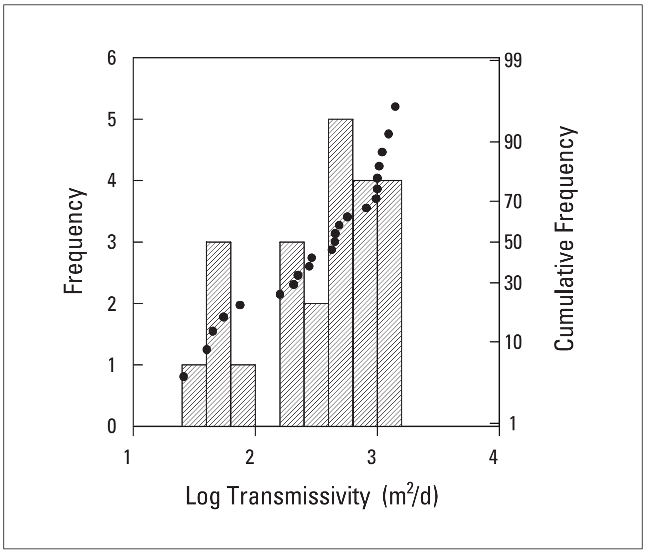


Figure 4.4.11 Distribution of transmissivity data from pumping tests in the Chalk of Hertfordshire.

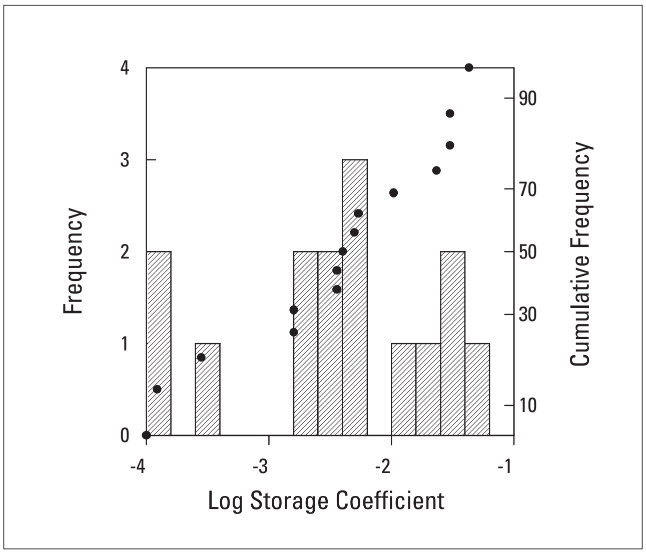


Figure 4.4.12 Distribution of storage coefficient data from pumping tests in the Chalk of Hertfordshire

4.4.3 Cambridgeshire

Geological and geographical setting

This area lies on the Chalk scarp slope between Newmarket in the north-east and Royston in the south-west. Cambridge is situated approximately in the centre of the area. The Chalk is largely drift-free, although some glacial deposits occur in the south-east of the area. The area falls within Anglian Region of the Agency; the Chalk groundwater units are the Cam, the Rhee, the Lodes and the Granta. These are all fully committed to licensed abstractions; total licensed abstraction from the Chalk in the area is around 190 000 m^3/d (figures are reviewed annually).

Lower, Middle and Upper Chalk outcrop in the area; the Upper Chalk reaches a maximum thickness of around 70 m in the south-east of the area. Hardgrounds also outcrop in the area; they are thought to be important water bearing zones and frequently give rise to springs. A buried channel is proved in the Cam valley from Quendon to Whittlesford, and appears to end abruptly. The fill consists of reworked clay and gravels. The channel is thought to connect with the channel further south in the Stort valley.

Groundwater investigations

The hydrogeology of the area has been described in detail by Woodland (1946). Other investigations include modelling of the Lodes/Granta catchment (University of Birmingham 1988) and the Cam/Rhee catchment.

Aquifer properties

Data has been collected from 125 pumping tests at 81 sites. Transmissivity values from pumping tests in the area range from 10 m^2/d to 7000 m^2/d and are approximately log-normally distributed, with a geometric mean of 670 m^2/d (Figure 4.4.13). 25% of the values are less than 323 m^2/d, and 75% are less than 1495 m^2/d. Transmissivity values greater than 2000 m^2/d have been recorded at Newmarket [TL 661 642], Fowlmere [TL 427 445], Hinxton Grange [TL 506 472], Westoe Farm, Haverhill [TL 600 450], Babraham [TL 511 505], Ickleton [TL 492 430] and Duxford [TL 456 460]. Values of around 1000 m^2/d are common along the Cam and Granta valleys (Hinxton, Ickleton, Duxford, Babraham), around the Lodes area (Chippenham, Dullingham, Newmarket), and in the area between Cambridge and Royston (Fowlmere). Very high and very low values are uncommon. Most of the boreholes tested lie on the outcrop of the Middle and Lower Chalk, although some are situated on Upper Chalk. The majority of boreholes are also in river valleys. The Melbourn Rock and Totternhoe Stone are significant water bearing horizons and feature in most of the boreholes tested; the Chalk Rock is present in boreholes in the south-east of the area. The consistently high transmissivity values found in the area may be due to the consistent presence of these hardgrounds.

Values of storage coefficient are also high, with a geometric mean of 0.0043, reflecting the predominantly unconfined nature of the aquifer (Figure 4.4.14). 25% of

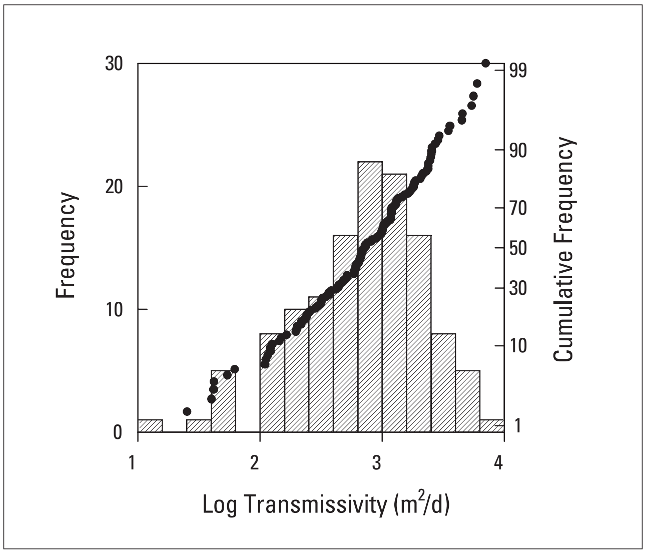


Figure 4.4.13 Distribution of transmissivity data from pumping tests in the Chalk of Cambridgeshire.

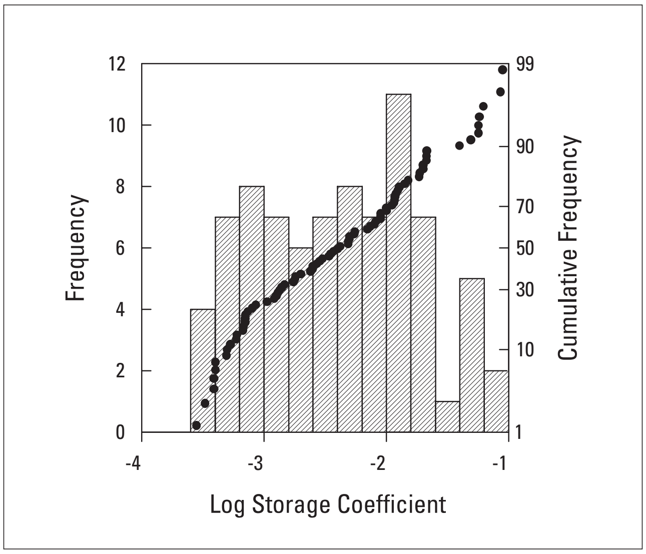


Figure 4.4.14 Distribution of storage coefficient data from pumping tests in the Chalk of Cambridgeshire.

the values are less than 0.0011, and 75% are less than 0.0119.

Most of the boreholes in the area show very good yields, although there appears to be a bias in the collected data towards high-yielding public water supply sources, as there are few industrial and agricultural boreholes in the area. Yields of 4000–5000 m^3/d are common, with drawdowns of around 15–20 m. More exceptional values are found in the Cam valley, where a borehole at Ickleton yielded 12 000 m^3/d for just 2.6 m drawdown after 11 days.

The Lodes/Granta model was developed to investigate groundwater/surface water interaction (University of Birmingham, 1988). The variation of transmissivity and storage coefficient due to fluctuations in the water table was found to be an important factor in calibration of the model. To model the transmissivity variations, it was assumed that the hydraulic conductivity is uniform at depth and increases linearly with water level in the zone of water table fluctuation. The storage coefficient was changed in two steps:

- for the water table between 5 and 10 m below the initial level, the storage coefficient was set at 75% of the original value
- for the water table more than 10 m below the initial water level, the storage coefficient was set at 40% of its original value.

It was thought that the latter reduction to 40% might be too large a change and the value could be increased due to delayed drainage during long periods of drought.

Figures 4.4.15 and 4.4.16 show the distribution of transmissivity and storage coefficient used in the groundwater model of the Lodes/Granta catchment (University of Birmingham, 1988).

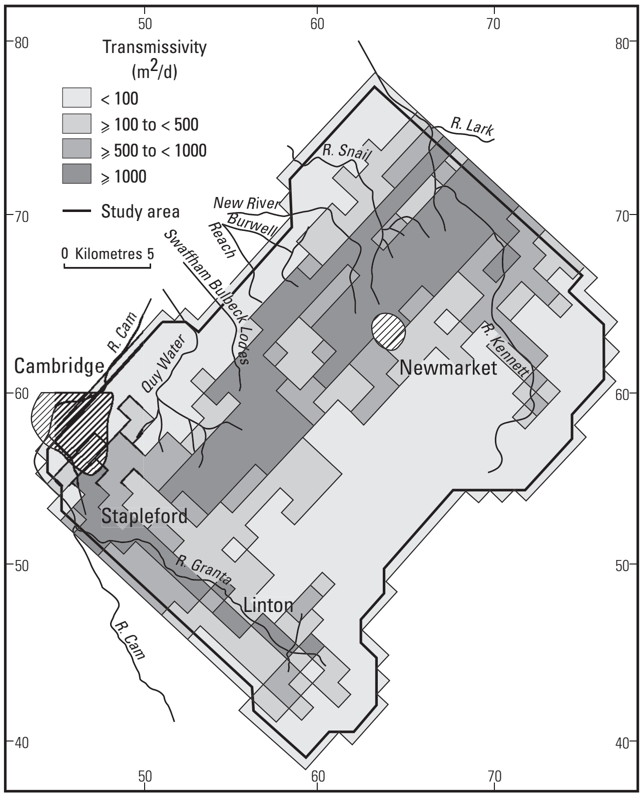


Figure 4.4.15 Lodes/Granta model — distribution of transmissivity (after University of Birmingham, 1988).

4.4.4 West Suffolk

Geological and geographical setting

This is the area west of the major groundwater divide which runs approximately north–south through East Anglia (Figure 4.4.1). The area extends from the groundwater divide north of North Pickenham to that south of Bury St Edmunds. The western boundary is formed by the edge of the Chalk outcrop and the surface water divide between the rivers Snail and Kennett, east of Newmarket. Thetford lies approximately in the centre of the area. The groundwater catchments in the area are the Lark, the Little Ouse and the Wissey. Total licensed groundwater abstraction from the Chalk in the area is around 210 000 m^3/d. There may be resources available for exploitation in the Wissey groundwater catchment, but the rest of the area is fully committed to licensed abstractions (Anglian NRA, 1993).

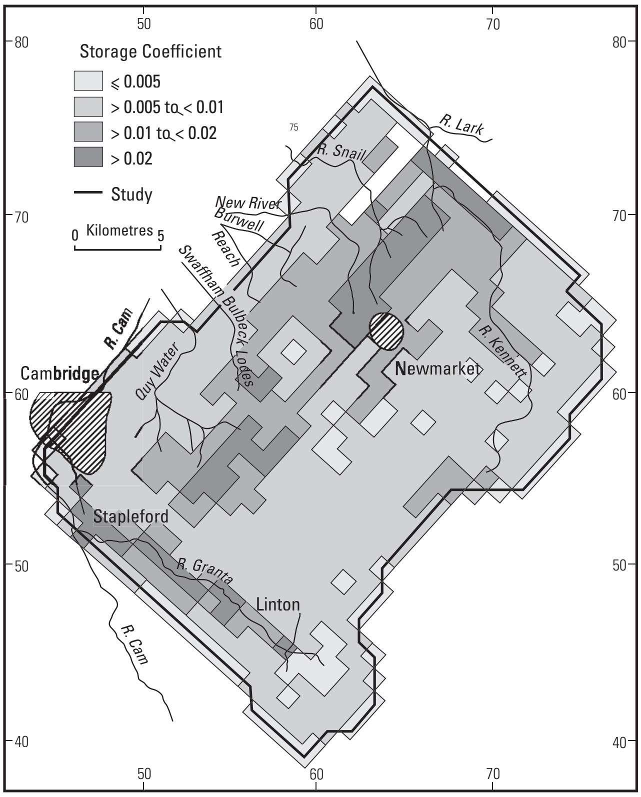


Figure 4.4.16 Lodes/Granta model — distribution of storage coefficient (after University of Birmingham, 1988).

Lower and Middle Chalk outcrop in the west of the area in bands. The Upper Chalk has a limited outcrop as it is largely overlain by glacial drift deposits, the exception being along the valley of the Little Ouse. These deposits overlie the Chalk in the east of the area, but large windows occur through which the Chalk outcrops, principally around Bury St Edmunds and around Euston. Crag deposits occur to the east of Ixworth and south-east of Bury St Edmunds.

The rivers of the area all drain westwards into the Great Ouse and thence into the Wash. From north to south they are the Wissey, the Thet/Little Ouse and the Lark/Kennett.

A buried channel probably follows closely the present course of the river Wissey from west of Hilborough to its source near Bradenham. This may connect eastward with the channel in the Tud valley. Drift thicknesses can be greater than 70 m in the upper part of the channel and several tributary channels also exist.

The area around Mundford, Shropham and Attleborough in the headwaters of the Thet has an interconnecting complex of deep buried channels which probably unite to form an outlet in the Wissey valley beyond Mundford. The channels do not appear to follow the present drainage to any marked degree. In the multiple channel area in the east, the fill is mainly described as clayey, and the records have generally been interpreted as till.

A pronounced drift-filled channel proved in the valley of the Lark extends for at least 16 km between West Stow and Little Welnetham. The course of this channel follows the present course of the Lark closely. Several boreholes along the Black Bourn, which flows north-north-westwards to join the Little Ouse south-east of Thetford, prove the existence of a deep channel, although the exact course is uncertain. The channel fill in the Lark valley appears to be a bedded complex of sands, gravels, silts and clays. The fill in the Ixworth valley is also variable, with considerable thicknesses of till over bedded sands and gravels.

Groundwater investigations

The area was described by Woodland (1946), and has subsequently been investigated during studies for the Great Ouse Groundwater Scheme — a pilot groundwater development scheme (Great Ouse River Authority, 1970). This involved the testing of 18 boreholes between 1968 and 1972. The boreholes were logged to ascertain major zones of inflow and test pumped to study the effect on river flows and investigate storage effects and recirculation. Modelling studies have also been carried out for the Lark catchment (University of Birmingham, 1992) and the Little Ouse/Thet catchment (Mott MacDonald, 1993).

Aquifer properties

General data

Data has been collected for the area from 256 pumping tests from 194 sites. Transmissivity values for the area range from 1 m^2/d to over 10 000 m^2/d, with a geometric mean of 680 m^2/d (Figure 4.4.17). The data approximate to a log-normal distribution with the exception of a few anomalously low values. The interquartile range is 302 m^2/d to 1754 m^2/d. There is a wide range in values of storage coefficient (measurements of storage coeffieicent greater than 0.1 have been omitted; see section 4.1.8 for further details) between 1.4×10^{-4} to 0.1, with a geometric mean of 3.7×10^{-3}, and interquartile range of 8.7×10^{-4} to 0.011 (Figure 4.4.18). The distribution of high values of storage coefficient tends to reflect the distribution of high transmissivity values.

Bristow (1990) suggests that the best yields in the area are obtained from Upper Chalk. The highest recorded yield of 120 l/s (10 400 m^3/d) is at Bury St Edmunds, where a 760 mm diameter borehole penetrated 45 m of Upper Chalk. A 530 mm diameter borehole through Upper and Middle Chalk at Rushbrooke [TL 873 623] yielded 53 l/s (4600 m^3/d). At Ixworth [TL 940 697], two connected boreholes treated with acid yielded 55 l/s (4800 m^3/d). At a site in Bury St Edmunds (TL 850 642), five shafts and boreholes yielded 115 l/s (9900 m^3/d) from Upper Chalk.

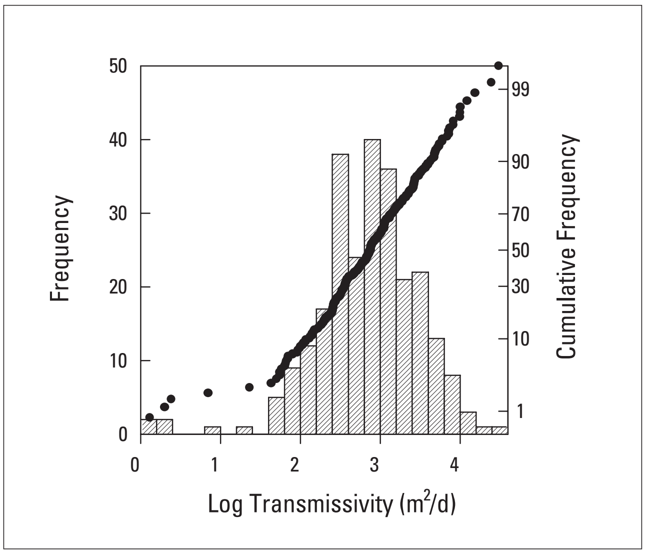


Figure 4.4.17 Distribution of transmissivity data from pumping tests in the Chalk of west Suffolk.

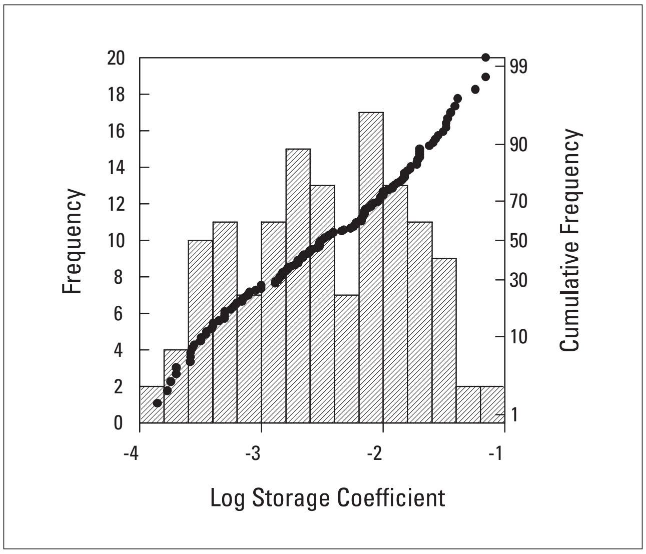


Figure 4.4.18 Distribution of storage coefficient data from pumping tests in the Chalk of west Suffolk.

Yields are generally good where the Chalk is overlain by a thin layer of glacial deposits. At Mildenhall [TL 729 759], Chalk overlain by 7.3 m of sand and gravel yielded 35 l/s (3000 m^3/d).

Vertical distribution in aquifer properties

As part of the Great Ouse groundwater scheme, 18 boreholes were investigated by geophysical logging and pumping tests. Geophysical logging was useful in indicating the effective thickness of the aquifer; it had previously been thought that the Chalk Rock (at a depth of 90–100 m from the top of the aquifer) would form a major inflow horizon. However, it was found that 90% of inflow to the boreholes was in the top 60 m of the aquifer, and the majority of this was in the top 30 m. The hard bands of the Top Rock and the Chalk Rock can however be major horizons for groundwater flow, for example around Thetford, where they are at a depth of 60–80 m and are targeted as major yielding zones.

In the model of the Little Ouse catchment (Mott MacDonald, 1993), the Chalk was modelled as a double layer aquifer, with a thin, high permeability layer, representing the well-developed Chalk, overlying a thicker, low permeability layer which represents the bulk of the Chalk. This double layer system was found to be necessary to achieve calibration of the model for both the piezometry and the river flows.

Areal distribution of aquifer properties

Very high transmissivity values are not uncommon throughout West Suffolk: values greater that 10 000 m^2/d have been recorded at Isleham, Mildenhall, Beck Row, Lakenheath, Elveden, Thetford, Euston and around Bury St Edmunds. The boreholes at Isleham, Mildenhall, Beck Row and Lakenheath penetrate the Lower and Middle Chalk rather than the Upper Chalk which outcrops to the east of these boreholes. The boreholes at Elveden, Thetford and Euston are in the valleys of the rivers Little Ouse and Thet, strengthening the view that high transmissivities are found in river valleys. It is unclear whether these high measured transmissivities are due to enhanced development of the Chalk or to leakage from the river. The Great Ouse Groundwater Study suggests that the low permeability of the river bed usually prevents significant leakage; however, modelling of the area round Brettenham indicates that leakage occurs from the river.

Pumping tests undertaken during the Great Ouse study indicated higher transmissivity values in the valleys. For the river Thet the range was 800 to 2000 m^2/d, the Wittle about 1300 m^2/d and the Larling and Roudham Brooks about 700 m^2/d. On the higher ground, values are generally about 350 m^2/d. An interesting feature is that the transmissivity is above average in the vicinity of buried channels where these cross the higher ground. The extensive buried channel system in the north of the tested area causes an extensive area of confined Chalk, but does not appear to act as a major barrier to groundwater flow.

Forson (1987) reports that transmissivities in the region of 300–500 m^2/d are common for boreholes which penetrate buried channels in the Mundford–Shropham–Attleborough area. Transmissivities near the centre of the deeper buried channels are lower, in the order of 130–170 m^2/d.

The Chalk around Thetford can be very well developed: pump testing of the Nunnery Lodge borehole [TL 879 823] gave a transmissivity of around 10 000 m^2/d, and a yield of 40 000 m^3/d can be obtained from this borehole with little drawdown and little contribution from the river. It is unclear why the Chalk in this area is so well developed; faulted zones may be responsible. There is also a possible fault zone around Elveden.

Figures 4.4.19 and 4.4.20 show the transmissivity values used in the models of the Lark and Little Ouse catchments (University of Birmingham, 1992; Mott MacDonald, 1993). Figure 4.4.21 shows the distribution of storage coefficients used in the model of the Lark catchment.

Effect of superficial deposits

Overlying deposits may influence Chalk aquifer behaviour due to either leakage or confinement. One of the tested boreholes along the river Thet gave transmissivity values of around 2000 m^2/d. Leakage occurs to the Chalk from the overlying drift deposits, which are around 5–10 m thick in the vicinity of the borehole. The high storage coefficient (around 3×10^{-3}) indicates that leakage probably occurred immediately pumping started (comparable sites in the area studied had measured storage coefficients of 4×10^{-4}). The leakage coefficient was estimated to be 0.01 day^{-1} sug-

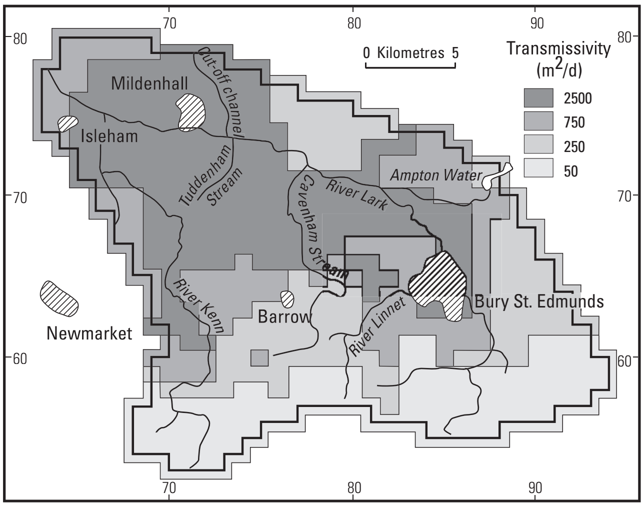


Figure 4.4.19 Lark groundwater model — distribution of transmissivity (after University of Birmingham, 1992).

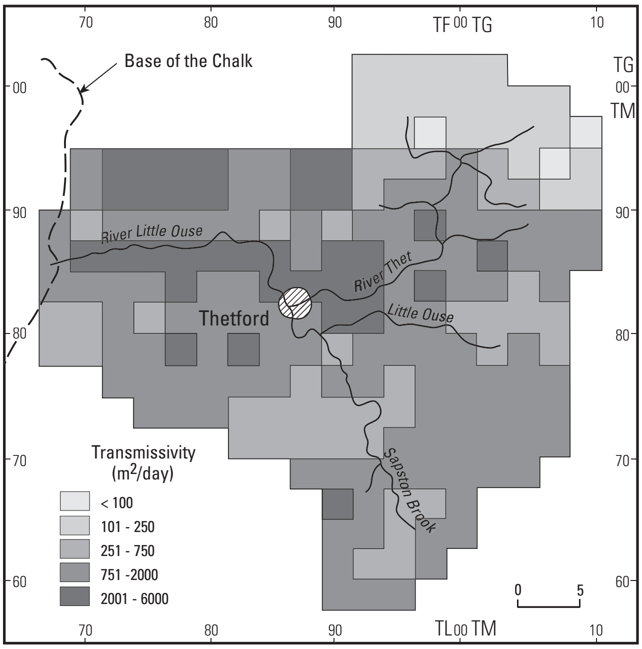


Figure 4.4.20 Thet groundwater model — distribution of transmissivity (after Mott MacDonald, 1993).

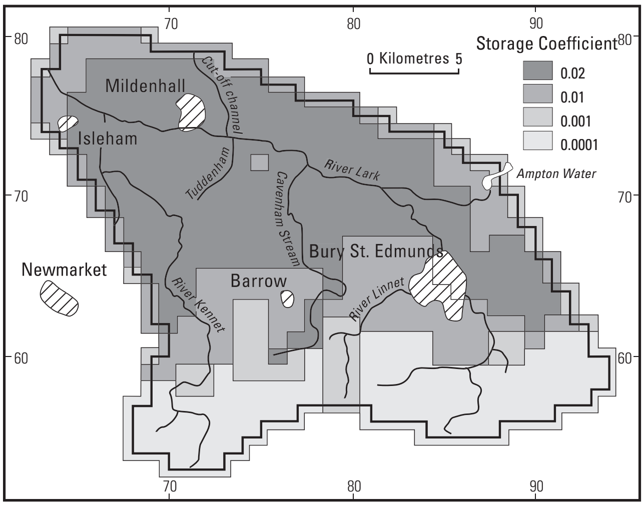


Figure 4.4.21 Lark groundwater model — distribution of storage coefficients (after University of Birmingham, 1992).

gesting an average vertical hydraulic conductivity for the overlying deposits of 0.085 m/d. The delayed drainage of these deposits increased the apparent storage coefficient of the Chalk to 0.03. The hydraulic head in the deposits was maintained by the river. It was estimated that steady pumping reduced leakage from superficial deposits to a minimum after about 10 days, indicated by a declining rate of drawdown in the Chalk. After about 30 days the abstraction rate was maintained completely by combined intercepted baseflow and leakage from the river.

A confined flow regime was found at another borehole in the area, where the Chalk is confined by till between 5 and 15 m thick. The drawdown trend up to 10 days was analysed by the Hantush-Jacob leakage model to give transmissivity values of around 320 m^2/d and a leakage coefficient of 4×10^{-4} day^{-1} for the superficial deposits. The average initial storage coefficient of the Chalk was of the order of 10^{-4} but storage in the overlying till probably contributed to an increase in the apparent value by nearly an order of magnitude.

The transition from a dominantly confined flow regime with negligible leakage to an unconfined regime is characteristic of a number of sites in the tested area. Values of storage coefficient can vary abruptly. Under unconfined conditions the storage coefficient ranges from 0.007 to 0.01, but much higher values (0.02–0.2) are due to drainage from overlying superficial gravel deposits. The storage coefficient of the Chalk under confined conditions ranges from 10^{-4} to 3×10^{-3}, but again where superficial deposits are being drained the long-term values are high (around 0.02).

4.4.5 West Norfolk

Geological and geographical setting

This area covers a narrow strip of Chalk about 20 km wide, mostly unconfined or covered by thin till deposits. The Lower Chalk outcrops in a thin band 1–2 km wide, overlain by Middle and then Upper Chalk. The Middle Chalk has a full thickness of around 50 m in boreholes, and the Upper Chalk also reaches a thickness of about 50 m in this area. The Chalk outcrop in this area does not form a pronounced scarp slope. The drainage of the area is to the west, from the topographic high of the West Norfolk Heights, formed by a ridges of drift deposits. The main rivers are the Ingol, the Babingley, the Gaywood and the Nar. All the major river valleys follow the course of buried channels.

Scattered boreholes proving excessive thicknesses of drift suggest a number of buried channels in north-west Norfolk, but their full extent cannot be assessed. A deep channel is indicated in the upper Nar valley, filled with an alternation of sands, clays and muds, and a complex of channels is indicated to the north.

Springs may occur at the base of the Chalk where it is underlain by impermeable Gault, and these are sometimes used for water supply. Springflows respond rapidly to changes in rainfall as they are fed by rain falling on the relatively short scarp slope of the Chalk. Historical springs from the base of the Chalk at Marham have now been intercepted to a large extent by boreholes [TF 728 113]; these boreholes are often unable to yield in the summer months due to the low saturated thickness of the Chalk.

Groundwater investigations

There have been very few hydrogeological investigations in the area, as it is an area of low population and groundwater is not fully exploited. The water resources of the area were investigated by Downing (1955). Ineson (1962) reported fairly high transmissivity values for the area, in agreement with Downing (1955) who suggests that fractures are better developed in the Lower and Middle Chalk of west Norfolk than in the Upper Chalk of east Norfolk.

Aquifer properties

Pumping test drawdown data tend to show an initial period of indefinite form, after which the curve indicates that the aquifer is unconfined. This is in accordance with the lack of drift deposits in the area. Data from 45 tests at 40 sites have been collected for the area.

Transmissivity values range from 2 m^2/d to 9500 m^2/d, with a geometric mean of around 500 m^2/d (Figure 4.4.22). Very high or very low values of transmissivity are rare, with only a few values below 100 m^2/d or above 2000 m^2/d; the interquartile range is 169 m^2/d to 1876 m^2/d. The

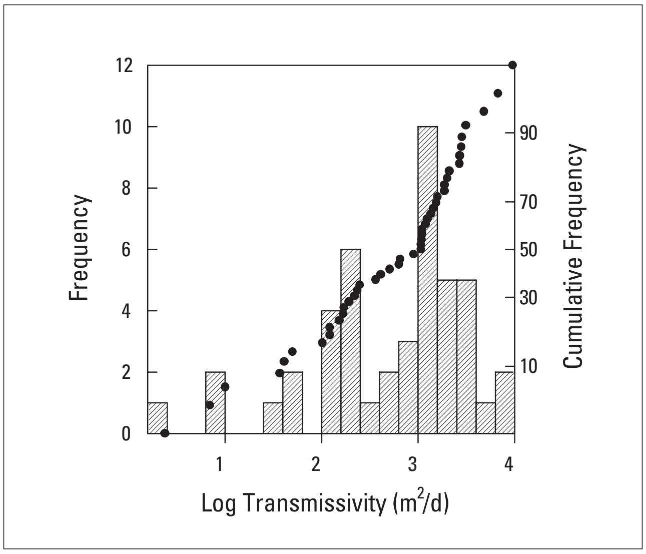


Figure 4.4.22 Distribution of transmissivity data from pumping tests in the Chalk of west Norfolk.

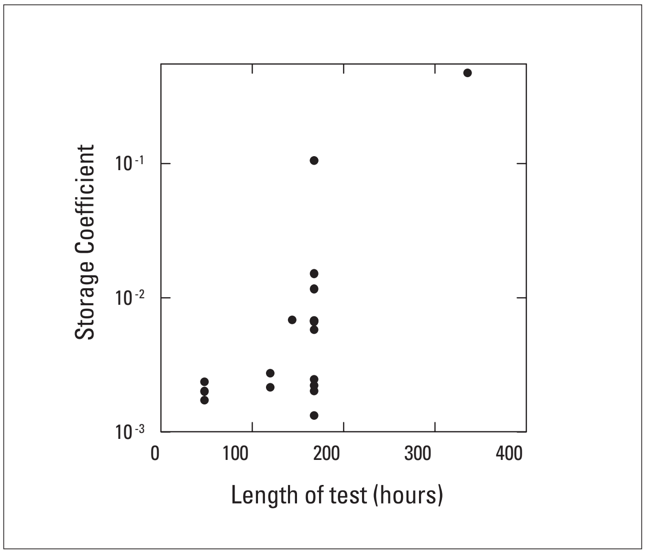


Figure 4.4.24 Plot of storage coefficient against test length for pumping tests in the Chalk of west Norfolk.

highest transmissivity values are found around Lexham, Great Bircham, Marham and Docking.

Twenty-two values of storage coefficient (measurements of storage coefficient greater than 0.1 have been omitted; see Section 4.1.8 for further details) exist in the database for the area. They range from 2.7×10^{-4} to 0.1, with a geometric mean of 5.9×10^{-3} and interquartile range of 2.0×10^{-3} to 6.7×10^{-3} (Figure 4.4.23). Figure 4.4.24 shows a correlation between the storage coefficient and the length of the pumping test, indicating that delayed drainage or leakage from overlying deposits increases the measured storage coefficient.

Downing (1955) found that the highest yields in the area were obtained from the borehole at Hillington (3900 m^3/d for 2.7 m drawdown and 7800 m^3/d for 20.7 m drawdown). Good yields are also obtained from boreholes at Fring and Great Bircham (1200 m^3/d for 1 m drawdown and 3300 m^3/d for 12 m drawdown respectively). These figures are supported by the collected data; the bore at Hillington [TF 743 263] was pumped at 4500 m^3/d for a drawdown of 30.6 m after 672 hours. The bores at Great Bircham [TF 751 340] were pumped at 4200 m^3/d for 29.8 m drawdown after 528 hours and 4700 m^3/d for 8.3 m drawdown after 72 hours. The data also show good yields at Battles Farm, Narborough [TF 770 098], which yielded 4100 m^3/d for 6.5 m drawdown after 168 hours. However, these yields are exceptional and yields in the area are generally low compared with those obtained from the Chalk elsewhere in the country.

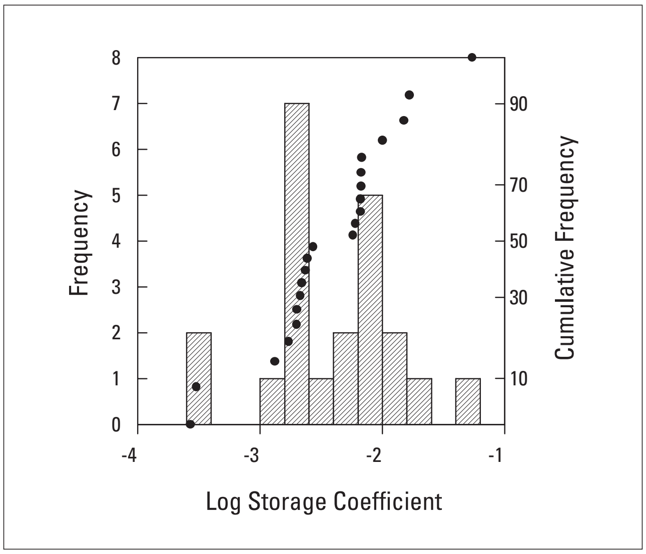


Figure 4.4.23 Distribution of storage coefficient data from pumping tests in the Chalk of west Norfolk.

4.4.6 East Norfolk

Geological and geographical setting

This is the area between Houghton St Giles in the west and the North Sea, extending down to the groundwater divide north of Lowestoft. East Norfolk is an agricultural area with a widely scattered population. Around half the population of the area is concentrated in Norwich and Yarmouth. The main rivers in the area are the Glaven, the Burn, the Stiffkey, the Bure, the Yare, the Wensum and the Lower Waveney. The Glaven, Burn and Stiffkey rise on the Cromer Ridge and flow north. The others flow generally eastward and enter the North Sea at Great Yarmouth. The major rivers have cut through both glacial deposits and Crag to expose Chalk inliers in the eastern valleys.

The dominant lithology is the Upper Chalk which underlies the whole area, and has a general easterly dip of less than 1°. In the east it is overlain by the Norwich Crag, which directly overlies the Chalk where Palaeogene deposits are absent. The Crag is of variable thickness and its base irregular, as the deposits have accumulated thickly in depressions and thinly on the intervening highs. Both the Chalk and the Crag are overlain by glacial deposits, consisting of glacial sands and till. The Upper Chalk forms the main aquifer unit, and the Crag is a minor aquifer. Where the Crag directly overlies the Chalk there is direct hydraulic continuity between the aquifers. The piezometric surface for the Chalk occurs within the overlying glacial drift causing the aquifer to be confined or semi-confined locally; the true confining nature of the drift is not known due to lack of detailed investigation of its permeability characteristics.

The total licensed abstraction from the Chalk in this area is around 200 000 m^3/d. The Chalk groundwater units are the north Norfolk, the Bure, the Wensum/Yare, and part of the Waveney. The Chalk is fully committed to licensed abstractions in the Bure groundwater catchment, but there is thought to be groundwater available from other catchments in the area, particularly the Wensum and Yare catchment (NRA Anglian Region, 1993).

Buried channels are found throughout the area (Woodland, 1970), roughly following parts of the valleys of the Tas, Yare, Tiffey, Wensum and Glaven. Buried channels also appear to be present in north-east Norfolk, which do not appear to follow the lines of present valleys, and in some cases even lie distinctly across the present drainage. The nature of the deposits filling the channels is variable.

Groundwater investigations

The groundwater resources of the area were described by Downing (1955) and by east Suffolk and Norfolk River Authority (1971).

Aquifer properties

East Norfolk is an area where both very high and very low transmissivity values are found. The database contains details of 454 pumping tests at 337 sites. Transmissivity values range from around 1 m^2/d to over 10 000 m^2/d (Figure 4.4.25). The geometric mean of the collected transmissivity values is 277 m^2/d, significantly lower than the mean transmissivity value for west Norfolk. Twenty-five per cent of the values are less than 101 m^2/d and 75% are less than 761 m^2/d. The highest values (greater than 2000 m^2/d) are found around Norwich, especially in the valleys of the Wensum and Yare. High transmissivity is also found at Glandford in the Glaven valley, Houghton St. Giles in the Stiffkey valley, Rackheath in the Bure valley, Ringland in the Wensum valley north-west of Norwich, and Dunston Common and Caistor St Edmund in the Tas valley south of Norwich, along which lies a buried channel. There is a very strong pattern of the highest transmissivity values being found in river valleys, with the lower values being generally found in interfluves. This correlation does not always hold and there are some cases of low transmissivity values at valley sites, such as at Taverham and at Attlebridge in the Wensum valley (albeit from tests lasting only a few hours) and around South Creake, in the Burn valley (obtained from 9 and 10 day pumping tests). There is evidence for a buried channel along part of the Burn valley, although it may not be continuous, which may affect the transmissivity.

Downing (1955) suggested that low permeability marly chalk layers are common in the Upper Chalk in east Norfolk. The presence of these beds reduces the percolation of water to the lower layers. The lower geometric mean transmissivity value for east Norfolk than for west Norfolk, where the Lower and Middle Chalk are more frequently the main aquifers, tends to support this idea.

Pumping test data from boreholes passing through the London Clay into the Chalk are scarce. The groundwater is mostly saline, and hence few boreholes for water supply have been sunk into Chalk below London Clay.

Storage coefficients (measurements of storage coefficient greater than 0.1 have been omitted; see Section 4.1.8 for further details) also show a large range, from 5×10^{-7} to 0.1, with a geometric mean of 2.2×10^{-3} and interquartile range of 4.69×10^{-4} to 7.75×10^{-3} (Figure 4.4.26). The highest values (greater than 0.01) are found in the river valleys west and south of Norwich, where sand and gravel deposits often overlie the Chalk. Other valley sites which have high transmissivity values also have high storage coefficients, such as Houghton St Giles and Ringland.

As expected from the transmissivity distribution, the highest yielding areas of the Chalk in the area are around Norwich. The most productive borehole is at Thorpe St Andrew [TG 253 084], where a 910 mm diameter public supply borehole yielded 16 100 m^3/d for a drawdown of only 15 m. This borehole is thought to penetrate a buried channel, with sand and gravel deposits overlying the Chalk contributing directly to the yield. South of Norwich, at Caistor St Edmund [TG 241 056], a 300 mm diameter borehole produced 2400 m^3/d for 0.3 m drawdown. In the west of the area, at Houghton St Giles [TF 931 357], a 760 mm borehole yielded 7200 m^3/d for a 3.5 m drawdown and at nearby Wighton [TF 934 408] 3300 m^3/d was obtained from a 300 mm diameter borehole for a drawdown of 8.8 m. These yields and drawdowns are exceptional for the area, and elsewhere yield/drawdown relationships are significantly lower. Yields of 1–2000 m^3/d with drawdowns of up to 30 m are more typical.

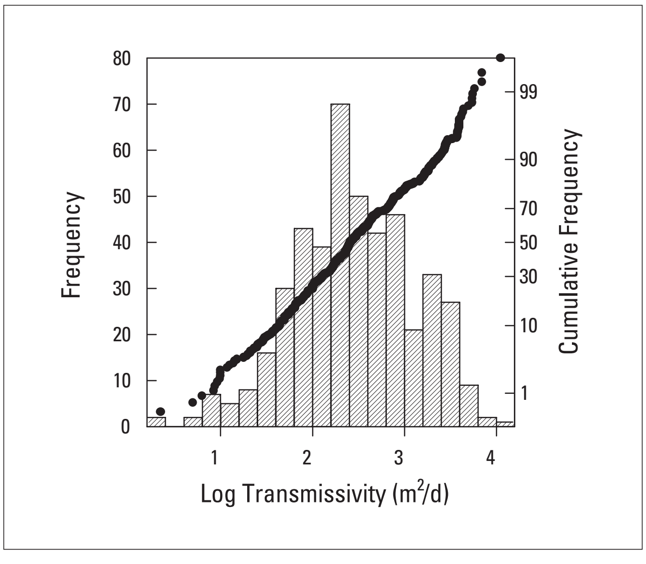


Figure 4.4.25 Distribution of transmissivity data from pumping tests in the Chalk of east Norfolk.

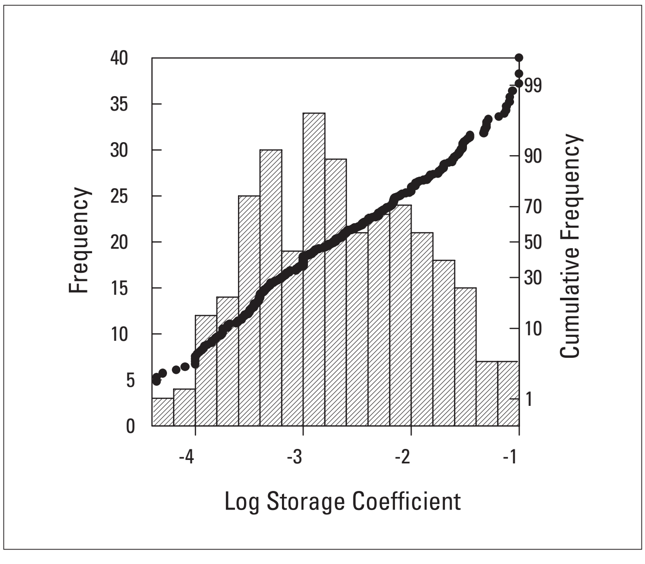


Figure 4.4.26 Distribution of storage coefficient data from pumping tests in the Chalk of east Norfolk.

High yields are often found associated with buried channels. Examples are at Syderstone, Easton, Rushall, and High Oak, near Wymondham, as well as the Thorpe St Andrew borehole mentioned above. Reasonable yields of 1–2000 m^3/d are found at South Creake, which is near a buried channel that has low transmissivity.

4.4.7 East Suffolk

Geological and geographical setting

This is the area east of the major groundwater divide through East Anglia. It extends from Lowestoft in the north to the groundwater divide between the Gipping and the Stour, which forms the south-western boundary. To the east is the coast of the North Sea. The Chalk is covered by Crag deposits throughout much of the area; in the east of the area the Ormesby Clay Formation, Lambeth Group and London Clay intervenes between the Chalk and the Crag. Both Chalk and Crag are covered by Lowestoft Till. The only Chalk outcrop in the area is found in the Gipping valley (between Stowmarket and Ipswich), where the river has cut through to the Chalk. The main rivers of the area are the Upper Waveney and Dove, the Blyth, the Alde, the Deben and the Gipping. The Chalk groundwater units correspond to these river catchments.

A deep buried channel exists along the Waveney valley between Redgrave and Stuston. West of Redgrave the main channel appears to depart from the present river and extend west-south-westward. No extension of the main channel down-river from Stuston has been proved. A buried channel can be traced in the Gipping valley from Badley downstream through Ipswich as far as the docks. The channel is relatively narrow and deep, and occupies only a small proportion of the main valley. The fill is very clayey in the northern part, but sandier at Ipswich.

Groundwater investigations

The hydrogeology of the area has been described by Woodland (1946) and the groundwater resources by East Suffolk and Norfolk River Authority (1971). Other investigations include a detailed study of Chalk boreholes at Rushall by Foster and Robertson (1977), a study by Anglian Water Authority for the River Waveney Groundwater Scheme (1983) and a study by Heathcote (1981) on the Gipping catchment. A subsequent model of the Gipping catchment (University of Birmingham, 1984) was largely based on Heathcote's work. More recently an investigation has been made of the groundwater resources of the Deben (Hydrotechnica, 1992).

Aquifer properties

Data has been collected from 110 pumping tests at 84 sites. Transmissivities in the area are generally low although they cover a large range (Figure 4.4.27): the geometric mean of the collected values is 255 m^2/d and the interquartile range is 69 m^2/d to 868 m^2/d. High values clearly lie along river valleys: 2000 m^2/d at Baylham, 1700 m^2/d at Bramford, 1400 m^2/d at Whitton, 1100 m^2/d at Westerfield and 5000 m^2/d at Ipswich, all in the Gipping valley, and 2450 m^2/d at Pettistree in the Deben valley. However, some lower transmissivity sites are found along the Waveney valley. The dataset contains a large number of low transmissivity values for the sites in the east of the area. Other low values are found scattered throughout the area; some clearly lie near groundwater divides, such as at Stoneham Aspel [TM 140 600], and low transmissivity is also found at Woodbridge in the Deben valley and Eye in the Dove valley.

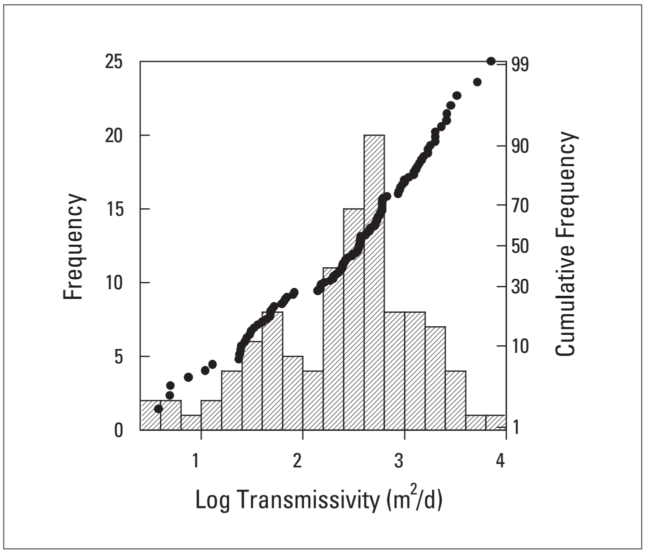


Figure 4.4.27 Distribution of transmissivity data from pumping tests in the Chalk of east Suffolk.

It is likely that the low values reflect restricted groundwater circulation in the Chalk. A recent investigation of the groundwater resources of the Deben (Hydrotechnica, 1992) suggested that the uniform groundwater levels in the upper part of the Deben catchment indicate that there is only limited flow in the Chalk. This was further reinforced by hydrochemical data. This may be as a result of preferential flow in the overlying Crag and drift deposits. The Deben does not cut through to the Chalk, and it is likely that most of the groundwater flow to the river is through the sandy aquifer units. Thus it appears that it is only in the valleys of rivers which cut through to the Chalk that significant Chalk groundwater circulation occurs. Elsewhere, glacial and Crag deposits overlying the Chalk are more significant transmitters of water.

Heathcote (1981) found from chemical data that very little groundwater circulation occurred in the Gipping catchment apart from in the valley areas. Elsewhere, the water in the Chalk is almost static, except in response to pumping, and is often saline at depth. Heathcote emphasised the need to consider the sand and gravel deposits overlying the Chalk and the degree of hydraulic connection between the aquifer units. In addition, Heathcote suggested the distribution of transmissivity within the Gipping Valley indicated in Figure 4.4.28. On the interfluves, where the Chalk is confined by till, transmissivity is less than 20 m^2/d. On the valley sides, where the Chalk potentiometric surface lies in the sand and gravel deposits, measured transmissivity is between 20 and 100 m^2/d. Within the valley, the Chalk is better developed and transmissivity increases to greater than 100 m^2/d. Using the collected pumping test data, transmissivity values for boreholes where the Chalk potentiometric surface lies in the till or in the sand and gravel deposits were examined. However, no significant confirmation of Heathcote's hypothesis was obtained, for this area or elsewhere in East Anglia.

The degree of interaction between different aquifers varies between catchments. Hydrograph analysis in the Gipping catchment tends to indicate that, although there may be some connection between the aquifers, they do not form a single aquifer unit. The River Waveney Groundwater Scheme (Anglian Water Authority, 1983) indicates that the Crag and sand and gravel deposits are in hydraulic

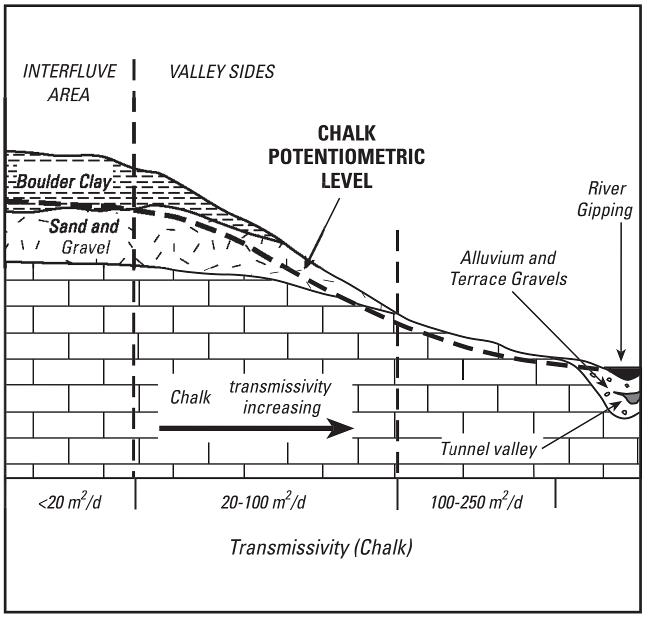


Figure 4.4.28 Schematic illustration of transmissivity variations between valley and interfluve in the Gipping Valley (after Heathcote, 1981).

continuity with the underlying Chalk aquifer. However, in the Dove catchment, Deeney (1980) considered that little, if any, hydraulic interaction takes place between the sand and gravel and Chalk waters.

Despite the generally low transmissivity of the area, there are a number of high yielding sites exploited for public water supply, for example at Baylham [TM 118 521], Whitton [TM 153 484] Westerfield [TM 170 481], Bramford Park [TM 113 470] and Shipmeadow [TM 387 904]. High yielding sites are also found around Ipswich and are exploited for public water supply and industrial use. Yields of around 1–3000 m^3/d are common.

Storage coefficients are also fairly low (Figure 4.4.29) (geometric mean 0.0032), although tending to be higher than in east Norfolk and north Essex, which have higher

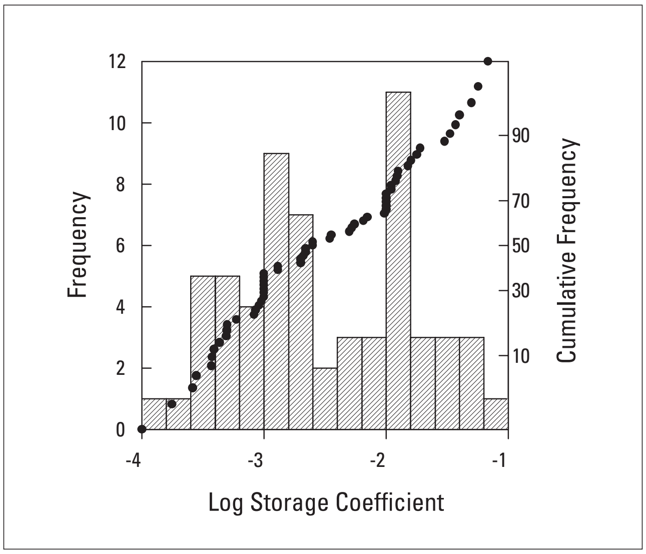


Figure 4.4.29 Dsitribution of storage coefficient data from pumping tests in the Chalk of east Suffolk.

mean transmissivity values. 25% of the values are less than 9.3×10^{-4} and 75% are less than 0.011.

Figures 4.4.30 and 4.4.31 show the distribution of transmissivity and storage coefficient values used in the model of the Gipping catchment (University of Birmingham 1984).

4.4.8 North Essex

Geological and geographical setting

This area of Chalk is bounded by groundwater divides and includes the catchments of the Roding, the Chelmer, the Brain, the Pant-Blackwater, Roman River, the Colne, and the Stour and its tributaries. The Chalk is covered by Palaeogene deposits south-east of a line from Thaxted to Sudbury to Hadleigh; these comprise the sandy deposits of the Thanet Sand Formation and Lambeth Group, the lower part of which is in hydraulic continuity with the Chalk, and the London Clay. Some Crag deposits overlie the Chalk and London Clay in the north-east of the area. The whole area is overlain by glacial deposits. Chalk outcrops are restricted to a few narrow valley-side strips along the Stour near Sudbury and in the valleys of the upper Stour, Belchamp Brook and the rivers Brad and Glem.

The Chalk is semi-confined by the glacial deposits. Under the London Clay the Chalk becomes fully confined. Towards the south of the area the aquifer becomes deeper and its yield and water quality deteriorate, and hence its usage decreases.

The Chalk surface is fairly uniform where it dips beneath the Lambeth Group, but is more irregular to the north, where it has been affected by glacial erosion. Buried channels are present in the Brett and Stour valleys. The Brett channel is not very deep, but the channel in the Stour valley is the deepest proved in East Anglia. Drift thicknesses up to 154 m have been proved at Cavendish, Glemsford and Clare, with channel bottom levels below 12 m AOD (Pattison et al., 1993). There is also limited evidence which suggests the presence of small tributary channels. The channel deposits consist of silts, sands and gravels, which are regarded as permeable (Anglian Water Authority, 1980). However, the top of the Chalk consists of 'putty chalk', which restricts hydraulic continuity between the Chalk and channel deposits. No significant movement of the piezometric surface in the sand and gravel due to pumping from the Chalk has been observed (Anglian Water Authority, 1980).

The full thickness of the Chalk is around 225 m. The depth to the Chalk reaches a maximum of around 160 m.

The NRA Chalk groundwater units of the area are the Stour and the Mid Essex. These are both fully committed to licensed abstractions; licensed abstraction from the Stour catchment is around 120 000 m^3/d and that from the Mid Essex chalk is around 40 000 m^3/d (Anglian Region NRA, 1993). Abstractions are generally made close to the major centres of population, which all lie in river valleys.

Groundwater abstraction south of the edge of the London Clay has caused a decline in groundwater levels to well below OD. The area of worst decline around Braintree is due to heavy abstraction from the chalk in the Pant valley over the past decades. Abstractions have also developed a depression in the lower Colne valley. Abstractions along the Stour estuary have drawn water levels to below OD introducing saline intrusion. North of the edge of the London Clay groundwater levels have declined little (with the exception of individual cones of depression around large abstractions). Artesian or near artesian conditions can be found along valley bottoms.

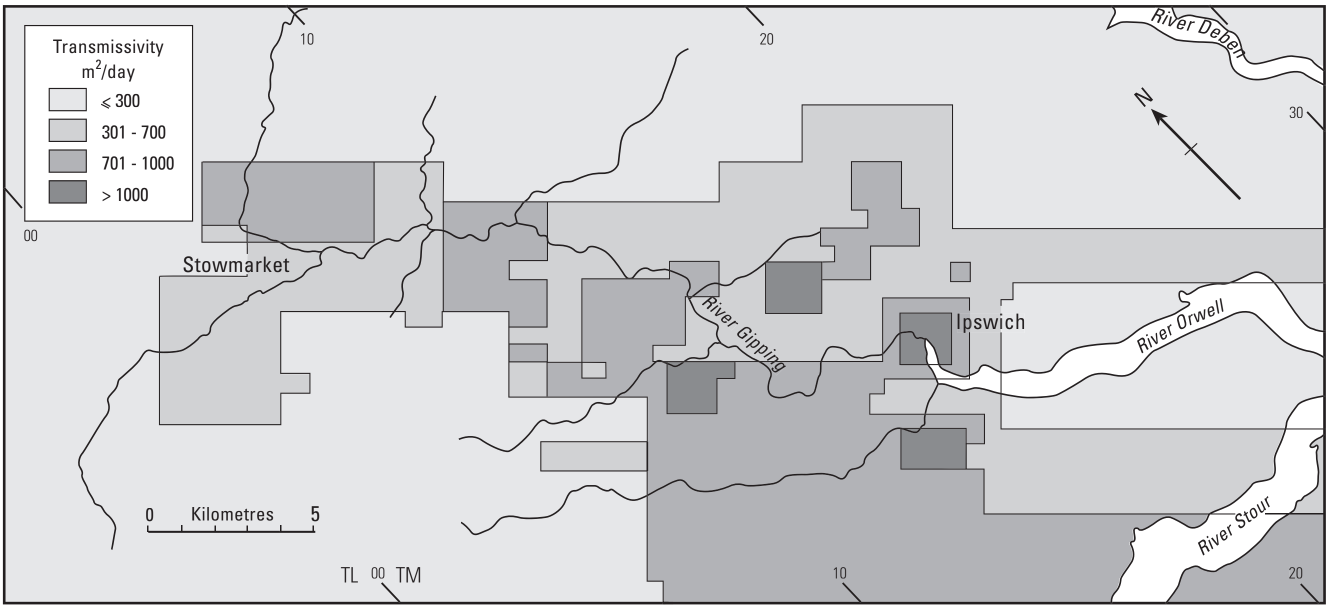


Figure 4.4.30 Gipping groundwater model — distribution of transmissivity (after University of Birmingham, 1984).

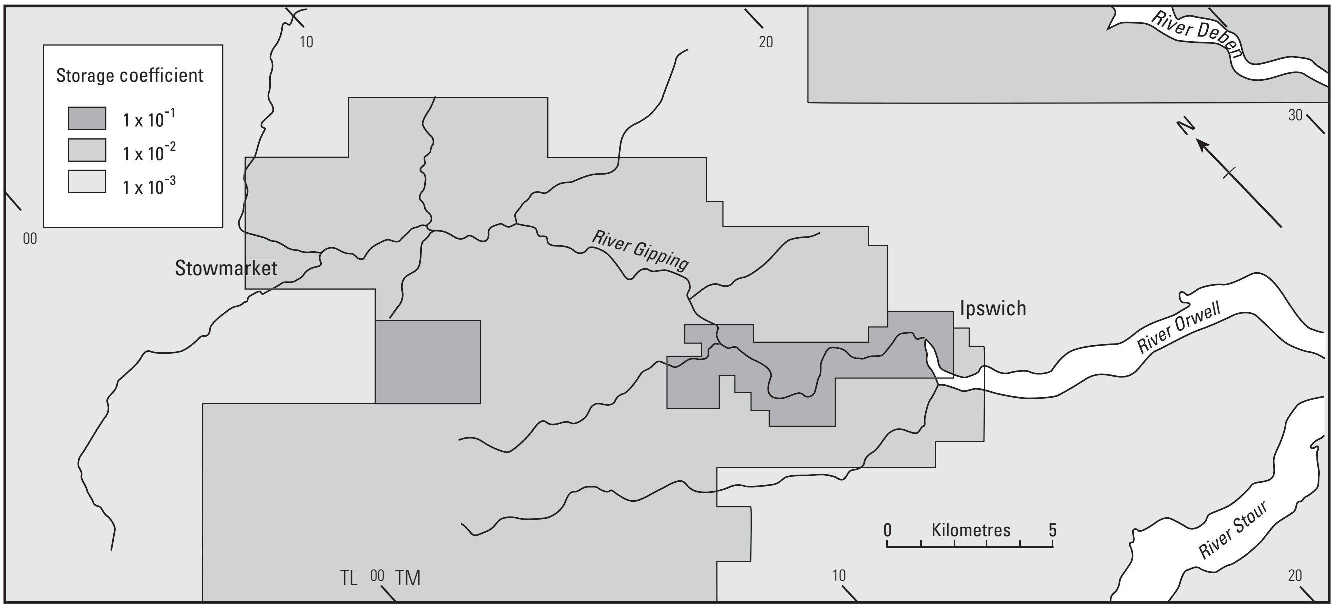


Figure 4.4.31 Gipping groundwater model — distribution of storage coefficient (after University of Birmingham, 1984).

Groundwater investigations

The area was the subject of an extensive groundwater investigation programme, known as the North Essex Chalk Investigation, by the former Anglian Water Authority, Essex River Division, from 1976–1980 (Anglian Water Authority, 1980). Part of this work has been summarised by Lloyd et al. (1981). The aim of the investigation was to study the properties and mechanisms of the Chalk aquifer to assess its potential for further development. It was based on the measurement and observation of aquifer parameters through pumping tests, geophysical logging and chemical analysis. A map showing the Chalk transmissivity of the area was produced from this investigation, based on Woodland's (1946) map of yields (Figure 4.4.3).

Aquifer properties

Data has been collected from 415 pumping tests at 207 sites. Typical transmissivity values in the north of the area, around the Stour valley, are around 300–1000 m^2/d in valleys, but lower in interfluves. Higher values of greater than 1000 m^2/d are found in the buried channel between Hadleigh and Higham. Transmissivity values beneath the Palaeogene cover decline towards the south-east as the thickness of cover increases; values are generally less than 200 m^2/d. Few data are available on aquifer properties south of Colchester as the aquifer has limited use beyond this point. In this area, the Woolwich and Reading Formations are up to 30 m thick and the London Clay is around 60 m thick. The collected data show a range of transmissivity values between 1 m^2/d and 7000 m^2/d, with a geometric mean of 370 m^2/d (Figure 4.4.32). 25% of values are less than 180 m^2/d and 75% are less than 1100 m^2/d. Very low values, of less than 10 m^2/d, are quite common, examples being around Maplestead, Great Tey and Haverhill. There is a bias of data towards the higher transmissivity valley sites, where the overburden is thin, and most of the centres of population are located. The difference in transmissivity between valley and interfluve sites is pronounced in this area.

The measured storage coefficients (measurements of storage coefficient greater than 0.1 have been omitted; see Section 4.1.8 for further details) of the area range from 7×10^{-5} to 0.1, with a geometric mean of 1.6×10^{-3} and interquartile range of 5.0×10^{-4} to 3.7×10^{-3} (Figure 4.4.33). The mean value is lower than in other areas of East Anglia, possibly reflecting the confining effect of overlying Palaeogene and Quaternary deposits.

Pumping tests from the North Essex Chalk Investigation (Anglian Water Authority, 1980) were analysed using Jacob's approximation method to the Theis formula. Many pumping tests showed a departure from the ideal straight line, with both increases and reductions in the rate of drawdown with time. The phenomena of a sharp change of rate of drawdown has been termed a 'dog-leg' response. Different types of dog-leg can be interpreted as representing different changes occurring within the aquifer or borehole. Examples are described below:

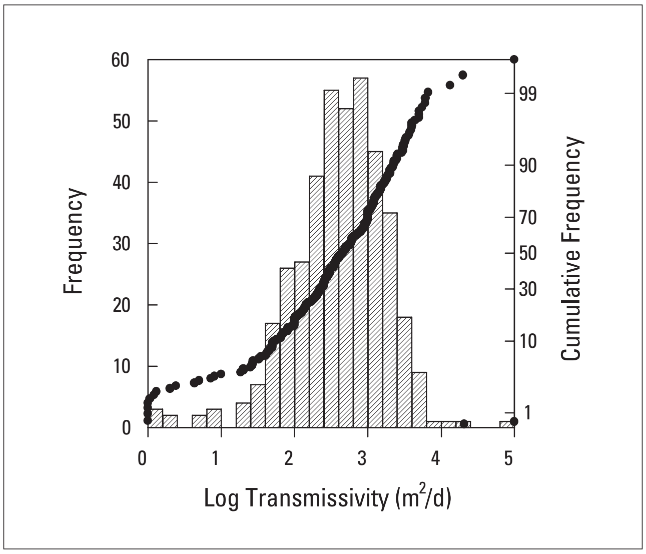


Figure 4.4.32 Distribution of transmissivity data from pumping tests in the Chalk of north Essex.

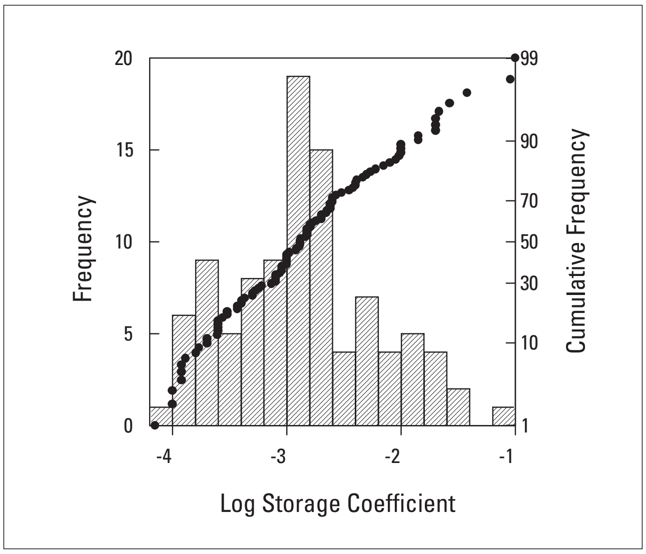


Figure 4.4.33 Distribution of storage coefficient data from pumping tests in the Chalk of north Essex.

a) A sharp reduction in the rate of drawdown after pumping for only about one minute was found in a number of boreholes. The rapid initial drawdown experienced in these boreholes was attributed to well losses; pumping tests conducted before and after borehole development by acidisation showed a marked reduction in the size of this initial drawdown. For this case the value of transmissivity from the gradient was taken to be representative of the aquifer.

b) A similar effect was a sharp reduction in the rate of drawdown after pumping for about 10 to 20 minutes. This effect was investigated in a study of well losses in PWS boreholes at Yeldham, Sudbury and Raydon. It was concluded that this effect represented poor connection between the regional network of fractures and the levels at which water could enter the boreholes, often as a result of casing out the major fractures, near to the top of the Chalk. The water flowing in the aquifer is forced to flow downwards through less permeable zones of minor fractures until it reaches other fractures deeper in the aquifer through which it can enter the borehole. Thus at the start of pumping water initially flows through lower transmissivity Chalk but as the cone of depression expands and water is drawn from a wider radius through the higher transmissivity zones then the rate of drawdown changes, giving the characteristic 'dog-leg' response. The later part of the curve should be taken to represent the true aquifer transmissivity.

Two further types of 'dog-leg' were observed to occur after longer periods of pumping. These were attributed to changes associated with the aquifer rather than the borehole construction. They usually show up as a gradual rather than a sharp change of slope:

c) Decreases in the rate of drawdown with time were attributed to either an increase in the aquifer's transmissivity at distance or to leakage from overlying strata or surface water in continuity with the aquifer.

d) Increases in the rate of drawdown with time were attributed to a decrease in the transmissivity with distance having the effect of a barrier boundary.

Geophysical logging from the investigation suggested that the fracture distribution in the Chalk has been determined by solution, irrespective of rock bands in the Chalk and the depth of overburden. The top 10 m of the Chalk is frequently weathered and is soft and unstable, and is usually cased out in boreholes. From 10 to 40 m the Chalk has been fractured by water movement through it, but lower than this there has been little solution. The investigation could not explain a secondary peak at depths of 55 and 65 m, with boreholes showing inflow at this lower level generally being north of the edge of the London Clay.

4.5 YORKSHIRE, HUMBERSIDE AND LINCOLNSHIRE

4.5.1 Introduction

Background

The Chalk outcrop in Yorkshire and Lincolnshire extends from Flamborough Head to Candlesby. In the north and west the outcrop forms the Yorkshire and Lincolnshire Wolds, which are typical Chalk downlands, consisting of a steep escarpment to an upland area, with a dip slope dipping gently eastward. The dip slope is partially covered by glacial drift, which becomes thicker to the east. The upland areas reach elevations of around 180 m AOD, but are lower around the Humber Estuary and in south Lincolnshire, rarely exceeding 100 m. In the east, where the Chalk is covered by thick drift deposits, the ground is a relatively flat, low-lying coastal plain, some of it only 1–2 m AOD, draining towards the Humber Estuary and the North Sea.

Groundwater movement on a regional scale tends to follow the dip of the Chalk; flow is away from a major groundwater divide which closely parallels the Chalk escarpment, generally trending north-west. The hydraulic gradient in the confined Chalk is very shallow, but is steeper in the Wolds, where it mirrors the topography. Flow velocities of 40 and 280 m/d respectively have been calculated from tracer tests in the Langtoft and Broachdale valleys (Ward and Williams, 1995); Foster and Milton (1974) suggested rates of flow of up to 200 m/d in the Etton area. The Chalk aquifer is unconfined in the drift free Wolds and confined where it is covered by glacial till. The unconfined-confined boundary coincides generally with the position of the buried cliff-line, east of which the thickness of drift covering the aquifer is considerable.

The groundwater head in the Chalk has declined historically, and boreholes which were once artesian now require pumping. The fall in head has resulted in saline intrusion from the Humber Estuary, which is controlled by groundwater management. Seasonal head variations in the confined aquifer are low, but in the unconfined aquifer can be as much as 30 m.

The transmissivity of the Chalk in Yorkshire and Lincolnshire tends to be high, owing to the greater hardness of the chalk here than in the southern province. Ineson (1962) made a study of the transmissivity distribution for the Chalk of the area. This is shown in Figure 4.5.1.

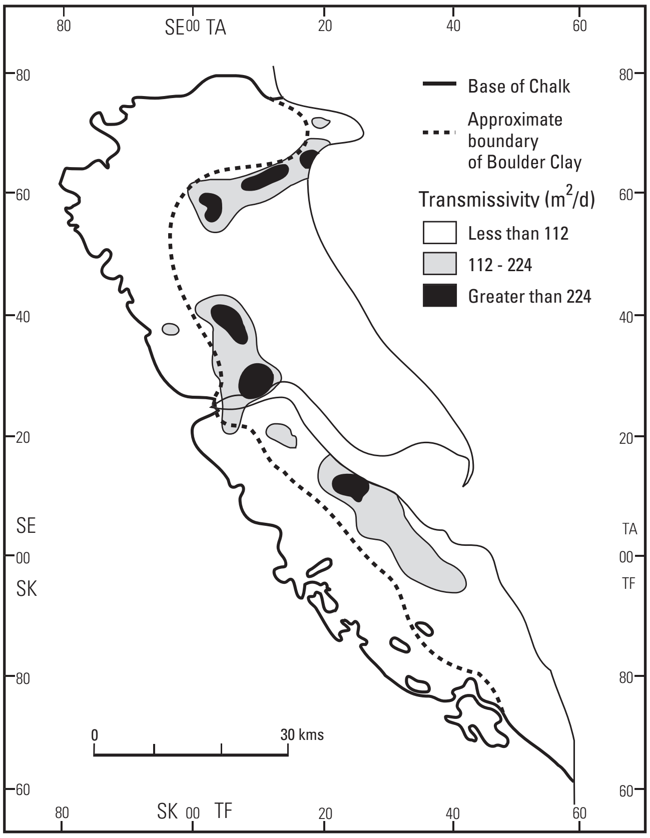


Figure 4.5.1 Chalk transmissivity variations in Yorkshire and Lincolnshire (after Ineson, 1962).

Geological sequence and lithology

The simplified geology of the area is shown in Figure 4.5.2. The distribution of the Cretaceous and Upper Jurassic formations in Lincolnshire is shown in Table 4.5.1. In Yorkshire, much of the Lower Cretaceous and Upper Jurassic strata present in Lincolnshire have been removed by erosion. Sedimentation of the Yorkshire rocks during Lower Cretaceous times was affected by the intermittent uplift of the Market Weighton Block. The Chalk oversteps this block, and unconformably overlies a variety of Jurassic strata. Most of these are aquitards, but some are minor aquifers, and hydraulic continuity may exist between these and the Chalk.

The junction between the Red Chalk and the Carstone in Lincolnshire is gradational. Minor faulting at the base of the Chalk into the Carstone (a potential aquifer) can provide hydraulic continuity between the two. In turn, the Carstone is separated from the Roach, another potential aquifer, by only a thin marl.

The Yorkshire, Humberside and Lincolnshire Chalk belongs to a different province from the Chalk of southern England, and the latter's division into Upper, Middle and Lower Chalk is not readily applicable here. In contrast to the massive Chalk with hardgrounds of the southern province, the northern Chalk is mostly relatively hard and thin-bedded. The northern province has its own lithostratigraphical classification (Wood and Smith, 1978):

- *Ferriby Chalk Formation*
  This approximates to the Lower Chalk of southern England and consists of flintless chalk with a variable clay content. The base of the Ferriby Chalk Formation is marked by the Red Chalk. Above this is soft nodular chalk with marly partings, overlain by a hard shelly limestone (Totternhoe Stone). At the top is a hard grey-white chalk containing pink bands. The formation outcrops along the upper slopes of the Wolds' escarpments in south-west Lincolnshire and north-west Yorkshire, and along valley sides and bottoms within the Wolds. It subcrops beneath thick drift at the foot of the Pre-Devensian cliff.

- *Welton Chalk Formation*
  This is approximately equivalent to the Middle Chalk of southern England. The bulk of the formation consists of massive or thick-bedded, fairly hard chalk. Discrete marl bands occur throughout the formation, including the Black Band near the base, the Grasby Marl and the Barton Group. Discontinuous flint bands also occur.

- *Burnham Chalk Formation*
  Medium hard white chalk with thin marl bands and abundant mainly tabular flint beds. The flint bands at the base often form a subsidiary escarpment. This

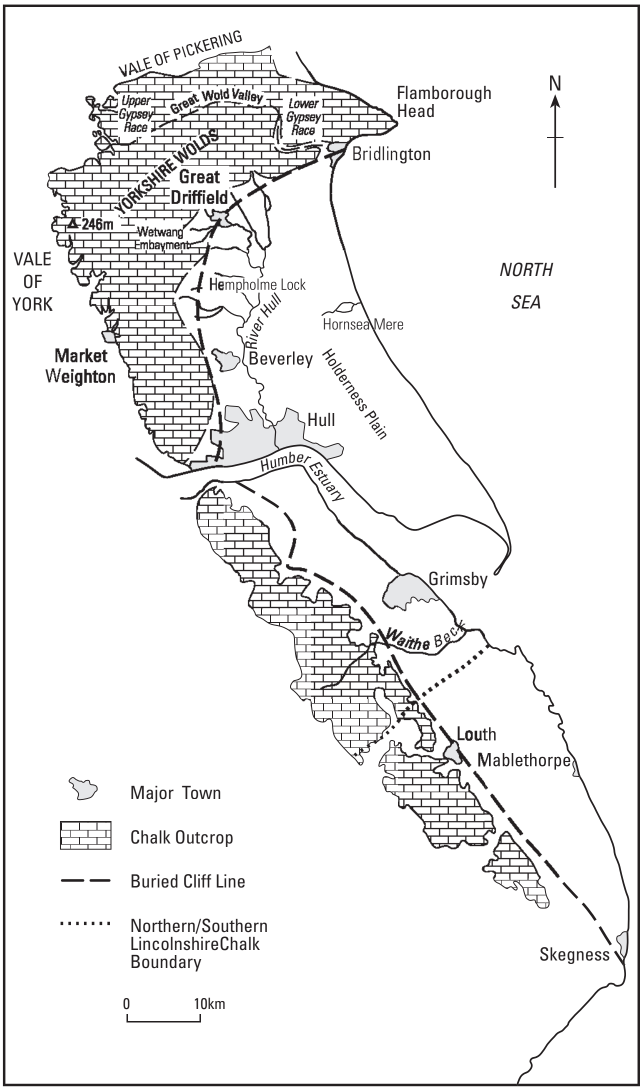


Figure 4.5.2 Outcrop of the Chalk in east Yorkshire and Lincolnshire.

formation corresponds to the lower part of the Upper Chalk of southern England.

- *Flamborough Chalk Formation*
  Soft white chalk with thin marl beds and negligible flint. This formation only outcrops in Yorkshire, but is widespread beneath the drift cover of Lincolnshire and continues eastward beneath the North Sea. This is equivalent to the upper part of the Upper Chalk of southern England.

Along the coastal plain, the Chalk is extensively covered with drift deposits, reaching a thickness of up to 45 m in parts of the Holderness Peninsula. It is probable that a thin covering of till formerly extended over the Wolds, but most has subsequently been removed by erosion. Some patches still exist; in Lincolnshire these are north-west of Louth, along the lower north-eastern fringe of the Wolds, and in many of the valley bottoms. Recent deposits of alluvium are found in the vicinity of the River Hull. These fill a shallow buried channel which approximately follows the course of the present river, with a second buried channel entering from a north-westerly direction.

The 'Chalk bearings' are a layer of broken chalk or chalk gravel occurring between the Chalk and many of the overlying glacial deposits. They are also found on the Wolds outcrop, particularly in dry valleys. They have variable development and thickness, reaching a maximum of about 10 m; in a few instances the bearings are absent and have been replaced by low permeability putty chalk. Both types of rock are thought to have been formed by alternate freezing and thawing under periglacial conditions.

The major structural features are shown in Figure 4.5.3. The Chalk forms an open syncline, plunging gently (2–5°) towards the south-east along an axis between Driffield and Bridlington, which extends out into the North Sea. The dip of the Yorkshire Chalk is slight (1–2°) except locally where tectonic and superficial disturbances are present. The Lincolnshire Chalk is on the south-western limb of the syncline and dips at 1–2° towards the north-east away from the escarpment of the Wolds.

Other major structural features are the Hunmanby Monocline in Yorkshire and the Caistor Monocline in Lincolnshire. The Hunmanby Monocline trends north–south and acts as a hydraulic barrier, affecting the course of the Gypsey Race. The Caistor Monocline trends east–west from Grasby to Grimsby, and has a downthrow of about 80 m to the north. It does not appear to affect the hydrogeology. One of the most notable faults is the Humber Fault, which has a downthrow of 30 m to the south and is considered to explain an offsetting of the Chalk north and south of the Humber.

There is some more minor folding and faulting, but in general the Chalk has a fairly simple structure, except in

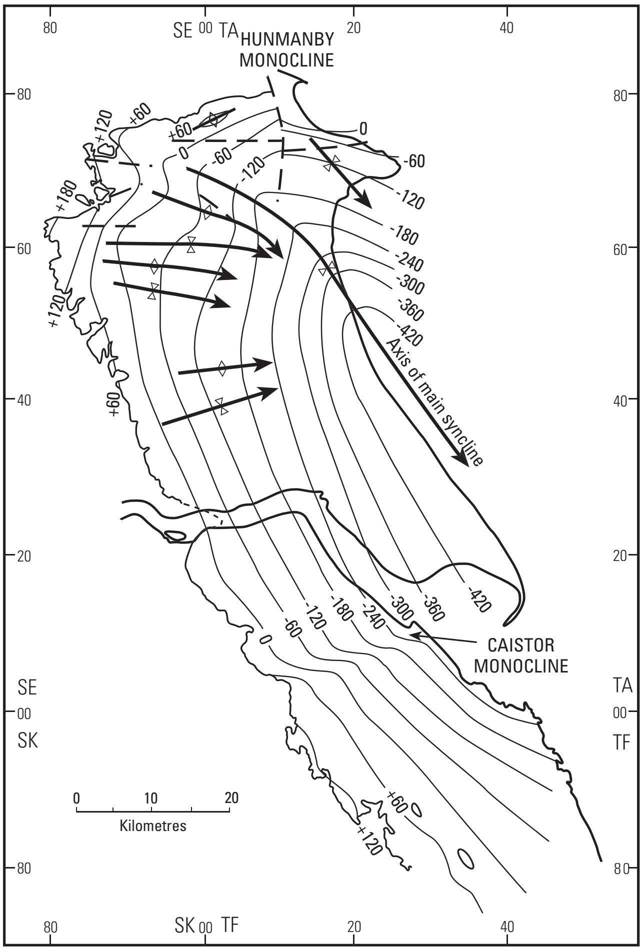


Figure 4.5.3 Contours on the base of Chalk (metres above OD) and major structural features (after Foster and Milton, 1976 and Barker et al., 1984).

Table 4.5.1 The Cretaceous and Upper Jurassic succession in Lincolnshire.

System	Stage	Formation	Lithological division	Approximate thickness (m)
		Flamborough Chalk		
	Senonian	Burnham Chalk		
Upper	Turonian			
Cretaceous		Welton Chalk		
	Cenomanian	Ferriby Chalk	Hunstanton (Red) Chalk	7
	Albian	Carstone	Carstone Grit	3
	Aptian		Carstone Sand and Clay	4
		Sutterby Marl		3
			Upper Roach	3
		Roach	Roach Stone	5.5
	Barremian		Lower Roach	7.5
Lower			Upper Tealby Clay	11
Cretaceous		Tealby Clay	Tealby Limestone	4
			Lower Tealby Clay	13
	Hauterivian		Upper Claxby Ironstone	
		Claxby	Hundlby Clay	9
	Valanginian		Lower Claxby Ironstone	
	Ryazanian		Upper Spilsby Sandstone	2
	Portlandian	Spilsby Sandstone	Lower Spilsby Sandstone	22

the northern part of the Yorkshire outcrop, where it is heavily disturbed and contorted. Several 'disturbance' zones occur, mostly trending west–east, with high-angle jointing. The 'Old Dor' disturbance is about 300 m wide at Scale Nab [TA 213 733] and associated with dips as high as 70°.

Minor faulting is a common feature and many small faults are thought to exist which have not been identified. Other fractures are also common, with origins related to lithology and bedding, as well as tectonics. Lines of disturbance have little surface expression, and are only easily seen in quarry exposures. Woodward and Buckley (1976) surveyed the major joints at quarry sites in the Yorkshire Chalk. They found that major joints often appeared as conjugate sets inclined at more than 50° to the horizontal, with strikes frequently aligned north-west and east-north-east. High angle joint sets are also common in Lincolnshire, generally with no recognisable trend (University of Birmingham, 1982). It is unclear how much such disturbances affect the hydrogeology of the Chalk.

The main features on the surface of the Chalk are dry valleys and buried channels, and a buried coastline. The Chalk coastline resulted from a sea-level rise during the Ipswichian interglacial period, and is now buried by glacial deposits. It runs inland from Sewerby via Driffield and Beverley to Hessle, and continues along the length of Lincolnshire, running from Barton through Barrow to Hollands Field, Ulceby, and then from Brocklesby to Louth (Figure 4.5.2). It is less distinct around the Humber, but in places reaches the dimensions of a buried cliff. South of Louth the Chalk has been completely eroded at the base of the cliff, so that the glacial deposits directly overlie Lower Cretaceous beds (Figure 4.5.4).

A strip of Chalk has also been removed along the Calceby valley, from the buried cliff area to the foot of the Chalk escarpment, which makes this southern area of Chalk an outlier, isolated from the main mass of the Chalk by narrow strips to the east and north.

There are a number of buried channels on the surface of the Chalk beneath the till, the major ones being beneath

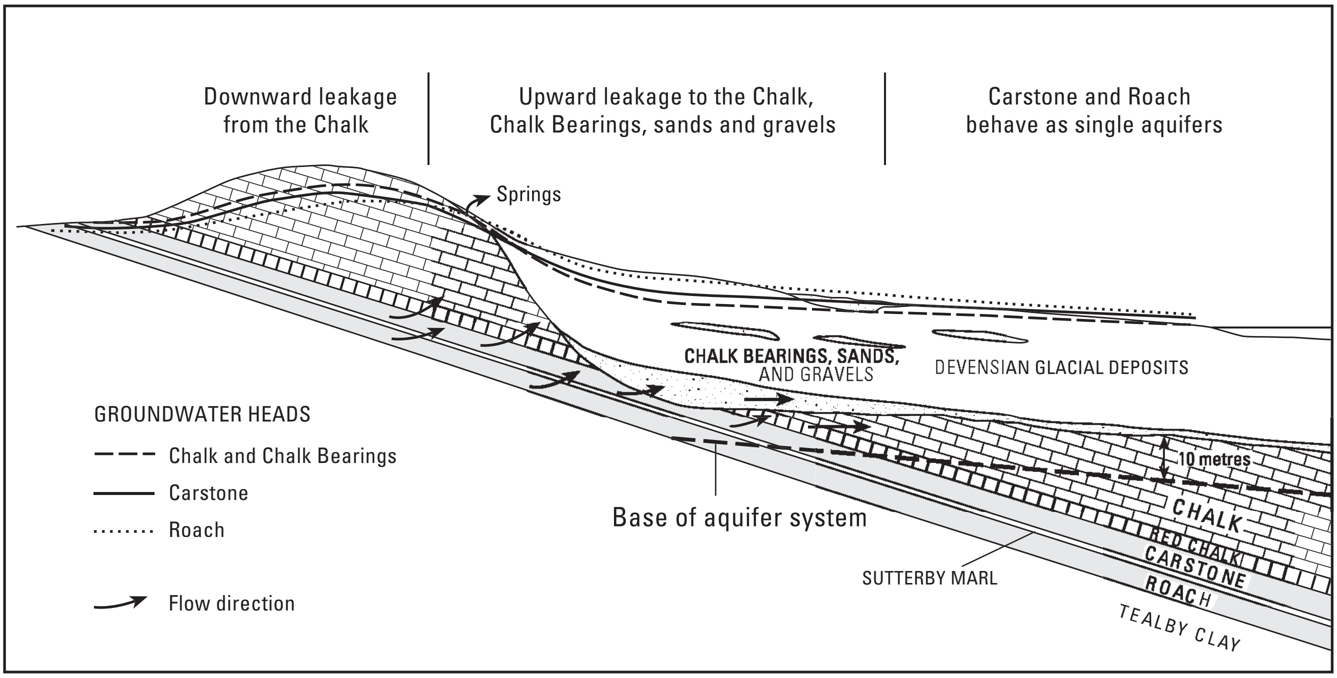


Figure 4.5.4 Hydrogeological cross-section through the Lincolnshire Chalk south of Louth, illustrating erosion of the Chalk along the line of the buried cliff (after University of Birmingham, 1982).

Hornsea and Ulrome in Yorkshire, the Humber estuary, and Kirmington Fjord in Lincolnshire. Several smaller buried channels exist just to the east of the Yorkshire Wolds, which seem to be an extension of the outcrop's dry-valley network. The Kirmington Fjord was formed during the Anglian glaciation, and is comparable to the buried tunnel valleys of East Anglia. The Yorkshire buried channels may also be of glacial origin, or may be of subaerial origin, produced during a period of lower sea-level. Lewin (1969) suggests that they were formed by subaerial erosion of major springs during the more humid Palaeogene/ Quaternary periods when higher water tables existed.

Hydraulic continuity with other units

Hydraulic continuity may exist between the Chalk aquifer and over- or underlying units. Overlying units likely to provide leakage to the aquifer include sand and gravel deposits; underlying units include the Carstone and Roach in Lincolnshire, and the Inferior Oolite/Cornbrash, the Kellaways Beds, and the Corallian Limestone in Yorkshire.

Continuity with underlying units is of particular importance in the southern Chalk around the vicinity of the buried cliff, as this determines whether flow can occur from west to east. Groundwater hydrographs from adjacent Chalk and Carstone boreholes at Belleau [TF 401 779] and Burwell [TF 351 795] indicate that continuity is well developed between the Chalk and the Carstone aquifers, and also indicate in which direction leakage is likely to occur. At Burwell, the more westerly of the two sites, downward leakage is thought to occur from the Chalk to the Carstone; progressing eastwards down the hydraulic gradient this reverses and flow is from the Carstone to the Chalk, and thence to baseflow. Further east, the Chalk thickens and hydraulic continuity between the high transmissivity Chalk bearings and the lower aquifer units no longer exists. There are no water level data to indicate leakage conditions between the Chalk and Roach aquifer units, but conditions similar to those between the Chalk and Carstone are thought to occur. The hydraulic relationships between the aquifers are illustrated in Figure 4.5.4. However, permeability studies of the Carstone and Roach, modelling work and hydrochemical analysis suggest that the amount of groundwater flow across the buried cliff area by this pathway is very small (University of Birmingham, 1982).

Where the Chalk overlies minor Jurassic aquifers in Yorkshire, there is likely to be downward leakage from the Chalk, but the size of the spring flows from the Jurassic outcrop suggests that this transfer is probably extremely small.

4.5.2 Yorkshire

Geological and geographical setting

The Chalk in Yorkshire varies from the unconfined Chalk of the Wolds, through the semi-confined Chalk in the Hull catchment, to the fully confined Chalk of Holderness. The Chalk of the Holderness peninsula is rarely used as an aquifer due to the restricted groundwater circulation and the poor quality. Groundwater flows down the hydraulic gradient from the Wolds, and either emerges as springs at the edge of the drift or is pumped from the semi-confined aquifer.

There is a network of dry valleys across the Wolds, some of which may have hydrogeological importance. There is little surface drainage on the Wolds outcrop, as the water table rarely intersects the ground surface; the only significant flow occurs in the Gypsey Race along the Great Wold Valley in Yorkshire. During periods of high groundwater level the Gypsey Race runs along the entire length of the valley; at times of lower groundwater level the flow is increasingly intermittent, and during the late summer and extended periods of drought the entire Wold Valley becomes dry.

Springs occur just south of the northern Chalk outcrop in Yorkshire, which flow over the glacial drift to form the tributaries of the River Hull. The tributary system can be divided into two: the West Beck and the Foston Beck sub-catchments. The West Beck and Foston Beck join near North Frodingham to become the River Hull, which flows south across the Holderness Plain and through Kingston-upon-Hull to join the Humber. It is tidal below Helphome Lock [TA 080 498].

Most of the major abstractions are located just off the outcrop or in the confined Chalk, although in Yorkshire a scattered network of boreholes in the Wolds area supplies the rural population. Large abstractions are taken from the Chalk in the area around Kingston upon Hull. Springflow from the Chalk is vital in maintaining sufficient flow in the River Hull to meet its environmental and abstraction requirements. The springs in the Driffield area and the abstractions in the Kingston area account for over 400 000 m^3/d.

Groundwater investigations

The area has been studied in some detail in the early 1970s (Foster, 1974; Foster and Milton, 1974; Foster and Crease, 1975; Foster and Milton, 1976; Foster et al., 1976). Some of the work was connected with investigation into the development of river augmentation from groundwater storage; the proposed scheme was not put into practice. Study was also made of saline intrusion into the aquifer from the Humber Estuary.

The northern part of the Chalk was modelled in the early 1980s for Yorkshire Water Authority by Birmingham University. A model to cover the whole of the Chalk aquifer was developed by Aspinwall and Co. (1995), based on the Birmingham University model.

Foster and Milton (1976) developed a schematic interpretation of the Chalk aquifer (Figure 4.5.5), which indicated that in the Wolds area there is a well fractured, high permeability zone in the zone of water table fluctuation, and another well fractured zone with fairly high permeability approximately 20 m below the minimum water level. This interpretation was used in the recent modelling of the aquifer (Aspinwall and Co., 1995).

Aquifer properties

The available data comprises 87 pumping tests from 68 sites. Test transmissivity values range from less than 1 m^2/d to over 10 000 m^2/d (Figure 4.5.6). The geometric mean is 1258 m^2/d and the interquartile range is 500 m^2/d to 5968 m^2/d. Storage coefficients (measurements of storage coefficient greater than oil have been omitted; see section 4.1.8 for further details) range from 1.5×10^{-4} to 1.0×10^{-1} (Figure 4.5.7). The geometric mean is 7.2×10^{-3} and the interquartile range is 1.5×10^{-3} to 0.018.

Figure 4.5.8 shows the distribution of transmissivity and storage coefficient used in the model of the Yorkshire chalk (Aspinwall and Co., 1995). As discussed above, the model is based on the interpretation that there are two zones of high permeability in the Chalk, one in the zone of water table fluctuation and one below this. Transmissivity and storage coefficient values are therefore given for both the upper and lower high-permeability zones.

Exceptionally high transmissivity values are found behind the back of the buried cliff line: Foster and Milton (1976) reported values of over 6000 m^2/d around Haisthorpe. Use of a close-circuit borehole television at Haisthorpe showed large numbers of open horizontal fractures, apparently associated with water entry into the borehole (Foster and Milton, 1976). The high transmissivity is probably due to enlargement of fractures by marine erosion at the time of formation, or the concentration of flow towards the springs which emerge along the line of the buried cliff.

The effect of dry valleys on transmissivity is unclear. Fracturing is well developed in the valleys due to the former concentration of flow, but the water table tends to be below the zone of fracturing (Foster and Milton, 1976). It is, however, thought that transmissivity in Yorkshire does tend to be higher along the valleys than in the interfluve sites but data are insufficiently dense to confirm this. High transmissivities are known to occur in the Great Wold Valley and the Kiplingcotes Valley, where the water table lies in the Chalk

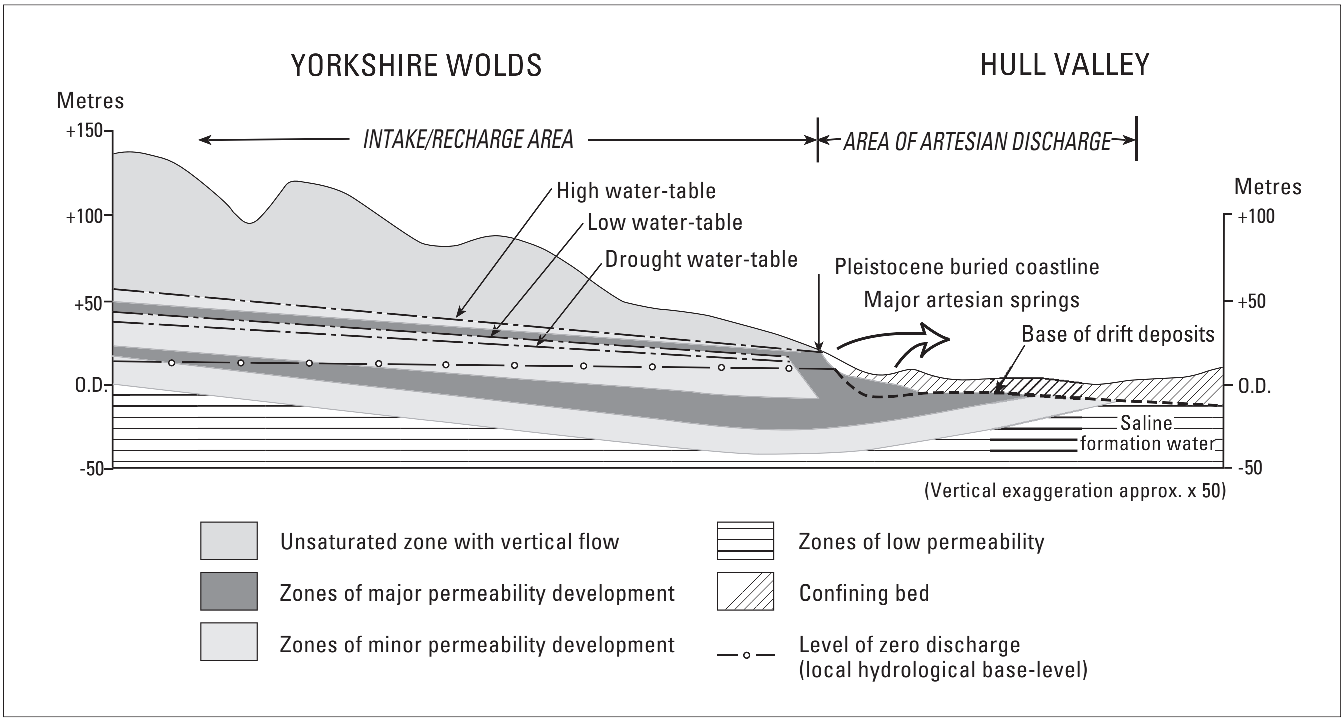


Figure 4.5.5 Schematic hydrogeological interpretation of the Yorkshire Chalk (after Foster and Milton, 1976).

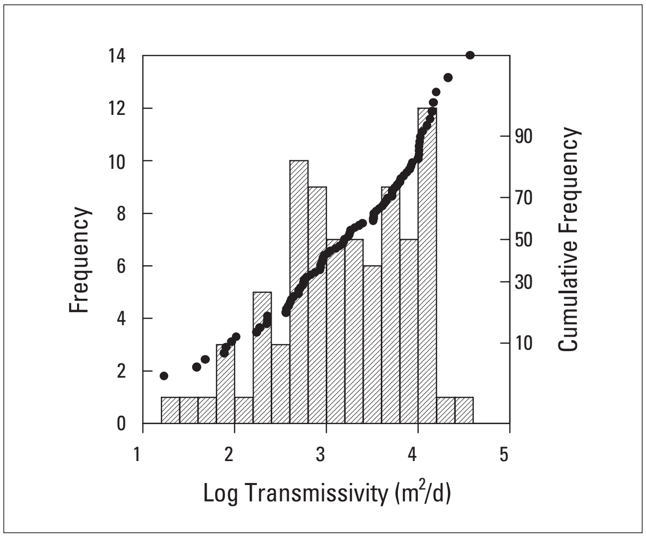


Figure 4.5.6 Distribution of transmissivity data from pumping tests in the Chalk of Yorkshire.

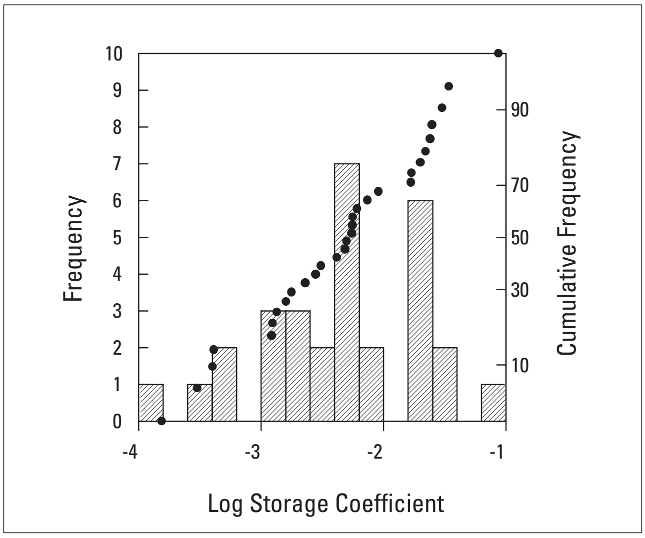


Figure 4.5.7 Distribution of storage coefficient data from pumping tests in the Chalk of Yorkshire.

Bearings and intermittent discharge occurs. A study by the University of Birmingham (1985) reported transmissivities of up to 8000 m^2/d along the Wold Valley, an order of magnitude higher than those on the Octon Ridge to the south.

Low transmissivity Chalk is found beneath the Holderness peninsula (less than 50 m^2/d). This is thought to be a consequence of the lack of groundwater circulation which has limited the enlargement of fractures by dissolution (Foster and Milton, 1976).

Little is known about the aquifer properties in the highly disturbed northern part of the Yorkshire Wolds, as there are very few groundwater abstractions and borehole construction in such distorted strata is difficult. A series of boreholes along the Hunmanby Monocline suggests that the disturbance has a fairly low transmissivity of about 350 m^2/d (Chadha and Courchee, 1978).

The aquifer properties for the unconfined aquifer are affected by seasonal water level changes. Foster and Milton (1974) found that in the Etton area, a major zone of fracturing 7 m thick existed in the zone of water table fluctuation. Pumping tests results showed a significant variation in transmissivity between times of low and high water level; when the water table was above the fracture zone the calculated transmissivity was 2200 m^2/d, compared to 1000 m^2/d when the water table was below the fracture zone. Borehole logging work carried out by Birmingham University, WRc and BGS has demonstrated two other major fracture zones. The lower fracture zone is around 20 m below present average water levels and is probably contemporary with the buried channel system. The higher zone is 20–30 m above the zone of water table fluctuation and is probably of Hoxnian age; it has been removed by erosion in many of the dry valleys (University of Birmingham, 1985).

Foster (1974), proposed that in the outcrop area the aquifer approximates to a layered moderate T/low S_y unconfined system, made up of storage elements. The storage coefficient measured from a pumping test corresponds to that of the particular storage element being drained, unlike the transmissivity, which is a combination of the values from the individual elements. Thus a drop in the water table may not affect the measured storage coefficient as significantly as the transmissivity.

Foster suggested values of S_y for the storage elements of 0.010, 0.015 and 0.005 to 0.010, which were calculated from the recession of groundwater levels. Higher storage values are associated with the presence of Chalk Bearings at the top of the confined Chalk. Modelling results from Yorkshire (University of Birmingham 1985) confirm that the Chalk Bearings have a much higher storage coefficient than the unconfined Chalk (0.10–0.15), and that the presence of Chalk Bearings is a significant factor in the availability of water supplies.

4.5.3 North Lincolnshire

Geological and geographical setting

This is the area of Chalk between the Humber in the north and Louth in the south. The Chalk outcrops in the west, forming the Lincolnshire Wolds. To the east it becomes confined by glacial till. There is little surface drainage over the Wolds. The Waithe Beck flows eastward over the confining till to the North Sea; there is no hydraulic connection with the aquifer. In the northern Lincolnshire Chalk, groundwater flows from the unconfined aquifer to the confined aquifer, with some flow escaping as seasonal springs at the edge of the till, representing the overflow from the Chalk. The confined aquifer becomes artesian and springs occur through thin or permeable patches in the drift. These are locally known as 'blow wells'.

A number of public supply sources are located in the confined Chalk, as well as significant industrial abstractions. Large abstractions are taken from the Chalk in the coastal areas between Grimsby and Killingholme. As described above, the aquifer is over committed to abstraction and licences are controlled on a voluntary basis to prevent over-abstraction of the aquifer. Licensed abstraction is around 200 000 m^3/d.

Groundwater investigations

The northern Lincolnshire Chalk was extensively studied and modelled in the South Humberbank Salinity Research Project (University of Birmingham, 1978). This used hydrogeological, hydrochemical and geophysical studies to increase understanding of the aquifer and its management, in order to minimise saline intrusion from the Humber Estuary. Little resources work has been carried out as the over-commitment of the aquifer leaves no scope for development.

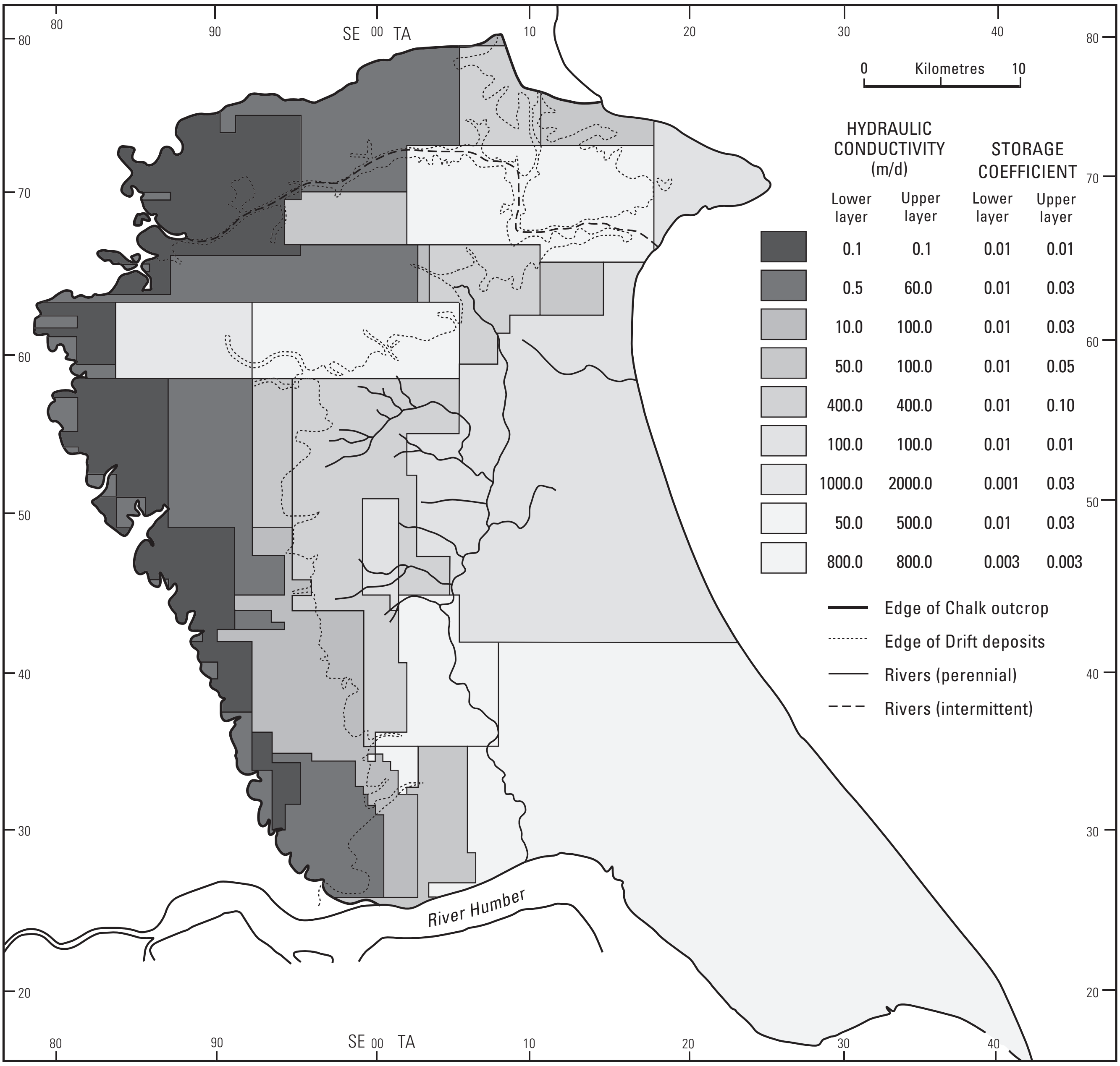


Figure 4.5.8 Modelled distribution of transmissivity and storage coefficients in the Yorkshire Chalk (after Aspinwall and Co. Ltd, 1995).

A study was carried out into the feasibility of a nuclear repository at Killingholme (Howard Humphreys & Partners, 1988). This involved a hydrogeological investigation, including geophysical logging and packer testing.

Aquifer properties

The data contains 16 pumping tests from 14 sites. Transmissivity values range from 60 m^2/d to over 1000 m^2/d; 25% of values are less than 1024 m^2/d and 75% are less than 6075 m^2/d (Figure 4.5.9). The geometric mean is 2347 m^2/d. Storage coefficients range from 2×10^{-6} to 0.056 (Figure 4.5.10), with a geometric mean of 2×10^{-4} and interquartile range of 3.5×10^{-5} to 1.5×10^{-3}.

The development of transmissivity of the Chalk has been influenced by many events such as marine transgression and glaciation, as well as by the inherent joint pattern in the rock. The South Humberbank Salinity Research Project (University of Birmingham, 1978) attempted to relate measured transmissivity with the surface drainage pattern during the Quaternary, which is likely to have influenced the development of fractures. No recognisable correlation was obtained; it is thought that there have been so many erosional events influencing the transmissivity distribution that no distinguishable pattern can be determined.

Borehole logs from the confined aquifer in north Lincolnshire give a clear indication that water flow through the Chalk is restricted in many places to the upper 30–40 m of the Chalk. The borehole log for Ciba Geigy No.1 [TA 2467 1156] borehole indicates major fracturing between 30 and 40 m depth. Logs also show that flow is often through one or two major fracture zones. Fractures may be present below 40 m but logs indicated that they contribute little flow. For example, the flow log for the former Lincoln River Division borehole at Kirmington [TA 1110 1120] showed that most of the water flowed from a major fracture at a depth of 33 m and other shallower fractures. Although a fracture was observed at 58 m there was little inflow measured at this depth. Hydrochemical data

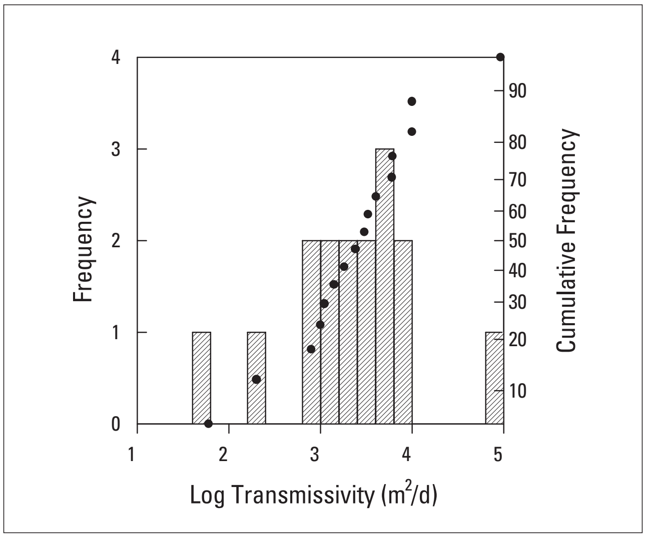


Figure 4.5.9 Distribution of transmissivity data from pumping tests in the Chalk of north Lincolnshire.

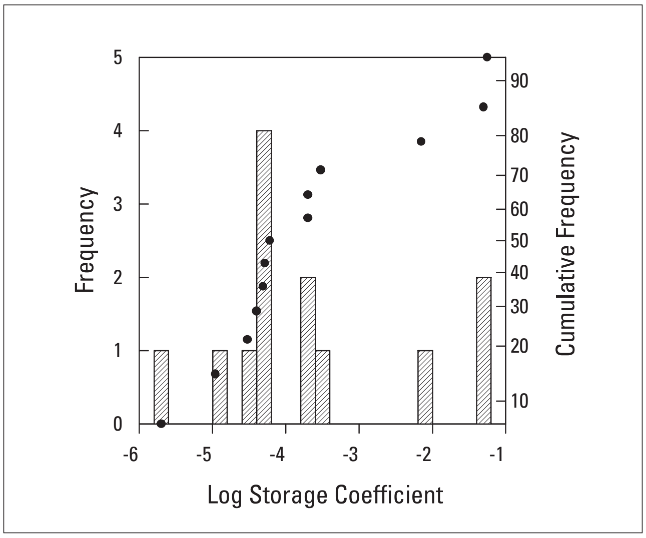


Figure 4.5.10 Distribution of storage coefficient data from pumping tests in the Chalk of north Lincolnshire.

from the South Humberbank Salinity Research Project also suggests a thin aquifer with tritiated water occurring at only shallow depths (up to 30 m deep) overlying non-tritiated waters.

As part of the South Humberbank Salinity Research Project, pumping tests were carried out in the gravel deposits at Laceby [TA 222 066] and Keelby [TA 158 111] in Lincolnshire, to assess the transmissivity and storage coefficient of these deposits. Values of around 1000 m^2/d for transmissivity, 5×10^{-5} for confined storage coefficient and 0.04 for unconfined storage coefficient were obtained. At Laceby, flow from the underlying Chalk was thought to contribute to the measured transmissivity.

The distributions of transmissivity and storage coefficient used in the model of the Chalk of north and south Lincolnshire (University of Birmingham, 1987) are shown in Figures 4.5.11 and 4.5.12.

There are few data for the unconfined Chalk of the Wolds, as most abstractions are taken from the confined Chalk.

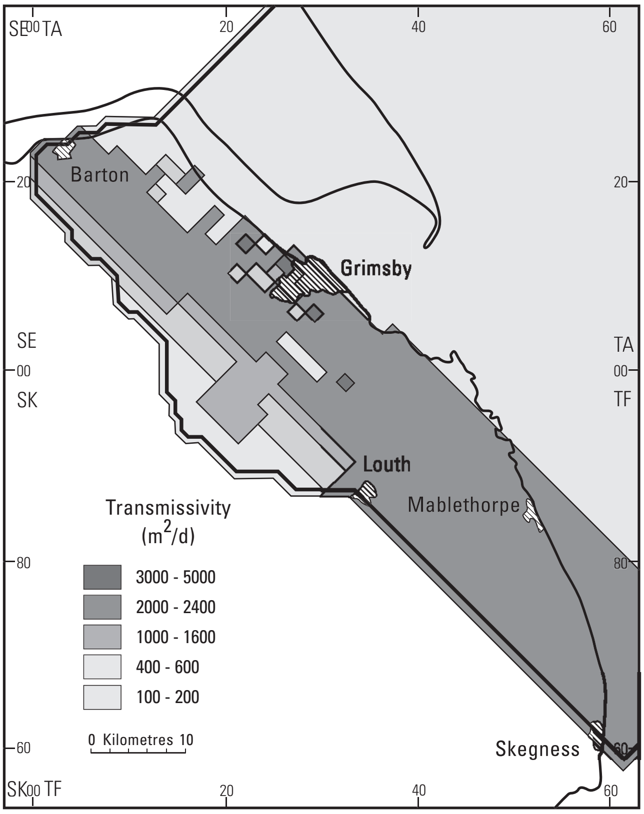


Figure 4.5.11 Modelled distribution of transmissivity in the Lincolnshire Chalk (after University of Birmingham, 1987).

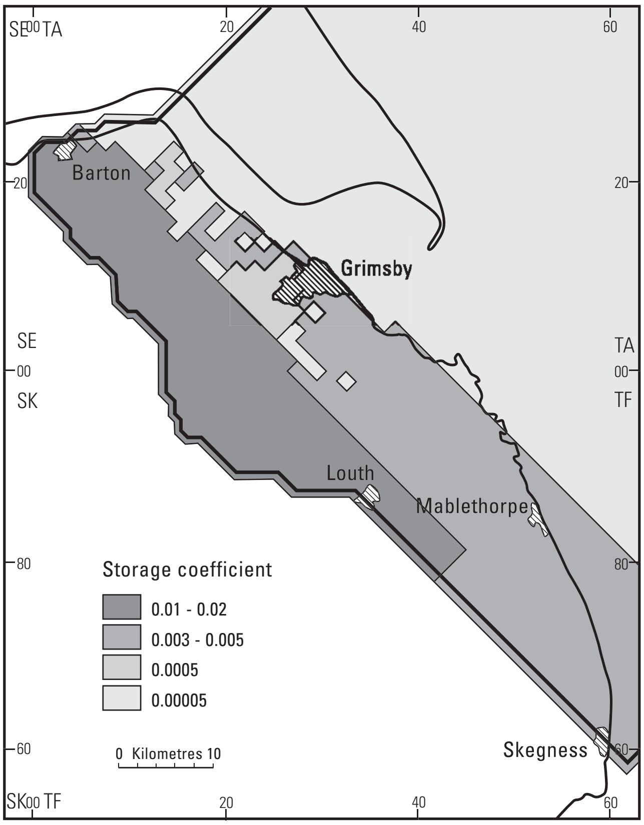


Figure 4.5.12 Modelled distribution of storage coefficients in the Lincolnshire Chalk (after University of Birmingham, 1987).

4.5.4 South Lincolnshire

Geological and geographical setting

The southern Chalk is the area south of Louth. Erosion of the Chalk has separated the Wolds outcrop in the west from the confined Chalk in the east and little recharge on the Wolds appears to reach the confined area. Erosion along a channel from Belleau to Driby has also resulted in isolation of the Chalk outcrop south of the channel.

In southern Lincolnshire the Chalk is completely eroded along the line of the buried cliff which restricts groundwater flow from west to east, and is thought to prevent most of recharge onto the Wolds from reaching the confined Chalk (Figure 4.5.4). Price (1957) suggested that permeable sands and gravels banked up against the Chalk at the base of the buried cliff are in hydraulic continuity with the Chalk, via the Carstone and Roach layers, and enable water from the Chalk catchment areas in the west to pass into the confined Chalk to the east. However, hydrochemical investigations and modelling by the University of Birmingham (1982) suggest that flow across the buried cliff is not more than 200 m^3/d. Instead, water escapes from the unconfined-confined boundary in a line of springs. The bulk of the flow in the confined aquifer is in the top 10 m of the Chalk and Chalk Bearings, and is thought to be recharged by flow from the north (University of Birmingham, 1982).

There is little surface drainage on the Wolds outcrop, but the River Lud and the Great Eau rise on clay covering the Chalk, and flow approximately north-east. Licensed abstraction from the southern Chalk is low: less than 10 000 m^3/d. All abstractions are taken from the confined aquifer. The aquifer is fully committed to licensed abstractions.

Groundwater investigations

The main study of the aquifer has been the Southern Chalk Hydrogeological Investigation (University of Birmingham, 1982). The model of the northern Chalk created as part of the South Humberbank Salinity Research Project was extended to include the southern Chalk (University of Birmingham, 1987).

Aquifer properties

The data contains 39 pumping tests at 38 sites. The majority of the data are taken from the Southern Chalk Hydrogeological Investigation (University of Birmingham, 1982). Transmissivity values range from 7 m^2/d to 4350 m^2/d (Figure 4.5.13). The geometric mean is 1376 m^2/d and the interquartile range is 848 m^2/d to 3012 m^2/d. Storage coefficients range from 1.1×10^{-5} to 2.5×10^{-3} (Figure 4.5.14) with a geometric mean of 1.5×10^{-4} and interquartile range of 6.1×10^{-5} to 2.7×10^{-3}.

The distributions of transmissivity and storage coefficient used in the model of the Chalk of north and south Lincolnshire (University of Birmingham, 1987) are shown in Figures 4.5.11 and 4.5.12. Low transmissivity Chalk is found in the south-west of the Lincolnshire Wolds. This is due to the low saturated thickness in the southern part of the Chalk.

The distribution of transmissivity values in the confined Chalk in southern Lincolnshire appears to reflect the effects of the sand, gravel and Chalk Bearings which overlie the Chalk. As noted in Section 4.5.2, Chalk Bearings may have some effect on aquifer properties. However, although they increase the transmissivity of the aquifer to a minor extent, they are unlikely to significantly affect aquifer storage. Sand and gravel deposits are likely to have a more important effect on the storage, especially in the region of the buried coastline. The Southern Chalk Hydrogeological Investigation (University of Birmingham, 1982) collated transmissivity values from a number of pumping tests. These show a range of values from 505 to 4350 m^2/d, with the lowest values occurring around Gayton-le-Marsh [TF 42 84], and the highest in the Saleby [TF 46 78], Bilsby [TF 47 76] and Thurlby [TF 49 75] areas (transmissivity of between 2000 and 4350 m^2/d).

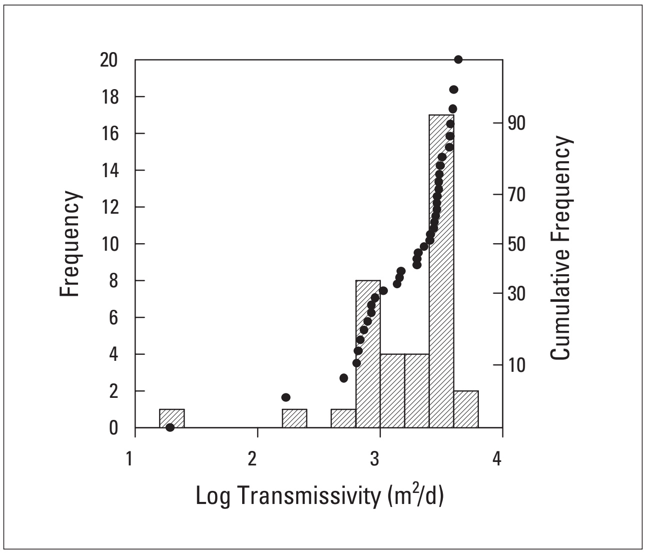


Figure 4.5.13 Distribution of transmissivity data from pumping tests in the Chalk of south Lincolnshire.

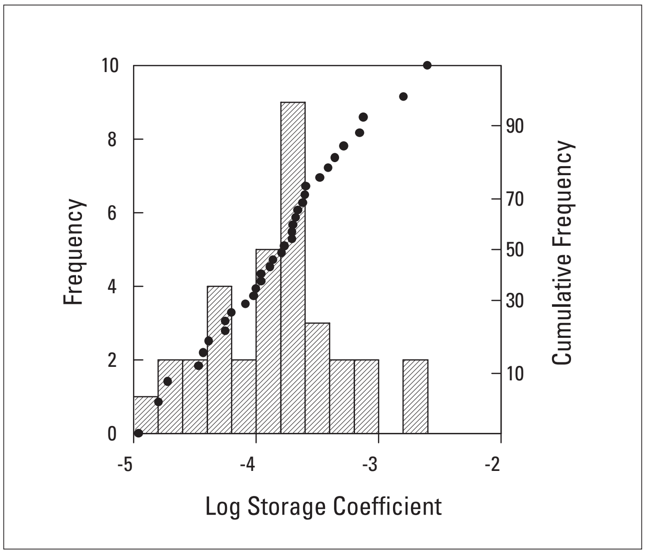


Figure 4.5.14 Distribution of storage coefficient data from pumping tests in the Chalk of south Lincolnshire.

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5 The Lower Greensand

5.1 INTRODUCTION

The Lower Greensand Group forms an important aquifer in the south-east of England. It is exploited to the north of London in Bedfordshire and Cambridgeshire, to the south of the London Basin around the Weald and also in the Isle of Wight and various other smaller outliers in southern England. Despite the small outcrop area of the aquifer, the high storage and generally good quality water render it a reliable source of water for many consumers in the south of England.

The Lower Greensand Group comprises a complex series of clays and sands, of varying degrees of cementation. A detailed treatise of the stratigraphy of the Lower Greensand Group was provided by Casey (1961) who defined the group as the sediments of Aptian and Lower Albian age underlying the Gault. The name 'Greensand' has long been acknowledged as a misnomer (the sediments are generally not green and not always sandy) but arose from confusion with the Upper Greensand in the early nineteenth century. However, by the time the stratigraphy was properly established the name had become so entrenched that it could not be changed.

The Lower Greensand Group was deposited in two main basins, Northern and Southern, separated by the London Platform. Each basin can be further subdivided into two provinces: Vectian and Wealden in the south; Lincolnshire–Norfolk and Cambridge–Bedford in the north (Figure 5.1.1). Between the various provinces the Lower Greensand Group varies significantly both in sedimentology and thickness. As a consequence the group is subdivided into different formations in each province (Table 5.1.1). The Lower Greensand Group is used extensively as an aquifer in only three of the provinces: the Vectian (Isle of Wight); Weald; and Cambridge–Bedford. To the north in Norfolk and Lincolnshire the Lower Greensand Group comprises a thin sandstone known as the Carstone Formation which is of little value as an aquifer and therefore not covered within this report.

This chapter is split into two sections, the first describing the Lower Greensand aquifer of the southern basin — the Weald and Vectian (Isle of Wight) — and the second the Lower Greensand aquifer of the Cambridge–Bedford province in the northern basin.

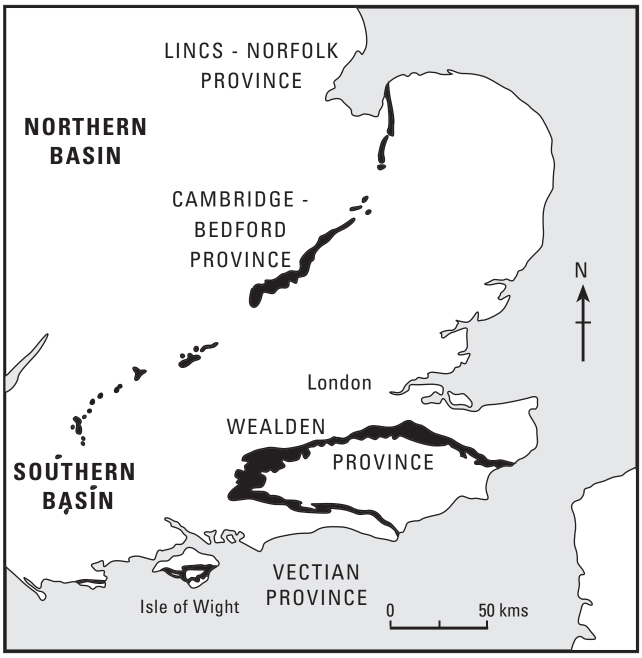

Figure 5.1.1 Distribution Lower Greensand Group (after Casey, 1961).

5.2 LOWER GREENSAND OF THE WEALD AND ISLE OF WIGHT

5.2.1 Introduction

Geological and geographical setting

The Lower Greensand Group of south-east England is exposed around the edges of the Wealden Anticline; erosion has resulted in the group being removed from the centre of the Anticline (Figure 5.1.1). Away from outcrop, the group thins to the north and has been proved to be absent under most of the London Basin, having been overstepped by the Gault (Figure 5.2.1). The narrower southern outcrop dips southward and again the group thins away from outcrop. The Lower Greensand Group gains its maximum thickness slightly down dip of the western outcrop (approximately 220 m), and thins eastward along both the northern and southern limbs.

At the time of deposition (Aptian and Lower Albian stages of the Lower Cretaceous) shallow marine and coastal environments persisted, giving rise to a complex series of clays and sands of varying degrees of cementation (Gallois,

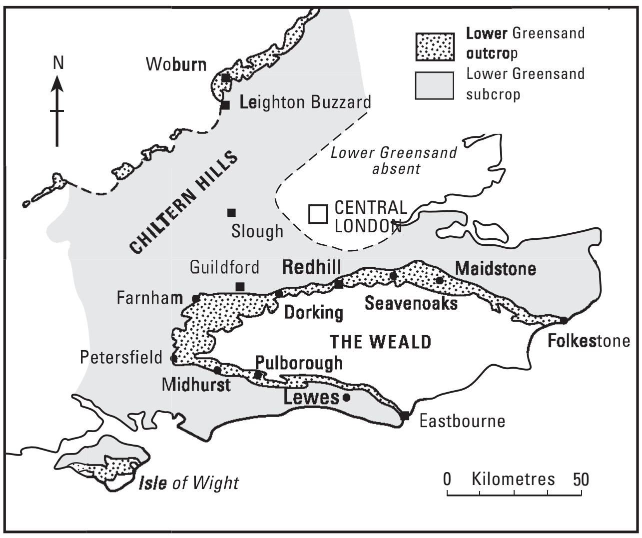

Figure 5.2.1 The extent of the Lower Greensand Group in southern England (after Egerton, 1994).

Table 5.1.1 Subdivision and correlation of English Albian and Aptian rocks (adapted from Rawson, 1992).

Stage	Weald	Isle of Wight	Bedfordshire/ Cambridgeshire	Lincolnshire/Norfolk
Upper Albian	U.G.S.	Upper Greensand Formation		Hunstanton Formation / Gault Formation
Middle Albian	Gault Formation	Gault Formation	Gault Formation	
Lower Albian		Carstone Formation		Carstone Formation
	Folkestone Formation	Sandrock Formation		
Upper Aptian	Sandgate Formation		Woburn Sands Formation	
	Hythe Formation	Ferruginous Sands Formation		
Lower Aptian	Atherfield Clay Formation	Atherfield Clay Formation		
Barremian	Weald Clay Formation	Vectis Formation		Roach Formation

1965; Casey, 1961). An outline of the geological succession of the Lower Cretaceous around the Weald is shown in Table 5.1.1. As a consequence of the varying conditions of sedimentation, the lithology of the four formations can change markedly from place to place. An important member of the Sandgate Formation, the Bargate Beds, is present only around the Godalming area. Away from outcrop the sequence becomes difficult to classify into the different formations.

The lowest formation within the Lower Greensand Group of the Weald is known as the *Atherfield Clay Formation*. It comprises brown and dark grey silty clays becoming more sandy in the upper parts beneath the Hythe Formation. The lower boundary with the Weald Clay is sharp and unconformable.

The *Hythe Formation* (previously known as the Hythe Beds) consists of fine-grained sands and sandstones, with sufficient quantities of the mineral glauconite to give them a green colour. At outcrop the colour of the sandstone changes, due to the weathering of the glauconite, to red and yellow iron-oxides. Detailed mineralogical investigations show the sandstone to consist of well-rounded to sub-rounded quartz grains in a micromass of quartz and clays (Morgan-Jones, 1985; Duff and Smith, 1992). The clays present are predominantly mica and smectite and constitute 5–10% of the sandstone. Towards the top of the formation impersistent beds of chert are found, the origin of which is uncertain (Middlemiss, 1975). At the base the clay content locally increases as the formation grades into the Atherfield Clay Formation.

In east Kent and westward towards Redhill in Surrey the formation consists of alternating layers of 'rag' and 'hassock'. The 'rag' (ragstone) consists of irregular bands of hard bluish grey sandy limestone 150–600 mm thick, which alternates with the 'hassock', grey loosely cemented calcareous argillaceous sandstone speckled with glauconite (Shephard-Thorn, et al., 1986). West of Redhill as the formation thickens (c 90 m) the Hythe Formation looses its calcareous component and constitutes loamy sands and sandstones. Southwards, through south Hampshire, the Hythe Formation becomes increasingly cemented and is difficult to distinguish in the Sussex area. In general, the Hythe Formation displays a greater degree of cementation in the upper strata.

The *Sandgate Formation* (previously known as the Sandgate Beds) consist of poorly sorted, limonitic and glauconitic sands and silts with some chert beds towards the base. The lithology varies considerably, locally comprising clays, muddy sandstones and some bands of weathered ironstone. In the southern outcrop, in Sussex and Hampshire a threefold sequence can be identified (Bristow, 1991): at the base of the Sandgate Formation a complex sequence of clays, silts and sands known as the Rogate Beds; then a sandstone called the Pulborough Sandrock; the youngest member is the Marehill Clay, a 10–12 m-thick clay layer. The three distinct layers give a unique signature easily identifiable on geophysical logs (Adams, M, personal communication). This sequence disappears, however, northward into Surrey, where the Marehill Clay becomes increasingly sandy. Fuller's earth deposits of economic value (montmorillonite clay) are found within the Sandgate Formation in the Redhill area. Eastward, towards Maidstone, the Sandgate Formation apparently thins to about 9 m, then thickens in East Kent where the formation is essentially made up of grey and green argillaceous silts and mudstones. The generally impermeable nature of the formation is illustrated by the poor drainage experienced at outcrop.

The Bargate Beds form part of the lower Sandgate Formation and are found only around Godalming (Surrey) as a distinctive mappable unit (Bristow [1991] includes Bargate stone in the Rogate Beds of the South Weald). They comprise grey sands and sandstones of variable grain size, characterised by large glauconite grains and reworked Jurassic fossils. Another distinguishing feature of the Bargate Beds is the presence of hard calcareous 'doggers' (known as the Bargate Stone) — the highest occurrence of these hard sandstone bands being taken as the top of the member.

The youngest formation within the Lower Greensand Group is known as the *Folkestone Formation* (previously known as the Folkestone Beds), consisting of poorly consolidated, cross-bedded quartz sand. The sands are thought to have been deposited in a shallow marine environment as mega-ripple structures or sand-wave complexes. Small bands of clay can be present, draped over ripple structures and in some cases even on individual foresets. In general the Folkestone Formation contains little clay — usually less than 2% of the total rock. The sands are characterised by rounded, well-sorted, medium-grained quartz grains with some secondary micro-quartz. Hard 'iron pan' deposits are common and also irregular ironstone veining, bearing little resemblance to the sedimentary structure. This is believed to be a result of the local re-precipitation of indigenous iron, initially dissolved by infiltrating rain. At outcrop the Folkestone Formation is often marked by barren heathland or woodland which reflects the good drainage.

In west Kent and Surrey the Folkestone Formation thickens and was subdivided through detailed study by Gossling (see Kirkaldy, 1947). One of the hydrogeologically significant subdivisions is a clay member, particularly well developed around Redhill in Surrey, which becomes increasingly silty towards the east. There is some doubt over the boundary between the Folkestone Formation and the Sandgate Formation in this area. It is possible that what has been taken to be the Folkestone Formation should be more correctly mapped as Sandgate Formation, especially where the Sandgate Formation has originally been mapped as a very thin unit. Interpretation of more recent data should help to clarify the stratigraphy (Shephard-Thorn et al., 1986).

In the Isle of Wight the Lower Greensand Group can be split into four formations. Maximum thickness (246 m) is obtained in the south of the Isle of Wight near to Atherfield, and the group thins to the north (61 m at the Dorset coast), east (183 m at the eastern edge of the island) and west (122 m at the western edge of the island). As in the Weald, the oldest formation in the Lower Greensand Group is the *Atherfield Clay*; this is followed by the *Ferruginous Sands* which comprise a succession of sands and clayey sands with iron, calcareous and phosphatic concretions. The *Sandrock Series* consists of coarse white and yellow sands and sandstones. The youngest formation, the *Carstone*, comprises gritty and pebbly sands with phosphatic nodules.

Groundwater investigations

There have been several investigations into the hydrogeology of the Lower Greensand Group of the Weald. In particular the recharge experiments at Hardham gave useful information on the hydraulic properties of the Folkestone Formation (Southern Water Authority, 1975; Ellison, 1973; Izatt et al., 1979; O'Shea, 1981). The recharge to the Lower Greensand Group in the London Basin has been subject to investigations at various times (Mather et al., 1973; Egerton, 1994). A review of the hydrogeology of the Lower Greensand Group was provided in an internal report by Southern Water Authority — this collates the knowledge and understanding of the aquifer at the time it was written (Izatt and Fox, 1981). The hydrogeochemistry of the aquifer has been described in a paper by Morgan-Jones (1985). A deep borehole was drilled through the Chalk into the Lower Greensand Group at Sompting in Sussex. This gave useful information on the nature of the aquifer in the confined zone downdip on the southern limb (Young and Monkhouse, 1980).

Currently, significant research is being carried out at Reading University in connection with Thames EA. This work is focusing on the western section of the Weald. Several investigatory boreholes have been drilled and the hydraulic and geophysical nature of the group is being reviewed giving more information about the behaviour of the aquifer.

In addition to the research projects mentioned above, several smaller investigations have been undertaken as part of MSc theses or on individual boreholes for licensing.

5.2.2 Aquifer properties

General statistics

Pumping test data exist at 40 locations for the Lower Greensand Group of south-east England. Each location has an estimate of transmissivity but only 27 provide estimates of the storage coefficient. To understand and describe trends in the data it is important to identify which formation within the Lower Greensand Group is being tested at each site. Unfortunately, this information has not always been readily available, therefore it is possible that significant changes in aquifer properties are not highlighted by the data. Another difficulty is the poor quality of some of the pumping tests. For large sections of the aquifer there might only be one data point and if it is of dubious quality, then the description of the aquifer properties for a large area might appear anomalous.

Using all the data for the Lower Greensand Group (one value per site), transmissivity values range from about 33 to 3400 m^2/d with the geometric mean and median both 270 m^2/d (Figure 5.2.2). The 25 and 75 percentiles are 140 and 500 m^2/d respectively. Estimates of the storage coefficient vary from 10^{-5} to 0.08 with a geometric mean and median equal to 6×10^{-4} (Figure 5.2.3). Only a weak relation exists between the logarithms of transmissivity and specific capacity (Figure 5.2.4).

Core data

There are limited core data available for the Lower Greensand Group since the friable nature of the sandstones make it difficult to recover core samples. Data that do exist come from tests carried out on both outcrop and borehole material and tend to be of poor quality. Histograms of hydraulic conductivity and porosity data are shown on Figures 5.2.5 and 5.2.6. Information on the particular Lower Greensand formation penetrated was not universally available, therefore the data could not be differentiated into the two aquifers, Hythe and Folkestone. There was sufficient stratigraphical information, however, to split the data into Folkestone Formation and undifferentiated Lower Greensand Group, although the data were too few to enable separate statistics to be generated. Some samples within the

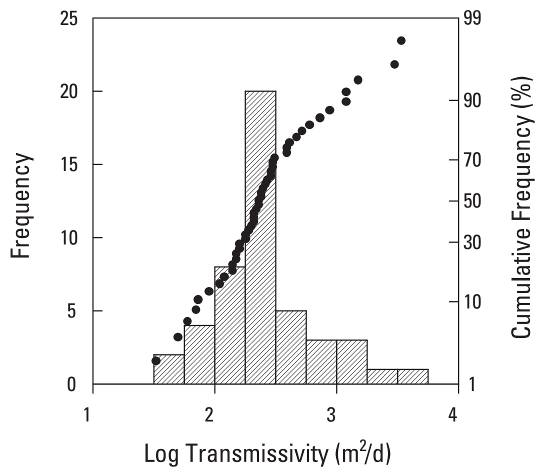

Figure 5.2.2 Distribution of transmissivity data from pumping tests in the Lower Greensand Group of southern England.

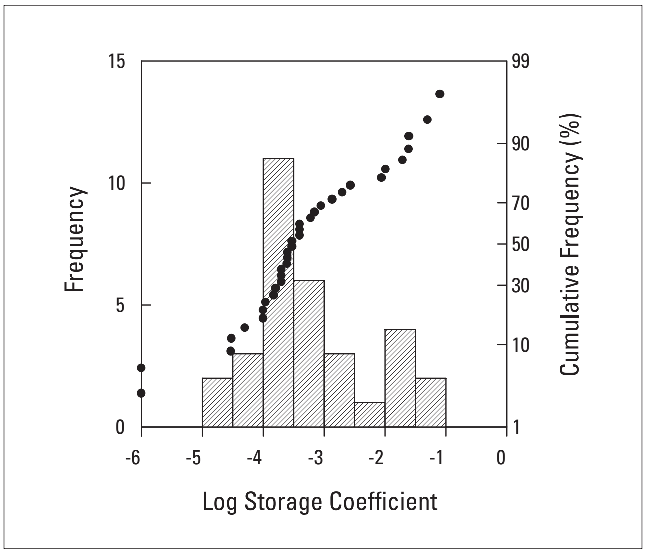

Figure 5.2.3 Distribution of storage coefficient data from pumping test in the Lower Greensand Group of southern England.

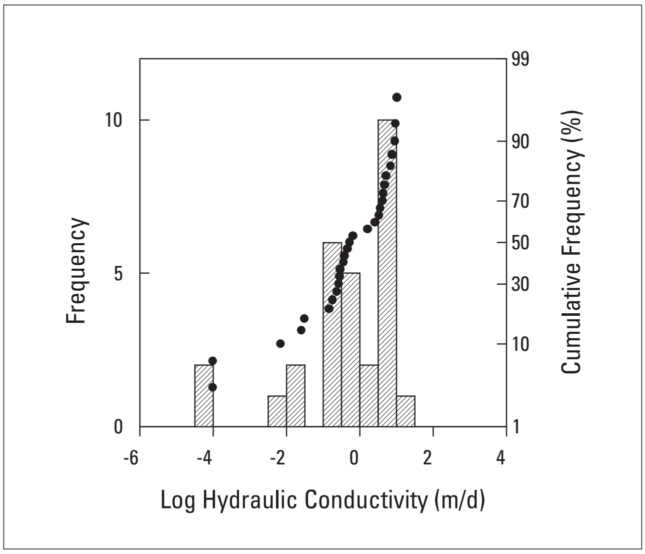

Figure 5.2.5 Distribution of hydraulic conductivity data from Lower Greensand Group samples from south-east England.

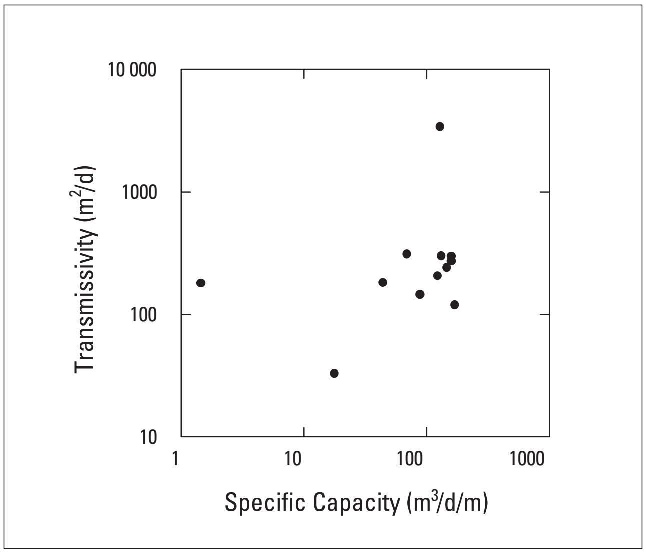

Figure 5.2.4 Plot of transmissivity against specific capacity (uncorrected) for the Lower Greensand Group of southern England.

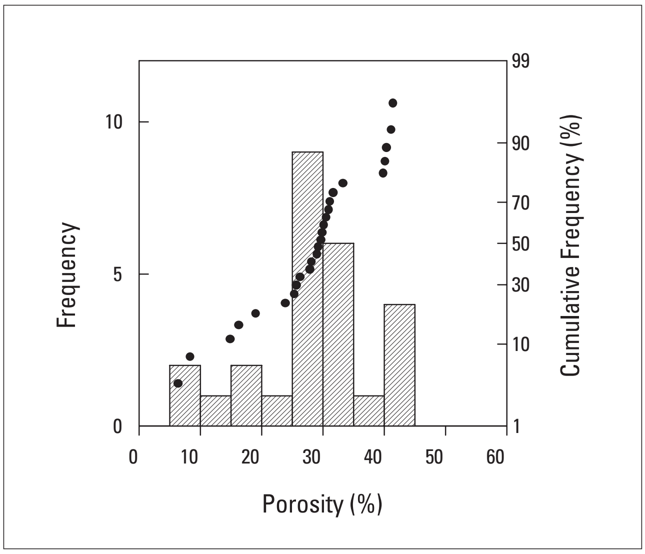

Figure 5.2.6 Distribution of porosity data for Lower Greensand Group samples from south-east England.

database specifically referred to as 'Atherfield Clay' were excluded from the analysis.

The hydraulic conductivity data varied from 10^{-4} to 10 m/d with a geometric mean of 0.46 m/d and median 0.53 m/d (29 samples). Data within the interquartile range varied from 0.21 to 4.6 m/d. Porosity data (26 samples) range from 6 to 41% with a mean of 28%, median of 29.5% and in interquartile range varying from 25 to 32%. There appeared to be some correlation between hydraulic conductivity and porosity (Figure 5.2.7). Samples with low porosity, especially within the Folkestone Formation are probably representative of ironstone layers which have low permeability and might therefore impede groundwater flow. The majority of the Folkestone Formation data, however, are clustered around high porosity and hydraulic conductivity — about 70% of the data have porosity greater that 25% and hydraulic conductivity between 1 and 10 m/d. Undifferentiated Lower Greensand Group samples illustrate poorer core properties.

The above observations from this limited available data set are, in general, consistent with other studies in the Lower Greensand Group. From grain size analysis, hydraulic conductivities for the Folkestone Formation of between 5–20 m/d have been suggested by M Adams (personal communication). Izatt and Fox (1981) report constant head tests carried out on reconstituted samples taken from Hardham. Hydraulic conductivity was found to vary from 3 to 60 m/d, the mean of which, 27 m/d they state as being very close to the value gained using the Hazen formula on grain size analysis. They quoted values of 12–40 m/d as typical. The core data above gives slightly lower values of hydraulic conductivity. The small difference could be explained by a natural selection of consolidated samples by coring and the increase in permeability gained by reconstituting samples.

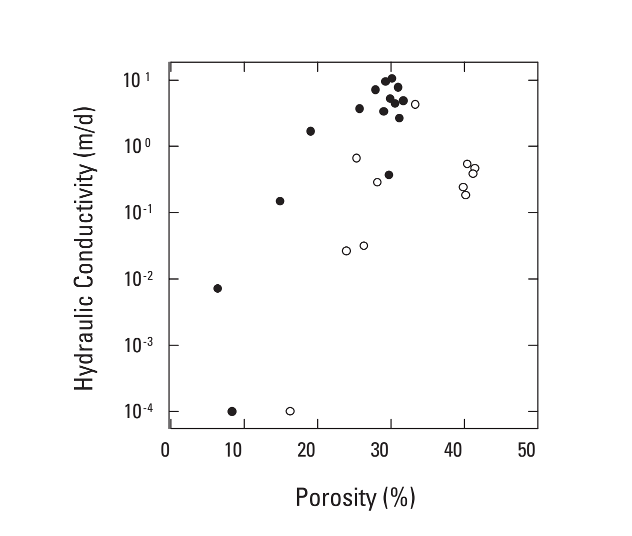

Figure 5.2.7 Plot of hydraulic conductivity against porosity for Lower Greensand Group samples from south-east England. Solid circles are data for the Folkstone Formation, open circles are undifferentiated Lower Greensand.

Porosity values from Hardham are quoted by Izatt and Fox (1981) as varying from 30 to 43% except for ironstone layers that had porosity of 7–15%. This agrees broadly with the core data above.

Core data for the Hythe Formation have been reported for one site, Haslingbourne Pumping Station (Izatt and Fox, 1981). Here the porosity measured in the friable sections of the aquifer ranged from 20 to 30%, while in the more consolidated bands porosity was generally less than 10%. Hydraulic conductivity measurements varied from 0.2 to 1.3 m/d and were generally less than 0.5 m/d.

The vertical hydraulic pattern of the Lower Greensand Group of south-east England

The Lower Greensand Group does not behave as one distinct aquifer unit, rather it can generally be split into two distinct aquifers. This split was first observed in the nineteenth century, when it was noted that the Folkestone and Hythe Formations comprised two different aquifers separated by the clay and silt layers of the Sandgate Formation. Other work has substantiated this claim: the piezometric surfaces of the Folkestone and Hythe Formations rarely coincide (Morgan-Jones, 1985); Carbon-14 and tritium dating suggest that groundwater within the two aquifers are generally of different ages with only a little mixing (Mather et al., 1973). Recent drilling, however, has indicated that the Sandgate Formation is often leaky and that the two aquifers could be hydraulically continuous in many places (Adams, M, personal communication).

The lower aquifer within the Lower Greensand Group is the Hythe Formation. There is some evidence that the formation is most permeable towards the top, possibly due to a general fining downwards as it grades into the Atherfield Clay Formation or a decrease in fracturing towards the base (Adams, M, personal communication). The Bargate Beds where present above do not act in a hydrogeologically consistent manner: in many places they can be considered an aquifer (for example at Greatham Pumping station [SU 77 30] where they contribute half the pumping station's supply), and in others are included in the Sandgate Formation as an aquitard. Where permeable, they are continuous with the Hythe Formation, therefore forming part of the lower aquifer.

The Sandgate Formation above the Hythe Formation forms an important aquitard. The clays and silts of the Rogate Beds at the base are generally of poor permeability and therefore impede the circulation of groundwater between the Hythe Formation and the overlying Folkestone Formation. However, the clay layers are rarely persistent, allowing a certain degree of mixing. Where the Sandgate Formation thins to the east its role as an aquitard is more difficult to assess. The Fuller's earth deposits around Redhill may provide a good barrier to vertical groundwater flow. Extensive excavation work, to extract the Fuller's earth, however, has severely altered the groundwater regime rendering the hydrogeology much more complex. The younger, more permeable members of the Sandgate Formation, for example the Pulborough Rock, can locally be important as aquifers. Where the overlying Marehill Clay is absent these small aquifers can be in direct continuity with the Folkestone Formation, forming part of the upper aquifer. Towards the east it can be quite difficult to distinguish stratigraphically between the Folkestone Formation and Sandgate Formation, therefore, the aquifer often ascribed to the Folkestone Formation, might have significant contribution from the Sandgate Formation.

The Folkestone Formation is generally homogeneous with high permeability throughout its thickness. Small ironstone layers might locally stratify groundwater flow but are not significant for regional groundwater flow (Izatt and Fox, 1981; MacDonald, 1992). A clay layer within the Redhill area is of much more significance, possibly splitting the aquifer into two. The extensive excavations within the Folkestone Formation for sand and gravel and through the Folkestone Formation to the Fuller's earth will again have complicated the hydrogeology. Away from outcrop, the Lower Greensand Group generally behaves as one aquifer unit as the sandstones becomes less differentiated.

In summary, the Folkestone and Hythe Formations can be considered as the major aquifers within the Lower Greensand Group of the Weald. The Sandgate Formation which separates them forms an inconsistent aquitard. Where present, the Bargate Beds can be included in the Hythe aquifer, and where the Marehill Clay is absent and the permeable layers of the Sandgate Formation are in continuity with the overlying Folkestone Formation, the younger parts of the Sandgate Formation can be included in the Folkestone aquifer. At depth, away from outcrop, where the Lower Greensand Group is undifferentiated, the sequence is believed to act as one aquifer.

Thickness of the Lower Greensand Group

The Lower Greensand Group gains its maximum thickness (about 220 m) just west of the western outcrop in the Weald. Along both the northern and southern limbs the group thins to the east becoming only a few metres thick near to the coast at Eastbourne and Folkestone. In addition the group thins away from outcrop: beneath Central London the Lower Greensand Group is absent being overstepped by the Gault. There is significant thickening, however, around Slough where the thickness of the Lower Greensand Group increases to about 80 m (Egerton, 1994).

The Hythe Formation achieves its maximum thickness of about 90 m near Farnham, thinning eastward along the northern limb to Maidstone (about 30 m) reaching about 9 m at Hythe (Figure 5.2.8). Along the southern limb the

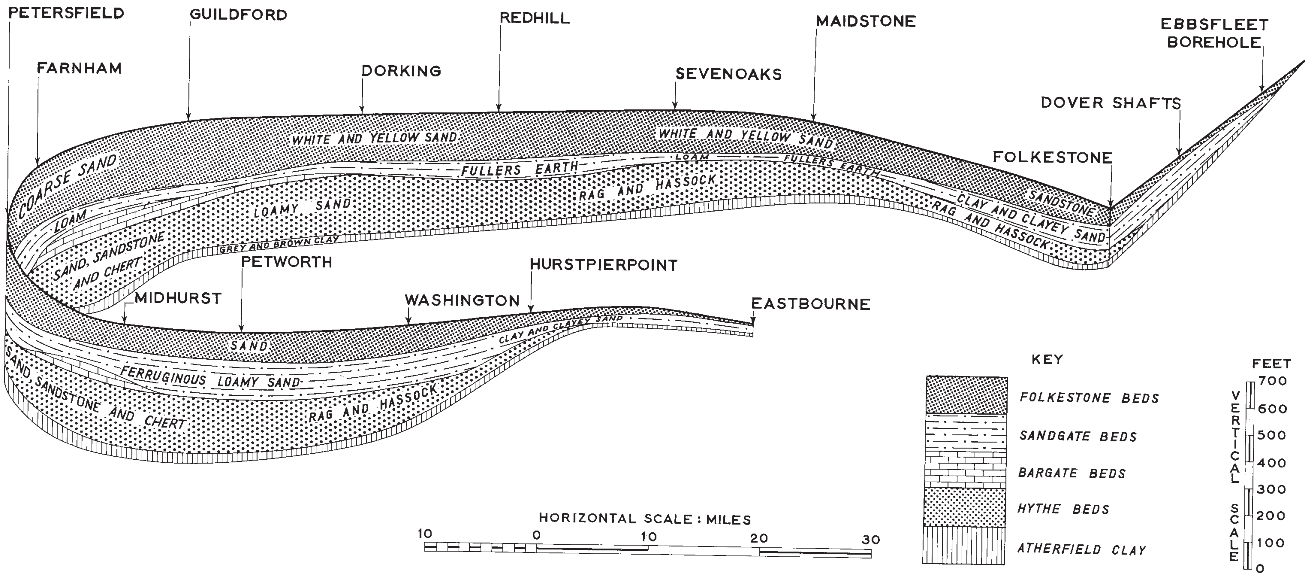

Figure 5.2.8 Ribbon diagram illustrating the lithological variations of the Lower Greensand Group of the Weald (from Gallois, 1965).

beds have been proved to be 90 m in Petersfield, then thin to about 60 m at Midhurst and continue to thin eastward towards Ripe (Young and Lake, 1988).

The Sandgate Formation is highly variable in thickness. At Sandgate the formation is 24 m thick and thins westward to the Maidstone area where apparently it is only 9 m thick. The formation thickens again to the west, becoming 24 m again around Redhill. Towards Petersfield the Sandgate Formation reaches its maximum thickness of about 50 m. Current research, however, is providing information that will probably revise the old estimates of the thickness of the Sandgate Formation, particularly as the boundary between the Folkestone Formation and the Sandgate Formation is more clearly defined (Adams, M, personal communication).

The Folkestone Formation follows the same general pattern as the Hythe Formation: thickest at Farnham (80 m), thinning along the northern limb to Redhill (55 m) and Maidstone (45 m) and thence to Folkestone (20 m). Along the southern limb the Folkestone Formation is about 60 m thick at Petersfield. 38 m at Washington. thinning to less than 3 m at Eastbourne (Gallois, 1965; Shephard-Thorn et al., 1986; Young and Lake, 1988).

In the Isle of Wight, the Lower Greensand Group is thickest to the south of the island at Atherfield where it gains a thickness of 246 m. The Ferruginous Sands vary from about 80 to 152 m, the Carstone Formation from 6 to 24 m and the Sandrock from 25 to 56 m.

Areal distribution of aquifer parameters

The Hythe Formation aquifer

The aquifer properties of the Hythe Formation aquifer are largely controlled by the cementation of the sands and sandstones within the formation. In well-consolidated areas, the groundwater flow is primarily through fractures, while in areas where cementation is poor flow is generally intergranular. Transmissivity in fractured areas tends to be high, but unpredictable, whereas where intergranular flow dominates, transmissivity values tend to be moderate and change little. Available pumping test data show little correlation between the thickness of the Hythe Formation and the transmissivity of the aquifer (Figure 5.2.9). The often highly fractured nature of the Bargate Beds can enhance the transmissivity of the Hythe Formation aquifer where present.

The geometric mean of all the data values for the Hythe aquifer is 310 m^2/d with a range of 140–1500 m^2/d. Regional variations in the data may be summarised as follows:

- transmissivity values in the southern province tend to be quite high, about 1000 m^2/d
- northwards, towards Guildford the transmissivity reduces to about 200 m^2/d
- virtually no pumping test data exist for the Hythe Formation in the northern limb east of Redhill or away from outcrop.

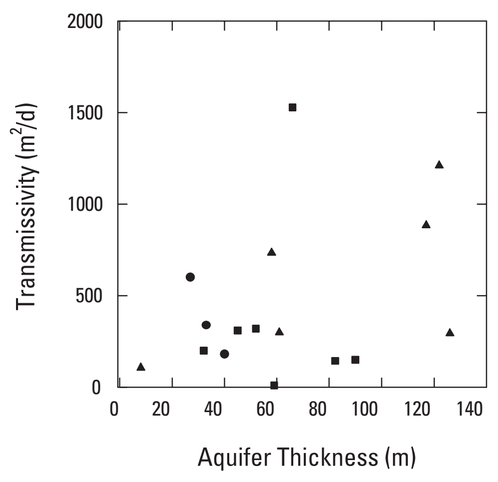

Figure 5.2.9 Plot of transmissivity against aquifer thickness for the Lower Greensand Group.

Key: Folkestone Formation ●, Hythe Formation ■ and Undifferentiated Lower Greensand ▲.

In Kent, the Hythe Formation is rarely exploited on its own, rather, boreholes generally penetrate both the Folkestone and the Hythe formations. The lack of abstraction boreholes and pumping tests does not, however indicate poor aquifer properties. In recent modelling work carried out by Mid Kent Water plc, regional transmissivity values of 300–700 m^2/d were used to model a small area of the Hythe Formation (approximately 30 m thick); these values are not necessarily representative throughout the region as aquifer properties can vary considerably (Irving, K, personal communication). Groundwater flow is primarily through fractures within the calcareously cemented ragstone beds.

In the north-west corner of the Weald, south of Guildford, the transmissivity appears to be quite consistent, averaging around 200 m^2/d. The more consistent but lower transmissivity is probably a result of the decreasing cementation of the sandstones; the poorly consolidated sands and silts have few fractures, therefore groundwater flow is primarily intergranular. The high silt and clay content within the Hythe Formation gives quite a low intergranular permeability, therefore even with a thickness of up to 80 m, transmissivity remains low. Flow logs imply generally uniform flow of groundwater into boreholes.

The Bargate Beds contribute to the transmissivity of the Hythe Formation aquifer in the western part of the Weald. These consolidated beds are often well fractured and can provide a significant proportion of borehole yield. For example at Greatham Pumping Station [SU 77 30] downhole flow measurements indicated that about half of the flow was derived from hard bands within the Bargate Beds with 17% of the flow coming from one fracture (Izatt and Fox, 1981).

In the southern limb towards Midhurst and Petersfield, the transmissivity of the Hythe Formation is quite high. Available pumping test data give values ranging from 150 to 3000 m^2/d, more usually around 1000 m^2/d. The high transmissivity is thought to be caused by the increasing dominance of fracture flow as the sandstones are more cemented. At Haslingbourne Pumping Station in the southern province, a small diameter borehole was cored in 1977 (Izatt and Fox, 1981). Laboratory measurements of hydraulic conductivity were low, generally less than 0.5 m/d, although core samples incorporating small iron-stained fractures had higher hydraulic conductivity (e.g. 1.3 m/d). Integrating the core permeability over the aquifer thickness yielded a transmissivity value of only 9 m^2/d. A pumping test at the same site gave a transmissivity value of 150 m^2/d, thus illustrating the importance of fracture flow at Haslingbourne.

Away from outcrop the Hythe Formation thins. As a consequence, transmissivity values reduce as the aquifer becomes increasingly confined.

Insufficient data exist to allow a description of the regional variations in storativity. Two estimates exist for the unconfined section of the aquifer, 0.009 and 0.026. The four estimates in the confined section were quite consistent, varying from 2×10^{-4} to 6×10^{-4}. As with transmissivity it is likely that the storativity of the Hythe Formation aquifer will vary with the degree of cementation. Where the sandstones are well consolidated and fractured, groundwater storage will largely be within the fractures, with slow seepage from the pores. The storage coefficient will therefore be low. Where groundwater flow is intergranular, the pore water will probably be more accessible and storage correspondingly high.

The Folkestone Formation aquifer

The Folkestone Formation is commonly regarded as one of the few UK aquifers that exhibits homogeneous, intergranular flow — however, at a local level, groundwater flow is more complex. Some iron-staining has been observed within small fractures on quarry walls (Izatt and Fox, 1981) implying that at some time groundwater flow was channelled through the fractures. Hard ironstone layers are also locally important. Ironstone hardbands have low porosity and permeability, and therefore act as aquitards, effectively stratifying groundwater flow within the aquifer (Izatt and Fox, 1981; MacDonald, 1992). These layers are not laterally extensive and are therefore only of importance at a local level. More significant is the presence of a persistent clay layer within the Folkestone Formation around Leatherhead — the clay effectively splits the aquifer into two.

Little pumping test information is available for the Folkestone Formation and what exists is mainly from the northern limb. From the limited pumping test data, transmissivity varies from about 150 to 1200 m^2/d with a geometric mean of 260 m^2/d. Higher values of transmissivity are generally found where the aquifer is thicker, for example in the north-west of the Weald. As the lithology of the Folkestone Formation does not vary much and regional flow is generally intergranular, the permeability of the aquifer is fairly constant. Thames Environment Agency and Mid Kent Water both model the aquifer as having constant permeability with changes in transmissivity arising from changes in aquifer thickness. Hydraulic conductivity is often taken as varying from 5–20 m/d (see above), therefore with an average hydraulic conductivity of about 10 m/d and aquifer thickness varying between 10 and 80 m transmissivity values consistent with those recorded would be expected. It is consistent therefore to assume the aquifer is *intergranular*. The transmissivity data however, does not give a convincing relation between recorded aquifer thickness and measured transmissivity (Figure 5.2.9) — this could be attributed to the poor quality and unreliability of both the lithological and transmissivity data.

Assuming intergranular flow and consistent lithology, the transmissivity should be highest around Farnham where the aquifer is 80 m thick, reducing to the east and south as the aquifer thins. More pumping tests and core analysis need to be undertaken before the mechanisms of groundwater flow and the transmissivity distribution are fully understood. The core data illustrated a direct relation between porosity and hydraulic conductivity. It appears that the well cemented iron-stone layers have low permeability and therefore could be important at a local level for impeding groundwater flow or contaminant movement. The extent and importance of these layers, however, is not well known or understood and like the rest of the aquifer requires further study.

No storage coefficient data exist for the unconfined Folkestone Formation aquifer, but an average value of 0.2 was taken for the unconfined aquifer by Izatt and Fox (1981) in their regional description of the Lower Greensand. Confined storage coefficients of about 10^{-3}–10^{-4} were observed in the northern limb, and a value of 0.02 was recorded at Hardham.

Deeply confined Lower Greensand

Away from outcrop, the distinction between the various formations below the Folkestone Beds tend to disappear leaving this part of the Lower Greensand Group undifferentiated. The Lower Greensand Group generally thins away from outcrop and becomes less significant as an aquifer — especially when it underlies the Chalk (Figure 5.2.10). The only place where the deeply confined aquifer has been exploited to any significant degree is beneath Slough where it thickens.

Some data exist for the deeply confined Lower Greensand aquifer at Sompting [TQ 166 064] Kingston [TQ 100 700] and Slough [SU 948 122]. Beneath the Chalk at Sompting, the aquifer properties were quite poor — transmissivity was 70 m^2/d. Likewise at Chatham, downdip of the northern outcrop a pumping test recorded the transmissivity reducing to about 60 m^2/d and a storage coefficient of 4×10^{-5}: the reduction in transmissivity can be attributed to the declining thickness of the Lower Greensand. To the north, below the London Basin transmissivity reduced to about 150 m^2/d at Kingston but then increased to around 700 m^2/d at Slough. The aquifer thickens at Slough to about 80 m, therefore it is feasible that the flow is intergranular and the increased transmissivity accounted by the increased thickness; alternatively fracture flow might occur. The storage coefficient was measured at three sites in the London Basin, each test giving a value of about 0.001.

The Isle of Wight

The lithology of the Lower Greensand Group in the Isle of Wight varies greatly from clays and silts to limonitic and glauconitic sands and sometimes pebble beds. Aquifer properties data are limited and unpredictable.

There are four pumping tests available for the Lower Greensand aquifer within the Isle of Wight. they indicate transmissivity values varying from 30 to over 4000 m^2/d with a geometric mean of 220 m^2/d. There are three values of storage coefficient ranging from 4×10^{-4} to 0.03.

Summary

Several trends have been identified from the aquifer properties data of the Lower Greensand aquifer of south-east England.

- at or near to outcrop the Lower Greensand Group can be split into two main aquifers, the Folkestone and the Hythe formations
- aquifer properties data are limited and of variable quality
- aquifer properties generally decrease as the Lower Greensand Group thins towards the eastern edge of the north and south limbs

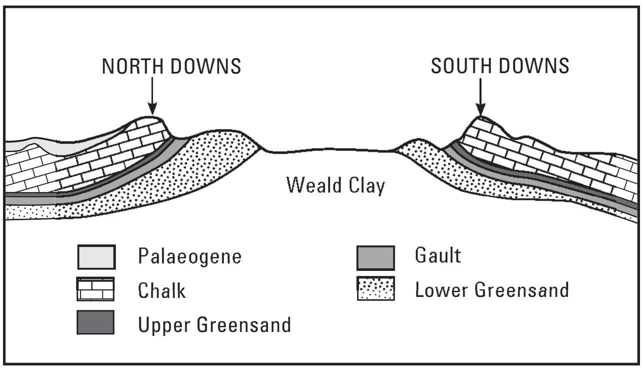

Figure 5.2.10 Schematic representation of the Lower Greensand Group of the Weald dipping away from outcrop.

- aquifer properties decrease away from outcrop with the exception of Slough where the Lower Greensand Group thickens
- the Folkestone Formation aquifer can include the upper sections of the Sandgate Formation where more permeable
- intergranular flow is dominant in the Folkestone Formation ranging from 5–20 m/d although ironstone hardbands can locally impede groundwater movement
- the transmissivity of the Folkestone Formation is generally poorer in the confined section on the northern limb than the unconfined area near Leatherhead or the confined zone at Hardham on the southern limb — this can be attributed to varying thickness
- the Hythe Formation aquifer can include the Bargate Beds where present
- intergranular flow through less consolidated layers is probably more dominant in the west with fracture flow dominant in the east and south, and locally elsewhere where the Hythe Formation is better cemented
- the transmissivity of the Hythe Formation is highest in the south-west where fracture flow dominates and the aquifer is of moderate thickness — transmissivity reduces to the north as intergranular flow dominates, and to the east as the aquifer thins
- the aquifer properties data of the Lower Greensand Group in the Isle of Wight are extremely variable

5.3 THE LOWER GREENSAND OF THE BEDFORD/CAMBRIDGE REGION (WOBURN SANDS AQUIFER)

5.3.1 Introduction

Geographical and geological setting

The outcrop of the Lower Greensand Group in the Cambridge–Bedfordshire region extends from Leighton Buzzard to north of Cambridge near Ely (Figure 5.3.1). The aquifer is important for water supply both at outcrop and also in the confined zone to the east of the outcrop to a distance of about 15 km. In the south-east of the region the Lower Greensand outcrop forms a broad ridge reaching a maximum height of about 200 m; this ridge continues north-eastward but becomes less prominent eventually disappearing north of Cambridge. The River Ousel and the River Ivel cross the outcrop flowing northward into the River Great Ouse. A series of small streams which flow into the Ousel, Ivel or directly into the Great Ouse drain the outcrop; north-east of Biggleswade the outcrop is drained by small tributaries of the River Cam. Due to the permeable nature of the Lower Greensand aquifer, surface drainage on the outcrop is generally uncommon apart from where it is covered by impermeable drift.

In Bedfordshire and Cambridgeshire, the Lower Greensand Group comprise a series of sandy marine sediments, known as the *Woburn Sands Formation* (Table 5.1.1), which were laid down in a basin bounded by the East Anglian Massif (Duff and Smith, 1992). The Woburn Sands rest on an eroded and irregular surface comprising Upper Jurassic strata. In many areas the formation is less than 60 m thick, although as a result of the irregular base, the formation varies considerably in thickness over relatively short distances. The greatest thickness proved is

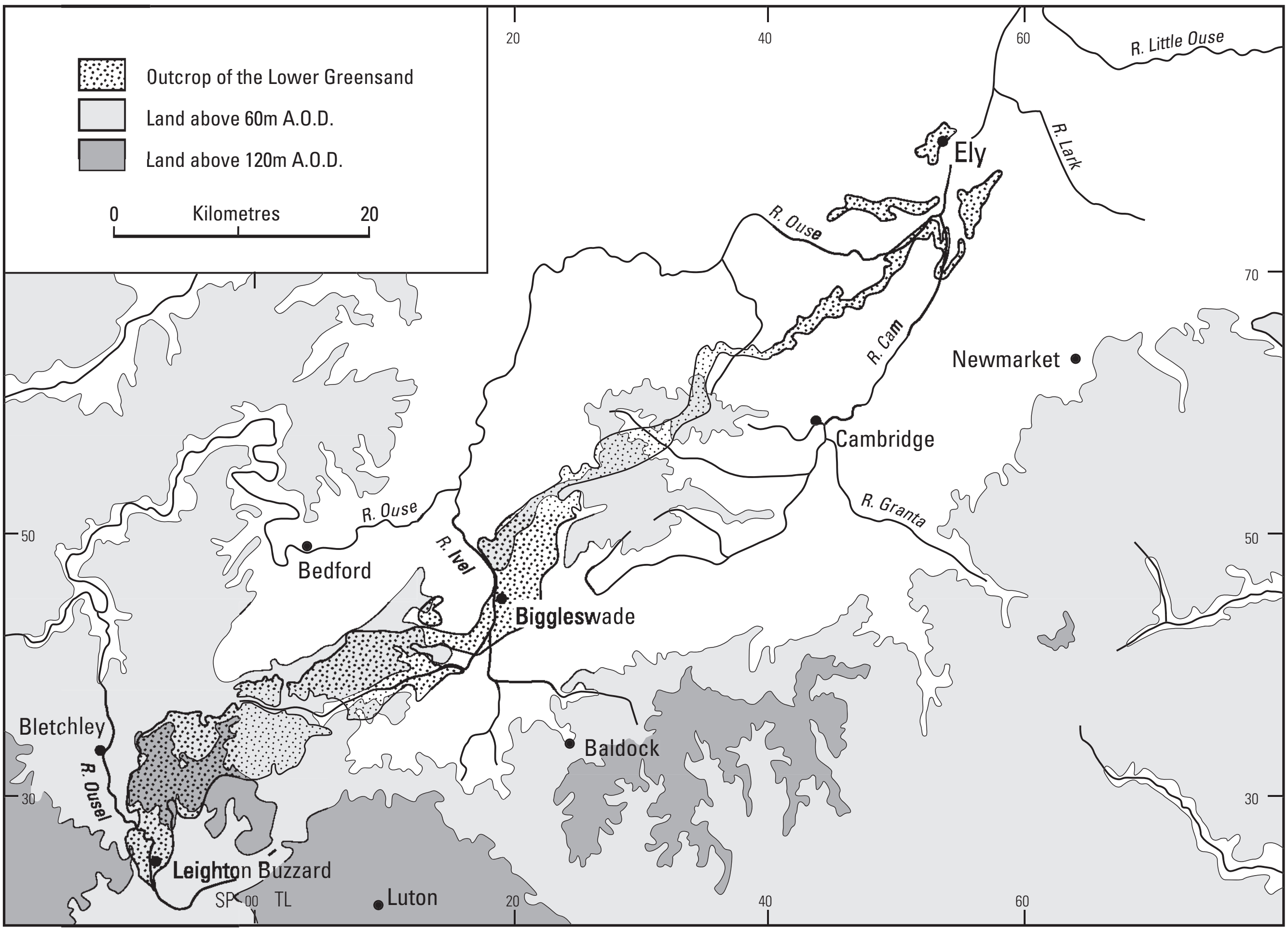

Figure 5.3.1 Location map for the Lower Greensand Group in the Bedford–Cambridge region (after Monkhouse, 1974).

89 m at the BGS Potsgrove Borehole [SP 9411 3096] to the south-west of Woburn, although nearby the formation may be more than 120 m thick. There are several outliers around Ely.

The sediments that comprise the Woburn Sands Formation are generally coarse-grained quartzose sands with large-scale cross-bedding (Duff and Smith, 1992; Shephard-Thorn et al., 1994). In general the sands become increasingly cemented towards the top. Locally the uppermost beds are sufficiently indurated to be used as building stone known as 'sandrock'. Four different lithological units have been identified in sand pits in the Leighton Buzzard area. These are, from base to top: 'Brown Sands', 'Silver Sands', 'Silty Beds' and 'Red Sands'. The lateral variation in the Woburn Sands is such that it is unlikely that these units could be traced for more than a few kilometres. However, the distinction was found useful by Shephard-Thorn et al. (1994) in giving a general description of the sediments.

The 'Brown Sands' comprise 45 m of ferruginous fine- to medium-grained, cross-bedded quartz sands with glauconite (Shephard-Thorn et al., 1994). Irregular sheets of 'iron pan' are common. A bed of sandy, pebbly clay separates the 'Brown Sands' from the overlying 'Silver Sands'. The 'Silver Sands' comprise 6–15 m of white, pebbly, well-sorted and well-rounded, medium- to coarse-grained quartz sands with very little fine material. 'Carstone Reefs' are observed in some places. These are sandstone lenses with ferruginous cement which may be 2–3 m high and 10–25 m wide. The 'Silty Beds' are present locally and can be up to 4.5 m thick comprising silt, silty-sand and subordinate clay. They are usually abruptly overlain by the Red Sands which comprise medium- to coarse-grained sands, usually silty and sometimes pebbly (up to 5 mm well-rounded pebbles). The Red Sands vary in thickness from 4–11 m and to the south progressively replace the Silty Beds and Brown Sands.

Fuller's earth (calcium smectite) is found within the Woburn Sands Formation as impersistent lenticular seams. It has been worked commercially to the south of Woburn Sands village and to the east of Clophill. The main seam attains a thickness of 3.75 m dipping to the south-west (Shephard-Thorn et al., 1994; Shephard-Thorn, et al., 1986). Groundwater flow through the sands is impeded by the fuller's earth, which, where present, effectively divides the aquifer into two.

The structure of the Woburn Sands Formation is not complex with a very gentle dip towards the south-east. The presence of north-west–south-east-trending troughs is thought to be due to the pre-depositional erosion of the Jurassic basement rather than faulting (Shephard-Thorn et al., 1994).

About a third of the outcrop is covered in chalky boulder clay (till). The boulder clay is generally of low permeability and is thought to be about 6 m thick on average — although locally it can exceed 20 m. Alluvium is found in the main river valleys of the Ousel and Ivel. To the east of the outcrop the aquifer becomes confined by the Gault and boreholes become artesian.

Groundwater investigations

There have been few studies of the hydrogeology of the Woburn Sands Formation. The most significant study to date was undertaken in 1974 by the Water Resources Board (Monkhouse, 1974). In their investigation they assimilated all the existing data to provide a comprehensive review of the hydrogeology of the area with the intent of assessing the available groundwater resources. More recently the British Geological Survey produced an assessment of the sand and gravel resources of the Lower Greensand Group which included some hydrogeological data (Shephard-Thorn et al., 1986). In addition to these studies there are pumping test and licence files held by the Environment Agency which contain information on local conditions within the aquifer.

5.3.2 Aquifer properties

General statistics

There are 37 locations with aquifer properties data for the Woburn Sands Formation in the Bedford/Cambridge area. All 37 have transmissivity data while only 19 sites have measurements of storage coefficient. The transmissivity distribution is shown in Figure 5.3.2. Data are approximately lognormally distributed; estimates of transmissivity range from 23 to 6100 m^2/d with geometric mean, 260 m^2/d and median, 200 m^2/d. The 25 and 75 percentiles are 96 and 560 m^2/d respectively.

The storage data are represented in Figure 5.3.3. The data appear to approximate to a square function with equal probability of gaining a storage coefficient from about 10^{-4} to 0.1 (geometric mean, 0.004, median 0.004) — with the lower values expected where the aquifer is confined. The 25 and 75 percentiles of the data are 5.4×10^{-4} and 0.038 respectively. An approximate relation can be seen between transmissivity and specific capacity (Figure 5.3.4).

No core data are available for the Woburn Sands Formation.

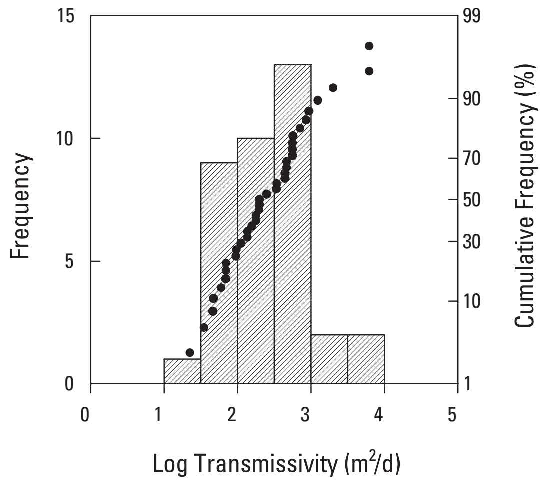

Figure 5.3.2 Distribution of transmissivity data from pumping tests in the Woburn Sands Formation.

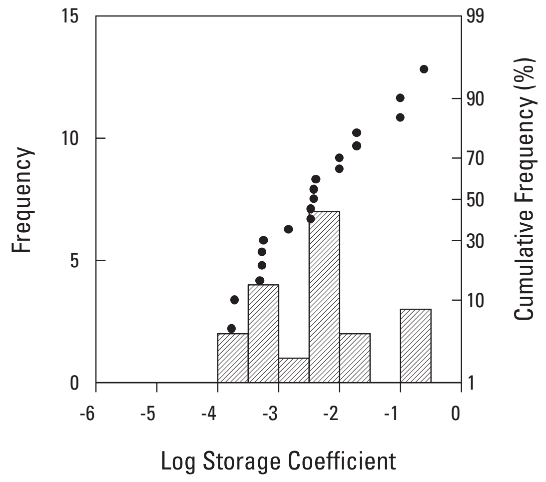

Figure 5.3.3 Distribution of storage coefficient data from pumping tests in the Woburn Sands Formation.

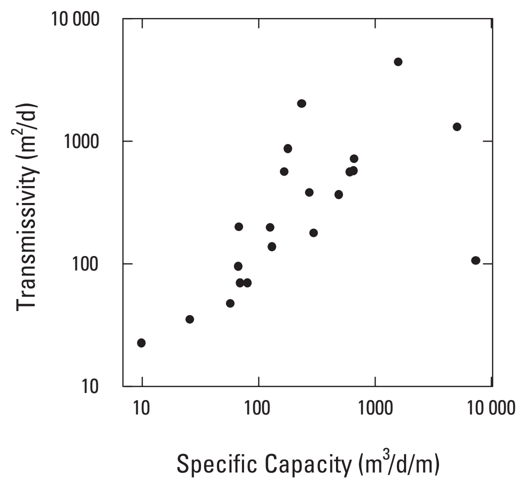

Figure 5.3.4 Plot of transmissivity against capacity (uncorrected) for the Woburn Sands Formation (r^2 = 0.43).

Thickness of the aquifer

General isopachytes are available for the Woburn Sands Formation where it is confined (Figure 5.3.5). They illustrate a thinning of the aquifer to the south-east and also to the north-east, and also identify a deep basin to the east of Leighton Buzzard. At outcrop, the Woburn Sands follow a similar pattern thinning to the north-east; in addition the formation thins north-westward towards its feather edge.

There are no logging data to identify which zones are most productive within the Woburn Sands Formation. However, it is likely that the less consolidated sands have the greater values of storage coefficient and transmissivity. The sediments may be better cemented where the Woburn Sands Formation is thin, or near to the top of the formation (Monkhouse, 1974); here the aquifer properties are likely to reduce and groundwater flow may occur predominately in fractures.

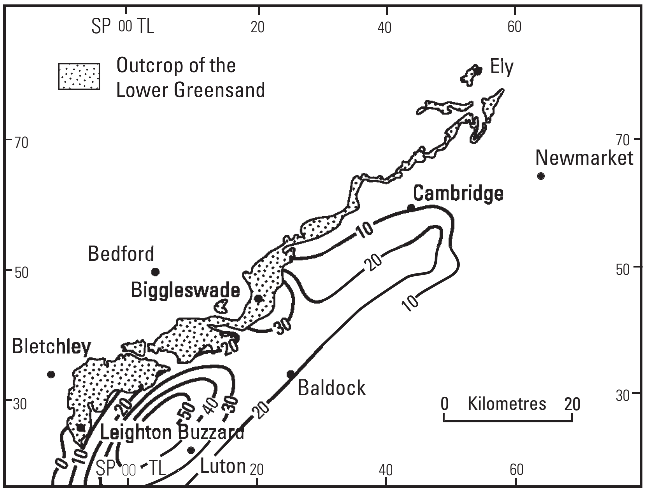

Figure 5.3.5 Isopachytes for the Woburn Sands Formation (in metres) where confined (after Monkhouse, 1974).

The available data indicate a tentative correlation between the thickness of the aquifer and transmissivity (Figure 5.3.6). In particular, as the aquifer becomes deeply confined beneath the Gault and consequently thins, the transmissivity reduces significantly. As the aquifer thins, it becomes increasingly cemented which further reduces the transmissivity.

Areal distribution of aquifer properties

The distribution of measured transmissivity within the Woburn Sands Formation is shown in Appendix 4. Some general trends are immediately apparent. Towards the south-west of the outcrop near to Leighton Buzzard and Woburn Sands (approx SP 93) the transmissivity tends to high, generally in excess of 500 m^2/d and in a few places more than 1000 m^2/d. West of Biggleswade the transmissivity remains high mostly about 500 m^2/d, although in some locations the transmissivity reduces markedly. There are few data from the outcrop of the Woburn Sands Formation to the north of Biggleswade, but those which exist indicate the transmissivity to be very low. North-east

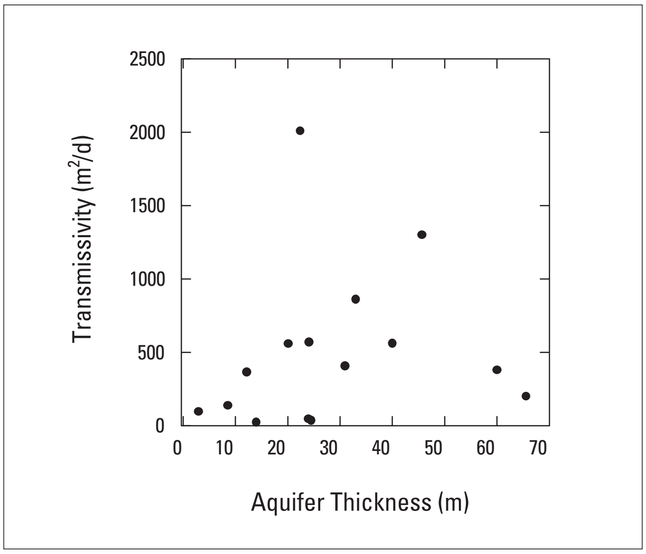

Figure 5.3.6 Plot of transmissivity against aquifer thickness for the Woburn Sands Formation ($r^2 = 0.25$).

of Biggleswade the transmissivity of the Lower Greensand aquifer is generally poor, usually less than 200 m^2/d and far from outcrop beneath Cambridge less than 100 m^2/d.

The transmissivity data for the Woburn Sands aquifer appeared to fall into three distinct categories (Figure 5.3.7):

(1) sites situated on the outcrop

(2) sites that were less than 2 km from outcrop (the top of the Lower Greensand Group is above OD in all these sites)

(3) sites that were more than 2 km from outcrop

On average the highest transmissivity values were measured in the second set — those less than 2 km from outcrop. Of the three sets, these sites will have the greatest saturated thickness and therefore it is plausible that transmissivity should be high (Figure 5.3.8). The more deeply confined sites had significantly lower transmissivity values, probably due to the reduced thickness and increased cementation of the aquifer. Most of the deeper confined sites were in the north of the area with no data available in the south. Therefore it is possible that in the south, where the aquifer is thicker and less cemented, the trend observed in the data

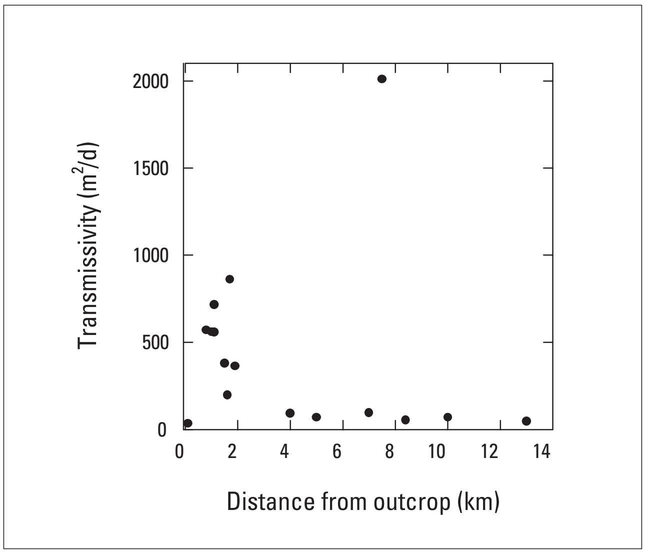

Figure 5.3.7 Plot of transmissivity against distance from outcrop for the Woburn Sands Formation.

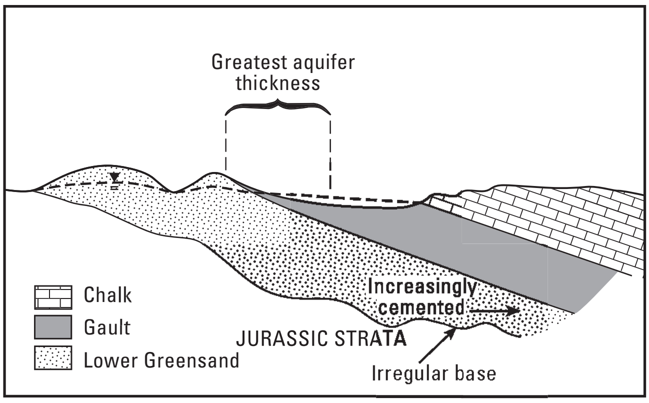

Figure 5.3.8 Schematic cross-section of the Woburn Sands aquifer.

does not apply and the transmissivity remains high even when deeply confined.

There is little storage information available for the aquifer. No definite trends could be identified from the data apart from a simple divide between confined and unconfined. However, in the better cemented parts of the aquifer, where the Lower Greensand Group thins, porosity is likely to reduce giving a similar reduction in storage.

A transmissivity map was created for the unconfined section of the aquifer using specific capacity data (Monkhouse, 1974). Similar trends to that outlined above are apparent: high transmissivity near to outcrop reducing to the north-east and south-east (Figure 5.3.9).

In summary the following trends exist within the aquifer properties of the Lower Greensand Group of Bedfordshire and Cambridgeshire:

- transmissivity values are generally higher in the south between Leighton Buzzard and Biggleswade
- the transmissivity reduces to the north-east and is quite low near Cambridge
- within 2 km of outcrop the transmissivity appears to be generally quite high (although following the regional trend of reducing to the north-west) — more than 2 km from outcrop the transmissivity reduces significantly
- the storage coefficient is highest at outcrop, reducing significantly in the confined zone.

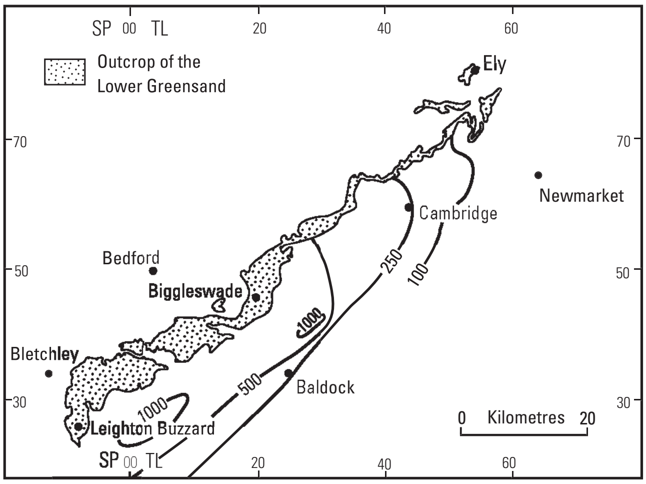

Figure 5.3.9 Transmissivity (in m^2/d) calculated from the specific capacity for the confined section of the Woburn Sands aquifer (after Monkhouse, 1974).

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6 The Jurassic limestones

6.1 INTRODUCTION

Rocks of Jurassic age crop out in a broad band trending south-west–north-east from the Dorset to the Yorkshire and Cleveland coasts (Figure 6.1.1). They are present at depth beneath Cretaceous rocks over all of eastern England except south-eastern East Anglia, and the London and north Kent areas. This chapter describes the aquifer properties of all the main Jurassic aquifers.

6.1.1 Geology

The sediments are up to 1500 m thick and generally dip gently eastwards. They were mainly deposited under tropical climatic conditions in water of less than 100 m depth, in one of three different depositional environments (Hallam, 1992):

- deep shelf (clays)
- shallow shelf (carbonates and sandstones)
- marginal marine to non-marine including:
  - — lagoons and supratidal flats (fine-grained calcareous and argillaceous deposits)
  - — coastal swamps and marshes (silts and clays with rootlets)
  - — river deltas and floodplains (sandstones, siltstones and carbonaceous shales)

Where the sequence contains a high proportion of limestones this indicates a low influx of clastics from neighbouring land areas. The general absence of debris-flow deposits, turbidites and slumping implies that depositional slopes were extremely low (Hallam, 1992).

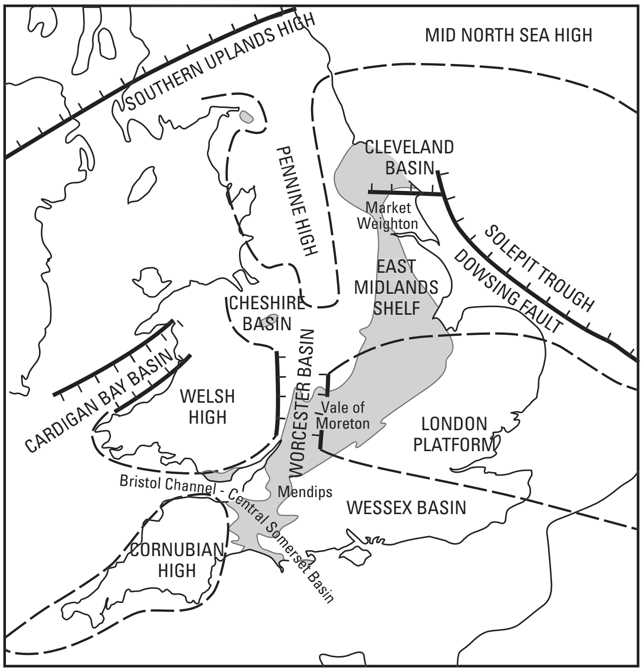


Figure 6.1.1 Outcrop area and principal structural features of the Jurassic (after Hallam, 1992).

Sedimentation was also controlled by a series of platforms and highs (where relatively thin sequences were deposited, most or all of which have subsequently been removed by erosion), separating basins and shelves (where thicker sequences occur). The Mendips, Vale of Moreton and Market Weighton axes therefore separate the four main depositional areas: Wessex (including Bristol Channel–Central Somerset) Basin, Cotswolds, East Midlands Shelf and Cleveland Basin. The sequence is different in each, although the first two are very similar (Table 6.1.1). However, the highs were not effective throughout the Jurassic and some sedimentation occurred across them with some deposits present across the country. West of the main outcrop, Lower Jurassic outliers occur in Cumbria, in Glamorgan, on the Shropshire–Cheshire borders and on the margin of Cardigan Bay.

The relative thicknesses of the various deposits are shown in Figure 6.1.2. Jurassic sedimentation was affected, throughout England, by a series of transgressions and regressions. The first transgression was in early Jurassic times with a predominantly clay sequence overstepping rocks varying in age from latest Triassic to Palaeozoic. A regression followed in the early Mid-Jurassic which commenced with the replacement of marine sediments by non-marine deltaic sediments in northern and some of central England. This was followed by large-scale limestone deposition during Aalenian to Bathonian times, except in the Cleveland Basin. A second transgression starting in late Bathonian times was followed by a long period of clay deposition. A final major regression occurred at the end of the Jurassic, with the sequence shallowing from the Kimmeridge Clay through the Portland beds to the marginal marine or non-marine Lulworth Beds of Dorset. Therefore the majority of the sequence comprises shales and clays, with limestones and sandstones forming a relatively small part of the total thickness, and their position and importance varying from area to area. However, the complex facies variation of the Jurassic, make it ideal as an aquifer in many places, due to the presence of limestones and the alternation of permeable and impermeable strata.

6.1.2 Hydrogeology

The major aquifers in the Jurassic are the limestones. They are characterised by sequences of relatively thin beds, which rarely extend over large areas. Therefore within a single depositional area, aquifer units may die out over distances of kilometres or less. In addition as the aquifer units are relatively thin, quite small throws on faults split the aquifer into separate compartments, which may be hydraulically isolated.

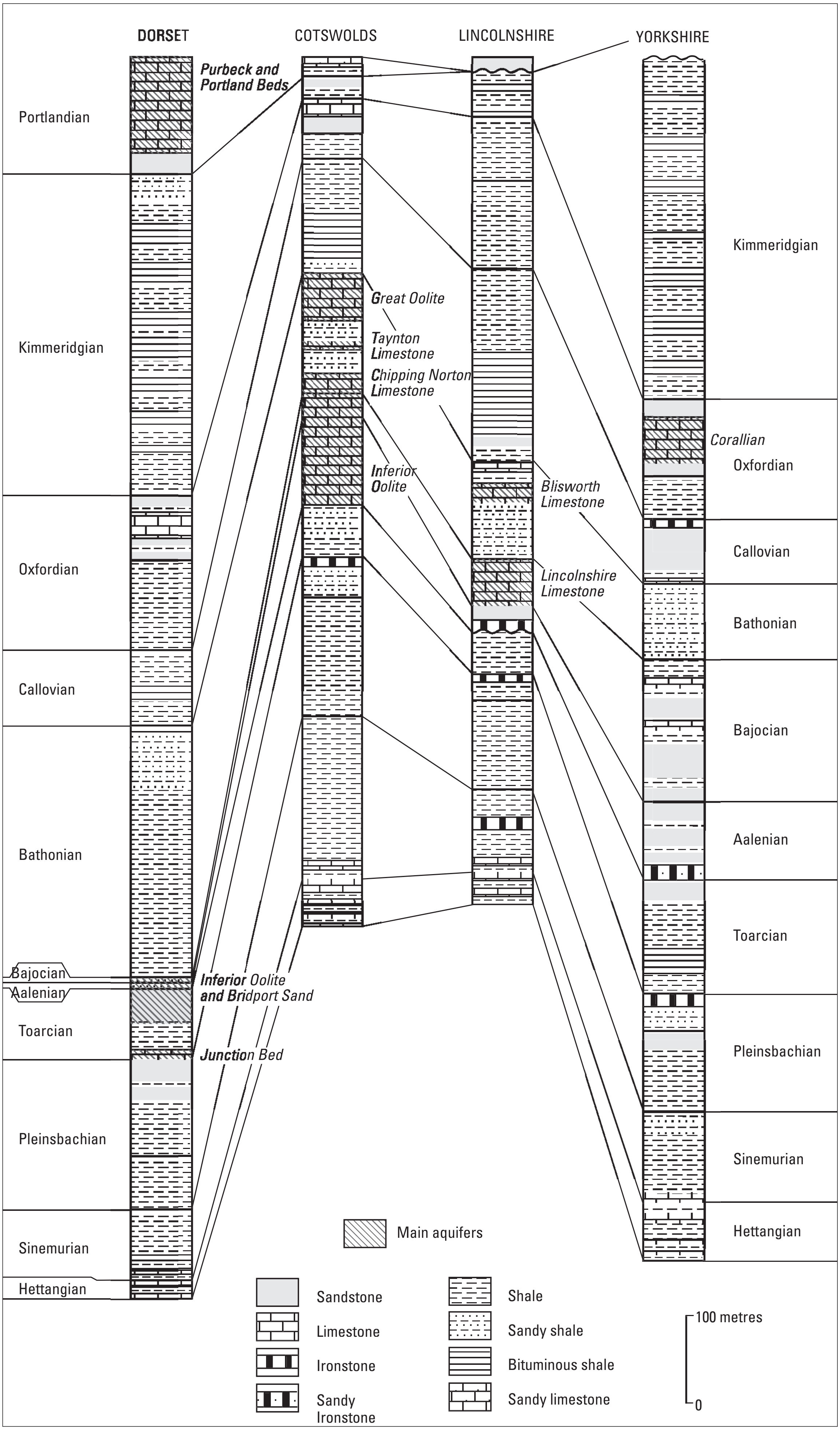
The over- and underlying strata are generally clays, therefore the limestones form distinctive scarps, often with deeply incised valleys, that rise well above the surrounding clay vales. Therefore, in the unconfined portion of the aquifer, the unsaturated zone is often thick, and unless wells are fully penetrating they are frequently dry for part of the year.

Table 6.1.1 Correlation chart of Jurassic rocks between the four principal depositional areas (adapted from Hallam, 1992).

STAGES	GROUP	DORSET	SOUTH MIDLANDS (Avon to Oxon)	EAST MIDLANDS (Northants. to Lincs.)	YORKSHIRE
PORTLANDIAN	Portland Group	Lulworth Beds Portland Limestone Portland Sand	‘Purbeck’ Beds Portland Beds	Lower Spilsby Sandstone	
KIMMERIDGIAN		Kimmeridge Clay	Kimmeridge Clay	Kimmeridge Clay	Kimmeridge Clay
OXFORDIAN	Corallian Group	Sandsfoot Grit Sandsfoot Clay Clavelatta Beds Osmington Oolite Nothe Clay Nothe Grit Upper Oxford Clay*	Coral Rag, Wheatley Limestones, etc. Lower Calcareous Grit Upper Oxford Clay*	Ampthill Clay West Walton Formation Upper Oxford Clay*	Ampthill Clay Upper Calcareous Grit Coralline Oolite Lower Calcareous Grit Oxford Clay
CALLOVIAN		Middle Oxford Clay* Lower Oxford Clay* Kellaways Formation Upper Cornbrash	Middle Oxford Clay* Lower Oxford Clay* Kellaways Formation Upper Cornbrash	Middle Oxford Clay* Lower Oxford Clay* Kellaways Formation Upper Cornbrash	Hackness Rock Langdale Beds Kellaways Rock Cornbrash
BATHONIAN	Great Oolite Group	Lower Cornbrash Forest Marble Upper Fuller’s Earth Clay Fuller’s Earth Rock Lower Fuller’s Earth Clay	Lower Cornbrash Forest Marble Great Oolite / White Limestone Upper F.E. Clay / Hampen Formation Fuller’s Earth Rock / Taynton Limestone Lower F.E. Clay / Fuller’s Earth/Sharp’s Hill Formation Chipping Norton Fm.	Lower Cornbrash Blisworth Clay Blisworth Limestone Rutland Formation	Scalby Formation
BAJOCIAN	Inferior Oolite Group	Upper Inferior Oolite Middle Inferior Oolite	Upper Inferior Oolite Middle Inferior Oolite	Lincolnshire Limestone	Scarborough Formation Cloughton Formation Eller Beck Formation
AALENIAN		Lower Inferior Oolite Bridport Sand	Lower Inferior Oolite	Grantham Formation Northampton Sand Formation	Saltwick Formation Dogger Formation
TOARCIAN	Lias Group	Downcliff Clay Junction Bed	Upper Lias Clay with Cotteswold Sand, etc.	Upper Lias Clay	Blea Wyke Sand Peak Shales, etc. Alum Shale Jet Rock, etc. Grey Shales
PLEINSBACHIAN		Thorncombe Sand Eype Clay, etc Green Ammonite Beds Belemite Marls	Marlstone Middle Lias Clays Lower Lias Clays	Marlstone Middle Lias Clays Lower Lias Clays with Frodingham Ironstone	Cleveland Ironstone Straithes Formation Ironstone Shales, etc.
SINEMURIAN		Black Ven Marls Shales with Beef Blue Lias	Blue Lias	Granby Limestones Hydraulic Limestones etc.	Siliceous Shales Calcareous Shales Shales at Redcar
HETTANGIAN					

* Upper, Middle and Lower Oxford Clay are now Weymouth, Stewartby and Peterborough Members respectively.

Figure 6.1.2 Principal facies and thickness variations in the Jurassic, illustrated by lithostratigraphic columns from the four main depositional areas (after Hallam, 1992).



Intergranular permeabilities are very low and water movement takes place through fractures which have been enlarged by solution. These openings are irregularly distributed vertically and horizontally but extend for considerable distances and where interconnected on an areal basis, may give rise to high yields. Therefore yields are variable depending on whether or not a borehole intersects an interconnected system of water-filled openings. However, unlike the Palaeozoic limestones, very few completely dry wells have been drilled. Locally, karstic features have been noted in all the main aquifers. Horizontal permeabilities are generally higher than vertical ones due to the presence of clay-rich layers within the limestones.

The Jurassic limestone aquifers are characterised by high transmissivities and low storage coefficients. At outcrop the aquifers respond rapidly to recharge and are characterised by large seasonal variations in water levels (20 m is not uncommon near the interfluves) and effluent rivers. The fast response times mean that the unconfined aquifers are not suited to development for river regulation, as the groundwater and surface water are in close hydraulic connection. However, this is not always the case in the confined part of the aquifer and one of the proposed methods for developing the Corallian in the Cleveland Basin is for river regulation using water from the confined aquifer. In the Cotswolds, abstractions from the confined portion of the limestone aquifers has to be very carefully monitored during the summer months to ensure their impact on streamflows is minimised. This abstraction also reduces peak winter flows, by decreasing groundwater discharge and making the streams less ‘flashy’. Around Malmesbury the confined portion of both the Inferior and the Great Oolite are used for river augmentation.

Where fractured the limestones are highly vulnerable to pollution and unless major, highly conductive flow paths are struck, wells with large yields have large cones of influence. This causes interference effects between sources.

The quality of water from the Jurassic limestones is generally good, but hard with calcium and bicarbonate ions predominating. The degree of mineralisation of the water is a good indication of its age; lower total dissolved solids concentrations occur in waters that have been in the aquifer for only a short time. Downdip, beneath confining horizons, sodium replaces calcium by ion exchange and eventually, several kilometres from outcrop, the water becomes saline. Therefore, within the exploited part of the aquifer, the chemistry can be linked to the aquifer permeability, with good quality water indicating high permeabilities and transmissivities where water moves through the aquifer system at a reasonable rate. Elsewhere the aquifer may still have a high fracture density, but because there is a lower throughput of water, the quality may be poor.

Previous research

The first person to publish work on the Jurassic aquifers was Walters (1936), who described and produced water level contours for the Corallian of Yorkshire, the Lincolnshire Limestone and the oolites from Peterborough to the south coast. Since then these three aquifers in particular have been studied in considerable detail and other aquifers, such as the Upper Lias Sands, have received some attention. However, due to the wide variation in aquifer properties that occur over small areas, some of the studies are inconclusive.

Parts of all the main Jurassic aquifers (Corallian [Aspinwall, 1994], Lincolnshire Limestone [Rushton et al., 1993, 1994], Oolites of the Cotswolds [Birmingham University 1987, Rushton et al., 1992]) have been modelled. Due to the flashy nature of the aquifers and their rapid response to recharge, the models need to incorporate the compartmentalised nature of the aquifers as well as their physical properties to represent recharge and calibrate water levels and streamflow; they are therefore often very complex.

6.1.3 Aquifer properties data availability

Pumping test data

There is limited quantitative information available for the Jurassic limestones from pumping tests. Table 6.1.2 summarises the locality pumping test data by geographic area. A large proportion of the pumping tests in all the aquifers (with the exception of the Lincolnshire Limestone) were carried out without observation wells and hence produced no storage coefficients. Transmissivity values will depend on the number, nature and interconnection of the fractures encountered in the saturated zone, and therefore change depending on the time of year or initial water levels. However there are no records of sites having been tested on several occasions with significantly different initial water levels.

Some of the transmissivity values quoted are exceptionally high (in excess of 10 000 m^2/d). These transmissivities are not true values, as the aquifer in these cases will not meet the normal assumptions (a homogeneous aquifer of infinite areal extent) required for standard pumping test analysis. However, they are included in the database as indicators that extremely large transmissivities can occur where large fractures are present, and possibly that non-laminar flow is occurring along enlarged solution features. The combination of low storage coefficients and the compartmentalisation of the aquifers means that most pumping tests do not reach equilibrium until after they have been affected by boundary conditions.

Storage coefficients less than 10^{-6} are probably unrealistic. The fact that a few values lower than this have been obtained indicate that the storage at these localities is very low but they are unlikely to be true values. They also indicate that the normal assumptions of pumping test analysis are not valid in a fractured aquifer.

Core data

A very limited amount of porosity and intergranular permeability data from laboratory analyses of rock samples is available for Jurassic strata. A synopsis of this information is presented in Table 6.1.3 by geographical area, for each of the major aquifer horizons. Maximum, minimum, interquartile range and mean values are presented for both porosity and permeability (expressed as hydraulic conductivity). The table indicates that the data are commonly derived from a relatively small number of analyses from a limited number of sample sources. A distinction has been made between data originating from samples taken from borehole cores and those from outcrops, since the physical properties of the latter may have been modified by weathering processes.

6.2 CLEVELAND BASIN

The Cleveland Basin is the area of Jurassic rocks north of the Market Weighton axis. The rocks crop out over the Cleveland Hills, Hambleton Hills, Howardian Hills and North Yorkshire Moors and underlie superficial deposits in the Vale of Pickering. As elsewhere, the Lower Jurassic sequence is predominantly shales and clays alternating

Table 6.1.2 Jurassic aquifers: physical properties from pumping tests.

Area	Aquifer	Transmissivity (m^2/day)					Storage coefficient			
		No. values	Interquartile range	Max.	Min.	Geometric Mean	No. values	Interquartile range	Max.	Min.
Cleveland Basin	Corallian	29	32 to 2100	16 000	0.2	318	6	4.7×10^{-7} to 1.5×10^{-2}	2×10^{-2}	4.0×10^{-7}
East Midlands Shelf	Great Oolite	9	105 to 1430	2800	0.5	184	2		5.1×10^{-3}	to 5.2×10^{-4}
	Lincolnshire Limestone	59	259 to 2265	14 000	1	665	37	4.9×10^{-5} 5.2×10^{-4}	6×10^{-1}	2×10^{-7}
Cotswolds	Great Oolite	34	37 to 825	5900	4	212	7	1.0×10^{-4} to 6.8×10^{-4}	4×10^{-3}	6×10^{-5}
	Great + Inferior Oolite	3	—	9900	4	—	0	—	—	—
	Inferior Oolite	14	18 to 1150	11 000	3	139	3	—	8×10^{-2}	7×10^{-5}
British Channel–Central Sometset Basin	Portland + Limestone	1	—	200	200	1	1	—	6×10^{-5}	6×10^{-5}
	Inferior Oolite	4	—	1400	57	—	2	—	8×10^{-5}	7×10^{-5}
	Inferior Oolite + U Lias Sands	1	—	2	2	—	1	—	1×10^{-4}	1×10^{-4}
	Upper Lias Sands	6	6 to 248	600	2	45	1		3×10^{-3}	3×10^{-3}

Table 6.1.3 Jurassic aquifers: physical properties data from laboratory analyses

Area	Aquifer	Sample source		No. analyses	Porosity %				Hydraulic conductivity (m/d)			
		No. boreholes	No. outcrops		Interquartile range	Max.	Min.	Arithmetic Mean	Interquartile range	Max.	Min.	Geometric Mean
Cleveland Basin	Coralline Oolite	5	—	25	10.9 to 27.2	37.4	6.0	17.4	1.4×10^{-5} to 1.6×10^{-3}	0.25	4.6×10^{-6}	1.8×10^{-4}
East Midlands Shelf	Lincolnshire Limestone	14	—	415	13.1 to 21.6	51.1	2.5	18.0	4.99×10^{-5} to 4.39×10^{-4}	0.17	$<1.9 \times 10^{-6}$	1.33×10^{-4}
Cotswolds	Great Oolite	2 —	— 1	90 6	11.2 to 17.9	25.0 25.3	5.1 20.7	— 14.5	2.54×10^{-4} to 2.97×10^{-3}	0.035 2.9×10^{-4}	$<1.9 \times 10^{-6}$ 1.4×10^{-4}	9.8×10^{-5}
	Inferior Oolite	5	—	36	15.7 to 21.3	34.5	12.2	19.1	3.1×10^{-4} to 4.9×10^{-4}	0.50	2.6×10^{-6}	5.0×10^{-4}
Bristol Channel–Central Somerset	Portland Limestone	—	5	26	13.4 to 18.0	29.8	9.4	16.4	3.1×10^{-4} to 0.702	15.5	2.9×10^{-4}	0.018
	Upper Lias Sands	6 —	— 3	135 22	13.7 to 23.1	29.7 33.91	3.5 7.3	— 18.9	1.1×10^{-4} to 2.1×10^{-3}	0.033 0.125	5.3×10^{-6} 3.1×10^{-4}	4.9×10^{-4}

with limestones, ironstones, siltstones and sandstones; however, the Middle Jurassic comprises a thick sequence of fluvial, estuarine and deltaic beds and the Upper Jurassic includes alternating marine calcareous and oolitic limestones (Corallian Group) overlain by clays (Ampthill and Kimmeridge clays).

The sequence is summarised in Table 6.2.1. The deposits reach a maximum thickness of around 1100 m. There are several minor aquifers within the area, namely the Osgodby Formation, Ravenscar Group, Dogger Formation, Cleveland Ironstone Formation and the Staithes Sandstone Formation. However, the principal aquifer is the Corallian Group.

6.2.1 Corallian Group

Geology

Lithology

The Corallian Group consists of three formations: the Lower Calcareous Grit, the Coralline Oolite and the Upper Calcareous Grit Formation. Its outcrop pattern is shown in Figure 6.2.1 and Figure 6.2.2 indicates the lateral variations in lithology. The Upper and Lower Calcareous Grit formations are dominated by fine-grained calcareous sandstones or sandy limestones. Both the grits and the Oolites are variable in lithology, but the variations are most marked in the limestones which have reefs associated with them. A fallen description is given in Kent (1980).

The Lower Calcareous Grit reaches its maximum thickness in the Tabular and Hambleton hills, thinning southwards towards Market Weighton and eastwards (from the Hackness Hills) to the coast. It comprises hard grits with subsidiary limestones.

The overlying Coralline Oolite includes two main oolite members, the Hambleton Oolite at the base, and the overlying Malton Oolite. They are separated by a sandstone member, the Middle Calcareous Grit which thins out at the western end of the Vale of Pickering. The Hambleton Oolite consists mainly of oolitic limestones, but includes some sandstones and detrital limestones. It is thickest around Kirbymoorside. The Middle Calcareous Grit is best developed between the Tabular Hills and Kirbymoorside where it comprises up to 12 m of sandstone with locally developed shelly layers and sandy and oolitic limestone beds. The Malton Oolite Member (formerly the Osmington Oolite) is the most persistent member of the Coralline Oolite Formation, being traceable from the coast where it is over 25 m thick as far inland as Helmsley; it gradually thins and becomes sandier westwards. The uppermost

Table 6.2.1 The Jurassic Sequence of the Cleveland Basin.

	MAPPED UNIT	THICKNESS AND LITHOLOGY
	Kimmeridge Clay Formation	up to 385 m mudstones (often calcareous) and oil shales
	Ampthill Clay Formation	45–50 m
	CORALLIAN GROUP	100–150 m calcareous sandstones and limestones
	Oxford Clay	up to 35 m
	Osgodby Formation	**IN WEST** *Kellaways Beds* up to 30 m soft sandstone with concretions
		IN NORTH-EAST *Hackness Rock* 2 m calcareous sandstone with interbedded limestones *Langdale Beds* 2–15 m sandstone *Kellaways Rock* 7–16 m chamositic sandstone
	Cornbrash Formation	Upper Cornbrash shale up to 3 m
		up to 3.5 m limestone (sandy in west, shelly in east)
	Scalby Formation (formerly Upper Deltaic Series)	40–70 m mudstones, siltstones and sandstones
Ravenscar Group	*Scarborough Formation*	up to 30 m limestone, sandstone and shale
	Cloughton Formation (formerly Middle Deltaic Series)	up to 95 m shales, sandstones and subordinate limestones
	Eller Beck Formation	4.5–8 m shales and ironstones overlain by shaly sandstone
	Saltwick Formation (formerly Lower Deltaic series)	up to 60 m sandstone and shale
	Dogger Formation	up to 12 m chamositic sandstone
	Blea Wyke Sandstone Formation	up to 18 m
	Whitby Mudstone Formation (formerly Upper Lias)	up to 105 m mudstone and shale with sandstone beds
	Cleveland Ironstone Formation	up to 25 m mudstone and siltstone with beds of oolitic ironstone
	Staithes Sandstone Formation	up to 30 m micaceous, calcareous sandstone and sandy siltstone
	Redcar Mudstone Formation (formerly Lower Lias)	up to 285 m mudstones and siltstones with subsidiary thin limestones, sandstones and ironstones

CAPITALS = main aquifers
Italics = other aquifers

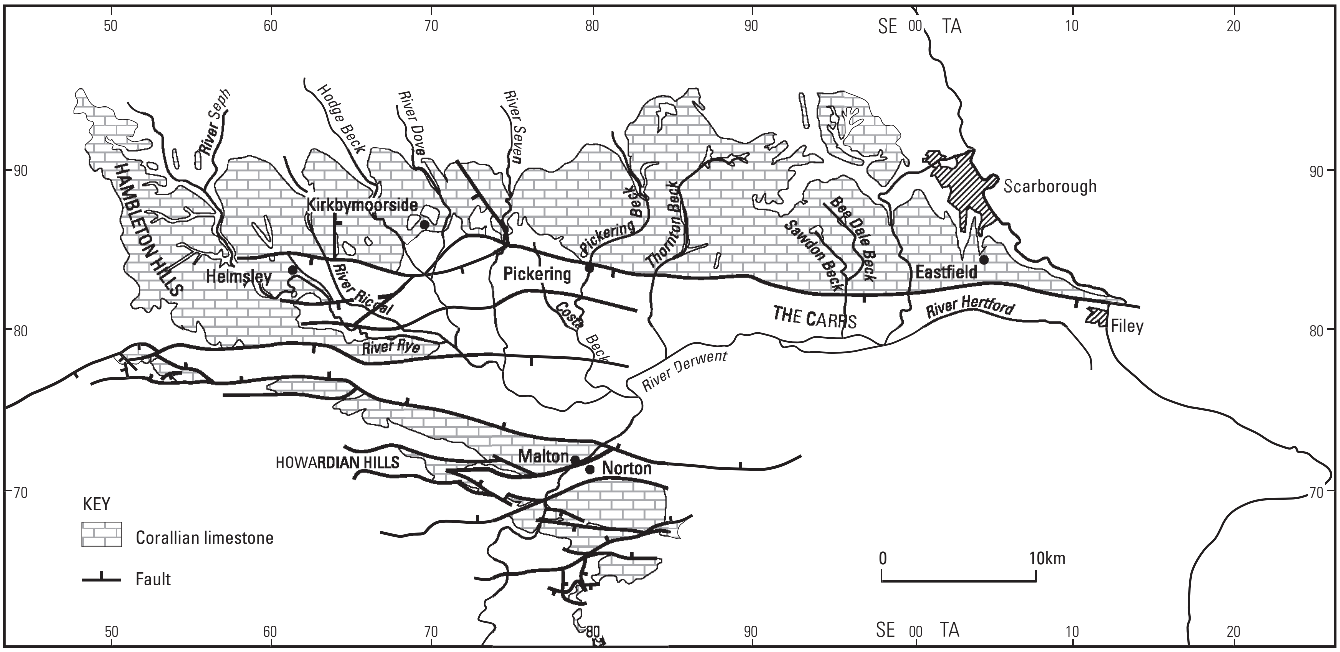


Figure 6.2.1 Geological map of the Corallian limestones of the Cleveland Basin.

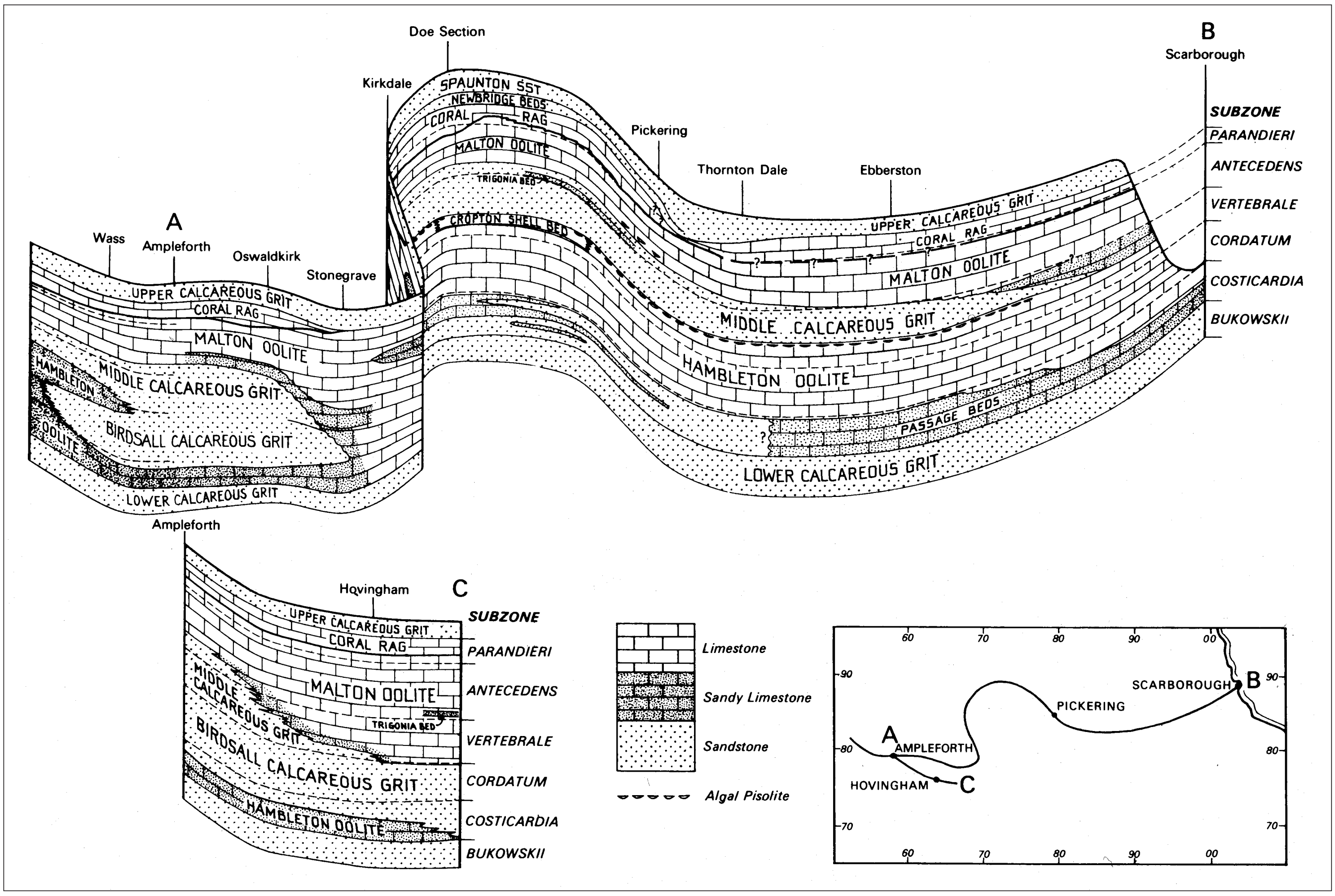


Figure 6.2.2 Ribbon section of the Corallian rocks of Yorkshire (from Kent, 1980).

member of the Coralline Oolite is the Coral Rag: richly fossiliferous reef limestones and detritus.

The Upper Calcareous Grit comprises up to 15 m of fine-grained sandstone.

Drift cover

Over most of the higher ground forming the outcrop area of the Corallian Group, the only superficial deposits overlying it are alluvium and river terrace deposits along the valleys; no glacial deposits are present. However, around Scarborough in the south-east, there are widespread glacial deposits. Along the southern margin of the Corallian, often masking its boundary with the Kimmeridge Clay, there are extensive sand and gravel deposits, locally underlain by 10–20 m of till.

Structure

The Cleveland Basin is an inversion structure, the area having been a major basin of deposition in the Jurassic, followed by uplift in the Cretaceous. The main structures within the basin all trend east by east-south-east, in line with Hercynian and Caledonian folding in the Askrigg Block and Austwick inliers (Dunning, 1992). The Cleveland Anticline centred on the North Yorkshire Moors is an east–west-trending broad arch with subsidiary domes, which extends eastwards into the Scarborough Dome and the Sole Pit Trough in the North Sea.

Towards the southern margin of the Basin lies the Howardian–Flamborough–Dowsing Fault Belt; of which the Helmsley–Filey Fault to the north of the Vale of Pickering Syncline is the most northerly manifestation. It acts as a hydrogeological boundary throwing Kimmeridge Clay to the south against Corallian limestones to the north.

Hydrogeology

The Corallian is highly fractured, with fracture flow being well developed. Transmissivities can be high (up to 3800 m^2/d) and large yields are obtained close to major springs and faults (Monkhouse and Richards, 1982). The highest yielding boreholes are in or close to the confined zone. It is underlain by Oxford Clay and overlain by the Kimmeridge Clay, both of which are impermeable. Both the River Rye and the River Riccal originate as springs issuing at the basal junction of the Corallian with the Oxford Clay. The aquifer has been studied in detail by Reeves, Parry and Richardson (1978). They concluded that the greatest hydrogeological potential is to the north of the fault bounded Coxford–Gilling trough. This splits the structurally relatively simple synclinal outcrop area in the north from the complex eastern extension of the Howardian Hills Fault Belt beneath the clay-covered Vale of Pickering; there is limited hydraulic continuity between the two areas. The southern area is compartmentalised by a series of tensional easterly trending faults.

Aspinwall (1994), produced a model of the eastern limestones, but only included the area north of the Ebberston-Filey fault, as the throw across this is up to 150 m. The throw is probably less in the east as there is some evidence that at Filey the public water supply south of the fault is fed by flow originating from the unconfined aquifer to the north. Figure 6.2.3 shows the variation in hydraulic conductivity used in the model.

Both the aquifer and the streams fed by it respond rapidly to recharge. In summer stream flows are maintained by a substantial baseflow component. The bulk of the groundwater discharge from the Corallian occurs via a series of major springs controlled by faulting. The springs

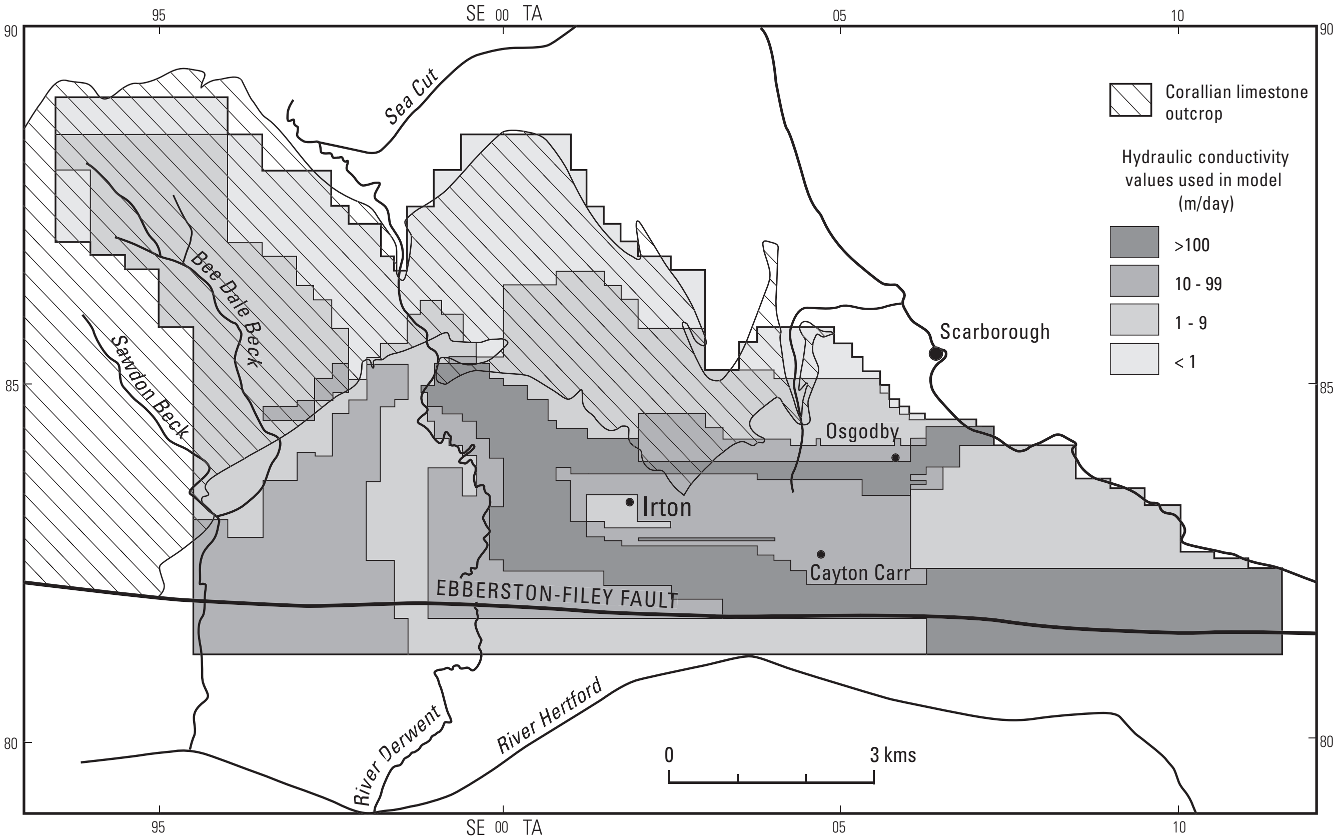


Figure 6.2.3 Distribution of hydraulic conductivity for the Corallian limestone in the eastern part of the Cleveland Basin (after Aspinwall, 1994).

generally appear at the boundary of the Corallian with the overlying clay cover, and in some cases break through the cover along fault lines. In summer, the sum of the discharges from all the springs exceeds the total discharge from the aquifer, as all the flow from some of the rivers crossing the Corallian outcrop disappears down swallow holes to reappear later as other springs. Large volumes of water are therefore transferred via well-developed conduit systems that are virtually caverns. The vast majority of flow through the aquifer is along these major flow paths towards a small number of major springs. This pattern of groundwater movement is self-perpetuating as the higher the flows the more carbonate dissolution takes place, and hence the more the fractures are enlarged.

At East Ness flow rates, through solution-enlarged fractures, ranging from 2 to 3500 m/d have been reported (National Rivers Authority, Yorkshire Region, 1989); transmissivities here exceed 1700 m^2/d.

Aquifer properties

Core data

Limited laboratory analyses of porosity and permeability are only available for the Coralline Oolite (Hambleton and Malton Oolites), a total of 25 samples from 5 boreholes (Table 6.1.3). There are no data for the Lower and Upper Calcareous Grits. The porosity interquartile range is 10.9 to 27.2% with an arithmetic mean of 17.4% (Figure 6.2.4a). The interquartile range for hydraulic conductivity values is 1.4×10^{-5} to 1.6×10^{-3} m/d with a geometric mean of 1.8×10^{-4} m/d (Figure 6.2.4b). There is no consistent pattern of vertical or horizontal values being higher. In general terms increasing hydraulic conductivity corresponds to higher porosity values (Figure 6.2.4c).

Pumping test results

The transmissivity and storage coefficient data for the Corallian is given in Table 6.1.2. There are only 6 locations with values for storage coefficient. They range from 4×10^{-7} to 0.023 and fall into three categories: those that are exceedingly small (less than 10^{-6}), those around 10^{-4} indicating confined conditions, and a couple around 2.4×10^{-2}. The inter-quartile range is 4.5×10^{-7} to 1.5×10^{-2}.

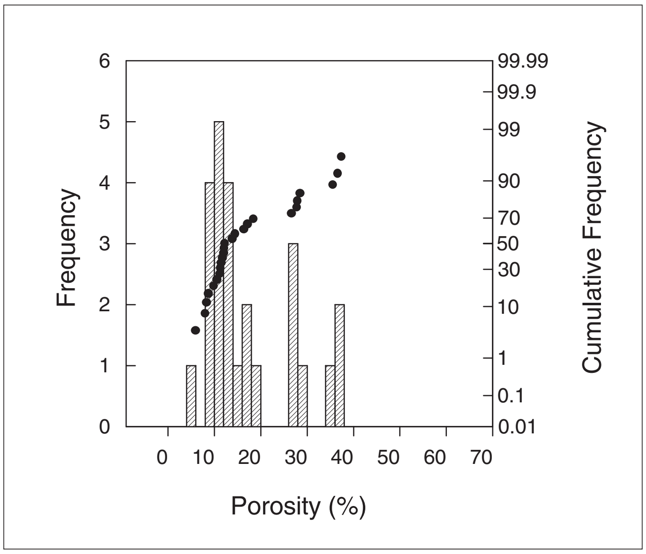


Figure 6.2.4a Distribution of porosity data for Corallian limestone samples from the Cleveland Basin.

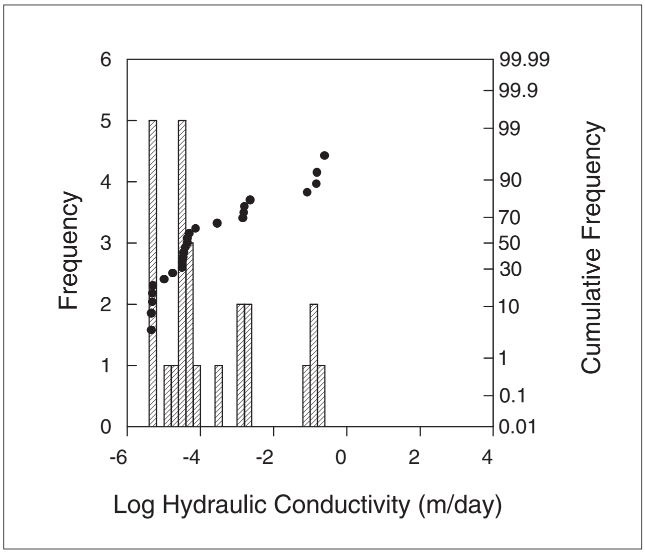


Figure 6.2.4b Distribution of hydraulic conductivity data for Corallian limestone samples from the Cleveland Basin.

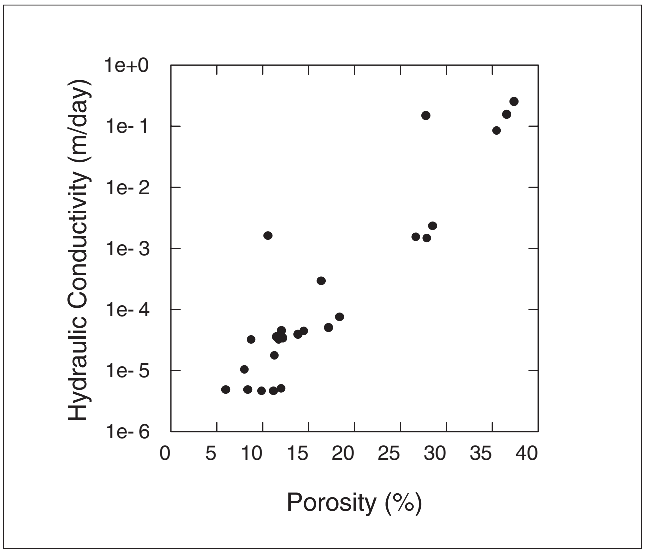


Figure 6.2.4c Plot of hydraulic conductivity against porosity for Corallian limestone samples from the Cleveland Basin.

There are 29 locations with recorded transmissivity values; their interquartile range is 38 to 2249 m^2/d and the geometric mean is 318 m^2/d (Figure 6.2.5). Many of the values came from boreholes put down to investigate the potential of the aquifer and some of these were sited to provide information on the geological structure rather than to obtain the highest yields. Transmissivities are generally very low from the main outcrop area of the aquifer, reflecting the small saturated thickness, being less than 10 m^2/d, except around Malton. Values are much higher towards the confined aquifer, and boreholes sited near to major springs (Keld Head [SE 787 844], Norton [SE 806702]) have very large specific capacities and hence probably high transmissivities (Yorkshire River Authority, 1973). Field measurements of permeability were obtained by dividing the transmissivity by the saturated aquifer thickness, these were about a thousand times greater than the laboratory values (Water Resources Board, 1973).

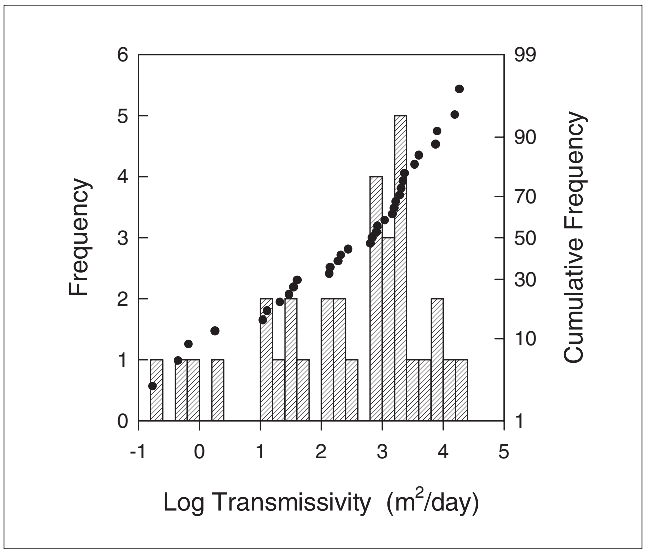


Figure 6.2.5 Distribution of transmissivity data from pumping tests in the Corallian limestone of the Cleveland Basin.

Fracture development and well behaviour

At Irton [TA 004 841] there are two wells 45 m apart. One had inflows at 35 and 56 m below ground level while the other was being pumped at 158 l/sec. Both flows were downwards and had high tritium contents suggesting an interconnection with the River Derwent. Tate (1968) logged this well and concluded on the basis of flow and conductivity logs that the two wells are probably interconnected below 79 m depth. Water entering swallow holes in the Derwent [SE 991 853] has been traced to the boreholes with a travel time of 8 hours.

Reeves, Parry and Richardson (1978) noted that at South Ings [SE 696 849], two thirds of the artesian flow entered the borehole at a depth of 64 m and most of the remainder at about 73.5 m. Fracturing is common in core to depths of 60 m below the ground surface and the fracture frequency is not related to borehole depth, rock type or yield. However, the yield is a function of the 'active' fracture frequency, indicated by rock discolouration due to oxidation. Aspinwall (1994) found no correlation between fracture development and the different stratigraphic horizons within the aquifer.

6.3 EAST MIDLANDS SHELF

This covers the area between the Market Weighton and Vale of Moreton highs. The outcrop of Jurassic rocks broadens from Market Weighton southwards across Lincolnshire into the Midlands. The straight outcrop in the north reflects the gentle eastwards tilting at 1–2°, and otherwise almost completely unfolded, nature of the rocks. Here the rocks thicken progressively southwards and, because of the decreasing overstep by the Cretaceous, the

Table 6.3.1 The Jurassic Sequence on the East Midlands Shelf.

	MAPPED UNIT	THICKNESS AND LITHOLOGY
	SPILSBY SANDSTONE (lower part)	up to 25 m glauconitic sandstone
	Kimmeridge Clay Formation	up to 180 m mudstones with thin argillaceous limestones and oil shales
	Ampthill Clay Formation	up to 100 m silty mudstones
	West Walton Formation	up to 25 m siltstones and muddy limestones
	Oxford Clay Formation	up to 120 m calcareous mudstones
	Kellaways Formation	*Kellaways Sand Member* up to 10 m Kellaways Clay Member up to 4 m
	Cornbrash Formation	up to 3 m shelly limestones with marly and sandy partings
	Blisworth Clay Formation (formerly Great Oolite clay)	up to 10 m clay
	Blisworth Limestone Formation (formerly Great Oolite limestone)	up to 8 m limestone
	Rutland Formation (formerly Upper Estuarine Series)	up to 20 m sands, silts and clay
	LINCOLNSHIRE LIMESTONE FORMATION	up to 40 m limestone
	Grantham Formation (formerly Lower Estuarine Series)	up to 8 m sands, silts and clays
	Northampton Sand Formation	up to 20 m ferruginous sandstone
	Upper Lias	up to 55 m mudstones and shales
Middle Lias	*Marlstone Rock Formation* silts and clays	up to 10 m calcareous ironstone up to 25 m
	Lower Lias	up to 115 m calcareous mudstones and shales *Frodingham Ironstone* up to 10 m argillaceous limestones and shales up to 130 m mudtones with thin limestones

CAPITALS = main aquifers
Italics = other aquifers

outcrop broadens. South of Peterborough the dip is south-easterly rather than to the east.

The generalised succession is shown in Table 6.3.1. The main aquifer in this area is the Lincolnshire Limestone Formation which is part of the Inferior Oolite Group and extends from North Newbald in Humberside southwards to Kettering.

Northwards from the Humber estuary the increased Cretaceous overstep of the Jurassic progressively truncates the outcrop of the latter rocks, such that only the Lias occurs at outcrop near Market Weighton. At the Humber the Lias, Grantham Formation, Lincolnshire Limestone, Rutland Formation (which is sandy in this area), Blisworth Clay, Cornbrash, Kellaways Formation, Oxford Clay, West Walton Formation, Ampthill Clay and Kimmeridge Clay are present. The Northampton Sand and Blisworth Limestone are absent at the Humber and and the Grantham Formation and Blisworth Clay have also disappeared by North Cave. The principal aquifer in this area is the Cave Oolite, which is stratigraphically equivalent to the Upper Lincolnshire Limestone further south.

South of the Humber estuary the whole Jurassic succession from the Lower Lias to the Spilsby Sandstone is present. The main aquifers are the Lincolnshire Limestone and the Spilsby Sandstone; the latter is not discussed in this volume as, although it is partly of Jurassic age, until recently it was considered to be wholly Cretaceous, which is where its hydrogeological affinities lie. Less important aquifers are the Marlstone Rock Formation, Northampton Sand Formation, Blisworth Limestone and Cornbrash, as well as the continuation south-westwards from Kettering of the Lincolnshire Limestone aquifer and the Corallian in the extreme south-west of the area.

6.3.1 Cave Oolite

Foster (1968) described the hydrogeology of the Jurassic rocks to the north of the Humber. The Cave Oolite, is a well-cemented oolitic limestone, which at outcrop decreases in thickness from 8 m at South Cave to 5 m at North Newbald. Downdip it is 62 m thick near Melton [SE 972 256]. At the Humber it is confined by the clayey Rutland Formation, but further north where the Rutland Formation is sandy the formations may be in hydraulic continuity. Further north between North Newbald and Market Weighton it is probably in hydraulic continuity with the Chalk. It is underlain in turn by ferruginous silts, limestones and shales (stratigraphically equivalent to the Lower Lincolnshire Limestone south of the Humber) and the Lias.

The Cave Oolite provides water supplies for market gardens in the area around Brough. Yields average 500 m^3/d, but one near Melton [SE 972 256] yielded 3300 m^3/d with a transmissivity value of 10–15 m^2/d for 8.8 m of aquifer at a depth of 59 m.

6.3.2 Lincolnshire Limestone Formation

Geology

The Lincolnshire Limestone outcrops for 130 km from the Humber Estuary in the north to Peterborough and Kettering in the south; the outcrop is between 3 and 5 km wide in the north and between 6.5 and 8 km wide in the south (Figure 6.3.1). It is underlain by the Grantham Formation (comprising pale grey sands, silts and clays), which thins significantly in places allowing contact between the Northampton Sand Formation and the Lincolnshire Limestone. It is overlain by the Rutland Formation, a series of sands, silts and clays, typically between 5 and 15 m thick which overlie the Lincolnshire Limestone unconformably.

The aquifer dips to the east at a variable angle, ranging from 3° north of Lincoln to 1° in the south (Figures 6.3.2a and 6.3.2b). It reaches a maximum thickness of over 40 m in south Lincolnshire, becoming thinner to the north and south. It is absent south of a line passing through Peterborough and Kettering. It also thins from west to east, eventually 'pinching out' downdip.

The Lincolnshire Limestone has conventionally been divided into three areas:

- The Northern area from the Humber to the Lincoln Gap
- The Central area from the Lincoln Gap to the Ancaster Gap
- The Southern area south of the Ancaster Gap

The Lincolnshire Limestone can be divided into two sub-units: the Upper Lincolnshire Limestone and the Lower Lincolnshire Limestone. The Upper Lincolnshire Limestone has a variable thickness, but is dominantly a coarse, shelly, cross-bedded oolite. The Lower Lincolnshire Limestone is mainly a fine-grained, micritic and peloidal limestone, sometimes misleadingly referred to as 'cementstone'.

Structure

A number of faults cross the Lincolnshire Limestone. In the south, these generally trend east–west, the largest being the Marholm–Tinwell and Duddington faults. The former has a throw of around 55 m downwards to the north, and sometimes completely dissects the Lincolnshire Limestone. Further north, the eastern edge of the limestone outcrop is bounded by roughly north–south-trending faults, known as the Washingborough–Scopwick fault belt. These downthrow to the east by approximately 15 m. Near Lincoln the throw to the east is 20 m, and the fault appears to separate the outcrop area of the limestone from its confined area. This fault has been identified as a significant obstacle to groundwater flow, as steep head gradients exist across it (Peach, 1984).

Hydrology and hydrogeology

The major rivers in the area are the Ancholme, Witham, Slea, East and West Glen, Gwash and Welland. The interaction between the rivers and the Lincolnshire Limestone is complex and depends on the geology. Alluvial deposits in the valleys of the Slea and the Witham may locally enhance transmissivity and allow hydraulic continuity between the river and the aquifer. The River Witham virtually cuts through the aquifer where it crops out near Lincoln. However, there is evidence that groundwater can flow from north to south below the river. The River Slea also cuts through the Limestone at Ancaster.

As the Lincolnshire Limestone is part of a succession of aquifers overlain and underlain by relatively impermeable beds, dissection of the area by streams results in a complex pattern of aquifer and aquitard outcrops which cause complicated interactions between groundwater and surface water. In addition, overlying Pleistocene deposits of till and sand, and fen gravels, add further aquifers and aquitards to the system.

Groundwater movement is almost entirely by fracture flow along well-developed bedding plane fractures and joints. Groundwater flows eastwards downdip from the outcrop to the confined area. Abstraction takes place mainly from the confined region, where artesian conditions occur. In the south, where the Lincolnshire Limestone dips gently eastwards, abstractions can take place up to 10 km from

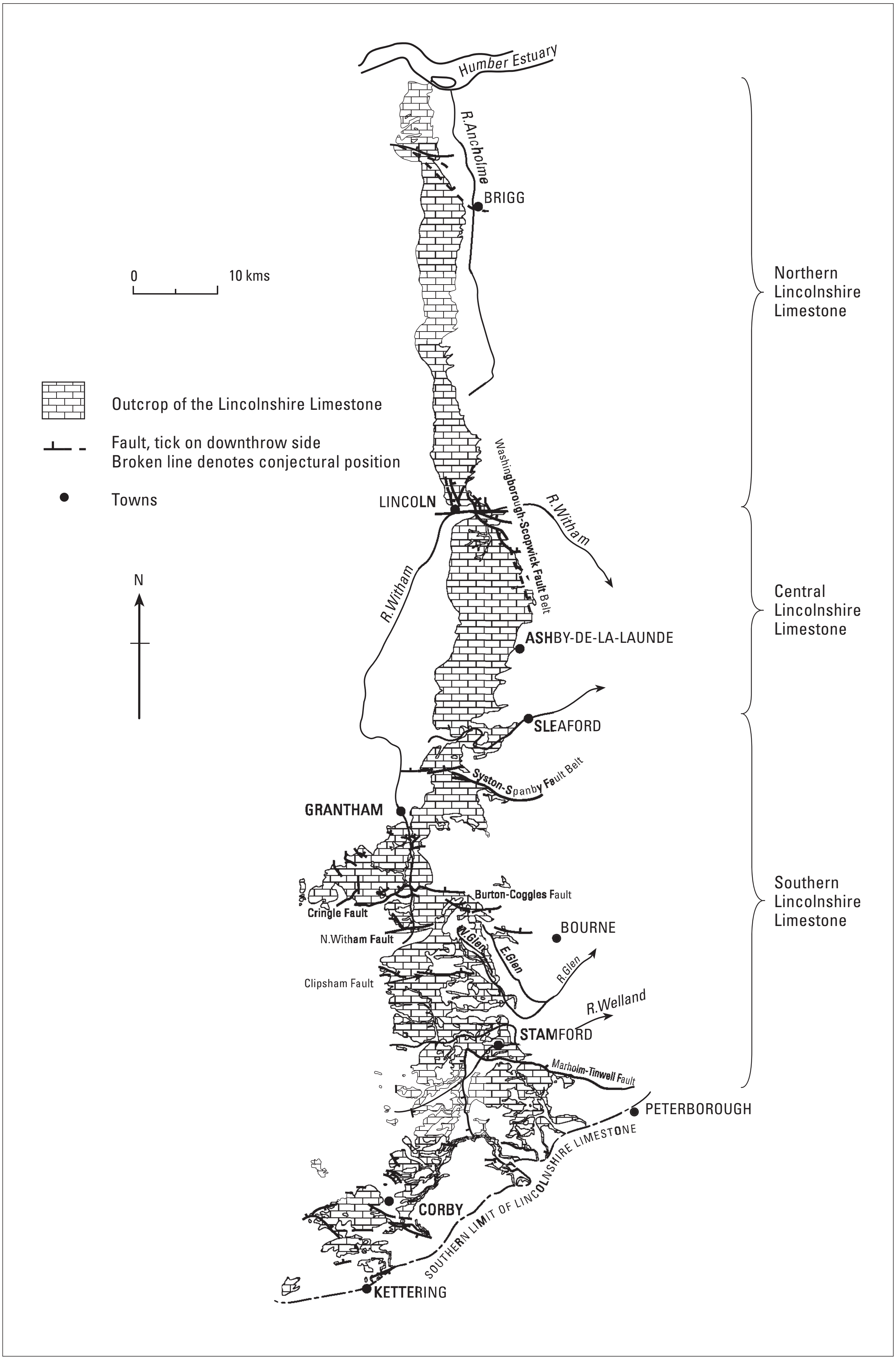


Figure 6.3.1 Simplified geological map of the Lincolnshire Limestone.

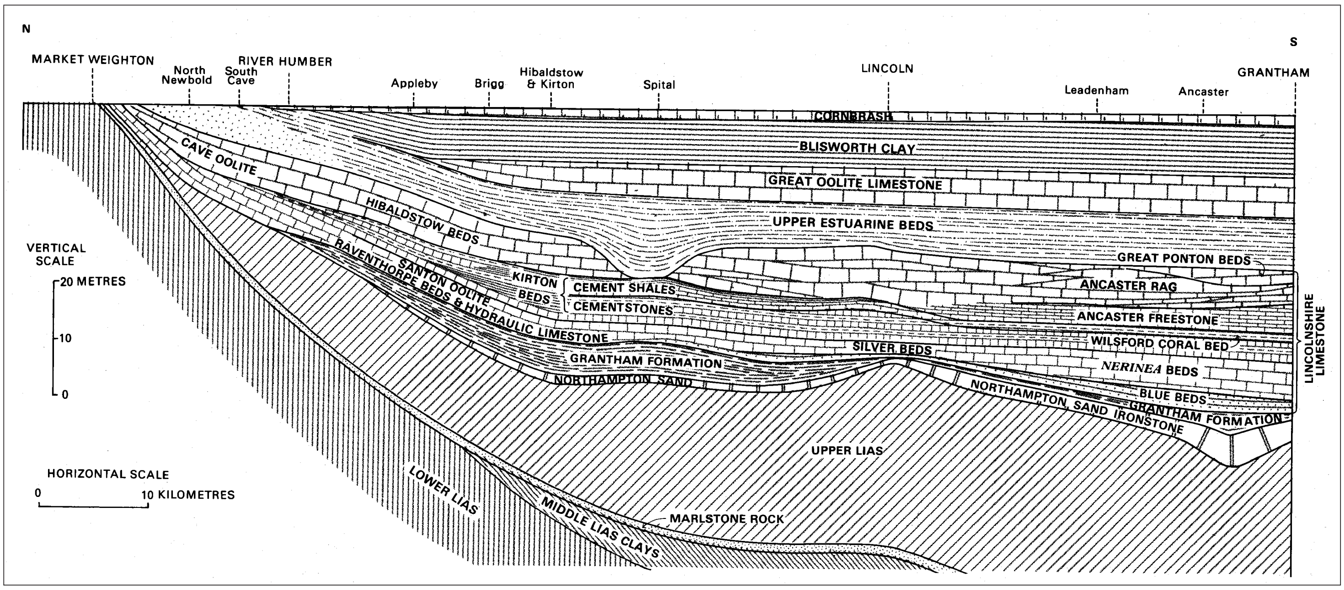


Figure 6.3.2a Generalised section of Lower and Middle Jurassic rocks from Market Weighton to Grantham (from Kent, 1980).

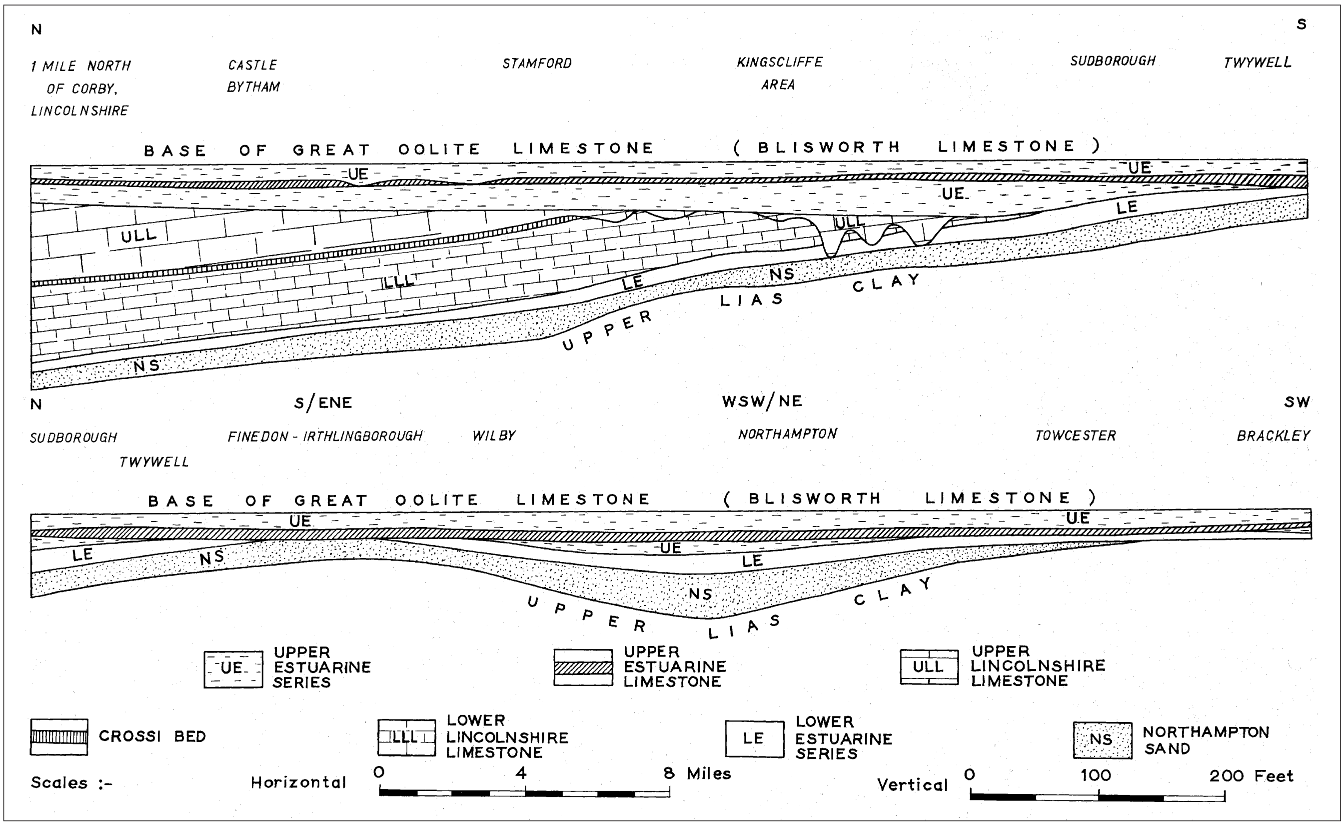


Figure 6.3.2b Generalised section of Middle Jurassic rocks from near Corby to Brackley (after Hains and Horton, 1969).

outcrop; further north where the dip is greater the aquifer becomes too deep to exploit just a few kilometres east of the outcrop area.

Springs occur at the base of the formation in the west. Part of the outcrop area is covered by low permeability till, restricting recharge. Locally the Lower Lincolnshire Limestone may be confined by the Crossi Bed (the uppermost of several thin micritic limestones with clay partings which occur at its junction with the Upper Lincolnshire Limetone in South Lincolnshire), as indicated by upsurges of water during drilling (Peach 1984). Often seasonal head differences are large, caused by the aquifer responding rapidly to recharge, as enhanced fractures allow runoff to enter the aquifer and be rapidly transferred down the hydraulic gradient.

Near outcrop, tracer tests have locally proved flow velocities of many hundreds of metres per day (Booker, 1981). Aggressive recharge water has enhanced solution of the limestone, particularly along the edge of the clay overburden where run-off from the clay contributes to the recharge, and along river valleys where swallow holes have been recorded.

Licensed abstraction from the Lincolnshire Limestone is around 150 000 m^3/d: over half of this coming from the southern area, with the remainder taken from the central and northern areas in approximately equal proportions. All major abstractions are from the confined aquifer.

Where the Grantham Formation is thin, hydraulic continuity is frequently expected between the Northampton Sand Formation and the Lincolnshire Limestone. There is also possibly small amounts of flow between the Lincolnshire and Blisworth Limestones through the Rutland Formation, but this is unlikely to be significant in terms of the overall aquifer resources.

The saturated thickness of the unconfined Lincolnshire Limestone is highly variable, as the water table shows a rapid response to recharge. In the central part of the area, the unconfined Limestone often becomes dewatered (Peach, 1984). However, the confined aquifer has a more constant saturated thickness of around 20 m in the south, decreasing north of Lincoln.

Aquifer properties

Core data

Porosity and permeability data are available for a total of 413 samples from 13 boreholes into the Lincolnshire Limestone (Table 6.1.3). Data from two samples obtained from the Cave Oolite, the lateral equivalent of the Upper Lincolnshire Limestone to the north of the Humber, indicate very similar physical properties to those of the Lincolnshire Limestone and have therefore been included in the data set.

Edmunds and Walton (1983) reported porosity values of around 13–18%; Smith-Carrington et al. (1983) reported interconnected porosities of 10–25%. The BGS core data indicate porosity has a normal frequency distribution (Figure 6.3.3a) with an interquartile range of 13.1 to 21.6% and an arithmetic mean of 18.0%. The overall range of porosity recorded was however considerable with a minimum of only 2.5% and a maximum of 51.1%. However, the fracture porosity, which is of primary importance to the aquifer properties, is generally thought to be around 1%. Wilson et al. (1990) suggested a primary porosity of 25% and a fracture porosity of 0.4%.

Edmunds and Walton (1983) considered that intergranular permeabilities are very low ($<6 \times 10^{-4}$ m/d) due to partial cementation. The permeability of a considerable number of samples tested by BGS was less than the minimum measurable. This has created a high frequency of very low hydraulic conductivity measurements (Figure 6.3.3b). Otherwise the data approximate to a log normal distribution with the generally low permeability being well illustrated by an interquartile range of only 5.0×10^{-5} to 4.4×10^{-4} m/d. The geometric mean is also low at 1.3×10^{-4} m/d; probably indicating the presence of minor fractures. Core permeabilities of up to 0.17 m/d indicate the presence of larger discontinuities.

In general permeability increases with porosity, although this relationship is better defined at lower values. Again the extremely low values (2×10^{-6} m/d) create a rather anomalous feature with corresponding porosities ranging

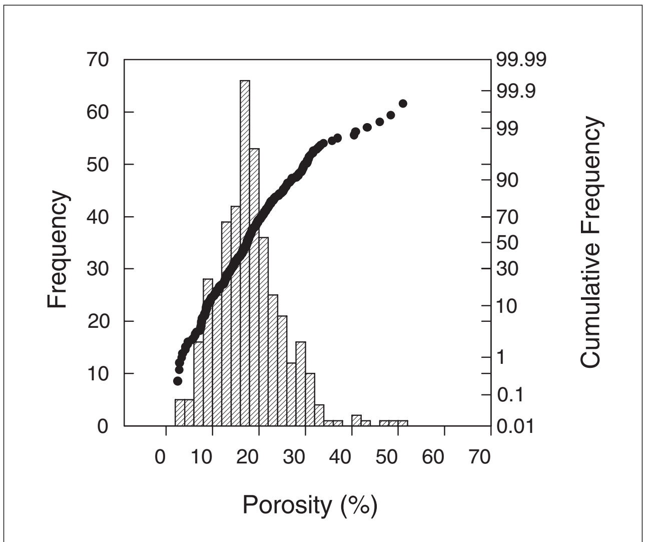


Figure 6.3.3a Distribution of porosity data for Lincolnshire Limestone samples.

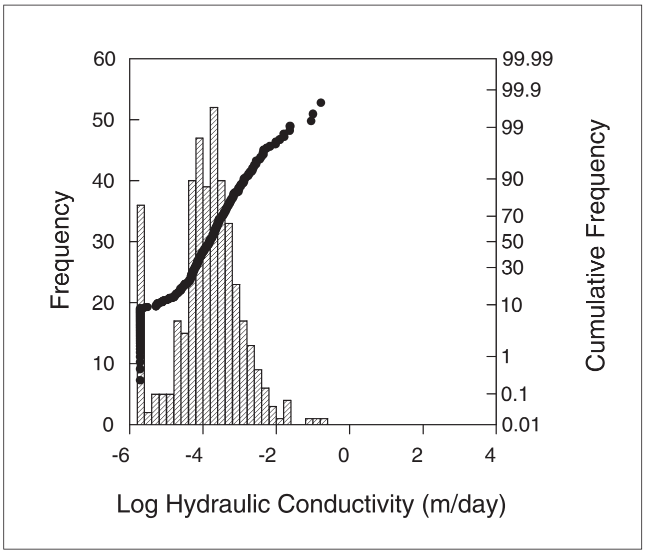


Figure 6.3.3b Distribution of hydraulic conductivity data for Lincolnshire Limestone samples.

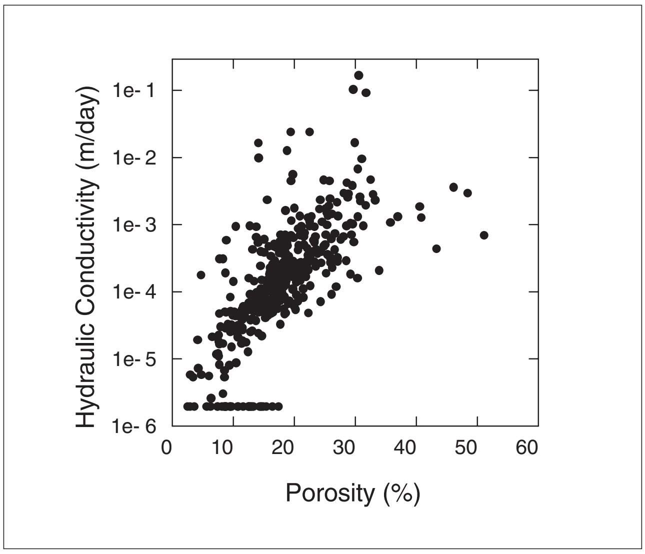


Figure 6.3.3c Plot of hydraulic conductivity against porosity for Lincolnshire Limestone samples.

up to about 17% (Figure 6.3.3c); this effect is possibly due to an increased presence of clay minerals. Samples possessing very low porosity and permeability are likely to be very hard and well cemented. There is no discernable trend in porosity or permeability with depth in any of the boreholes.

Permeability and transmissivity

Horizontal variations in permeability and thickness result in highly variable transmissivities and storage coefficients. The lateral distribution of transmissivity was described as follows by Downing and Williams (1969):

— to the south of Sleaford, transmissivity values exceed 1500 m^2/d, and may be as high as 4000 m^2/d.

— between Sleaford and Brigg the transmissivity is generally less than 450 m^2/d but to the north of Brigg values are generally higher (450 m^2/d to 900 m^2/d). The latter may be due to the proximity of the Humber which could have induced groundwater flow through the aquifer during the Pleistocene.

— the transmissivity is low in the Glentham area where the Hibaldstow Beds are absent and only the more argillaceous Kirton Beds exist, and also low in the east of the aquifer where the chemical quality of the groundwater indicates that water movement is very slow.

This distribution tends to be confirmed by the collected data (Table 6.1.2). There are 58 locations with transmissivity data. All the major abstractions are from the confined aquifer, therefore there are very few pumping tests, and hence transmissivity values and storage coefficients, available from the unconfined part of the aquifer. Figure 6.3.4 shows a large range of transmissivity values; between Lincoln and Brigg values are generally less than 1000 m^2/d, and often around 100 m^2/d; south of Lincoln most values are between 1000 and 5000 m^2/d. The highest values are found around Sleaford and near Stamford. Some values of over 10 000 m^2/d are recorded but confidence in these is low. Overall the interquartile range is 259 to 2265 m^2/d and the geometric mean 665 m^2/d.

The model of the southern Lincolnshire Limestone (Rushton et al., 1993) used initial values of transmissivity based on information from geological evidence, groundwater contours, pumping tests and previous modelling studies. These are shown in Figure 6.3.5. In the unconfined region, the transmissivity varies with changes in saturated thickness.

When modelling the Slea Catchment in the central Lincolnshire Limestone, Rushton et al. (1994) inferred transmissivities from the presence of gravels, groundwater gradients and responses to pumping, due to the lack of direct field information. The model shows an increase in transmissivity from 120 m^2/d in the west to 840 m^2/d around Sleaford. Pumping stations are situated close to the confining boundary and sited close to springs to utilise the enhanced transmissivities in these areas. In the confined region east of these pumping stations the transmissivity reaches 1300 m^2/d but falls significantly still further to the east. The transmissivity in the model is increased to 10 000 m^2/d in the valley of the River Slea between Wilsford and Sleaford due to the presence of river gravels. About 4 km south of Ancaster faulting has resulted in an outlier of Rutland Formation and Blisworth Formation and to the south-west and west of this high ground the transmissivity is increased to 2000 m^2/d to represent the result of enhanced recharge of runoff.

Controls on permeability and transmissivity

As described above, the flow in the Lincolnshire Limestone is highly fracture-dependent. However, Downing and Williams (1969) suggested that, although the secondary

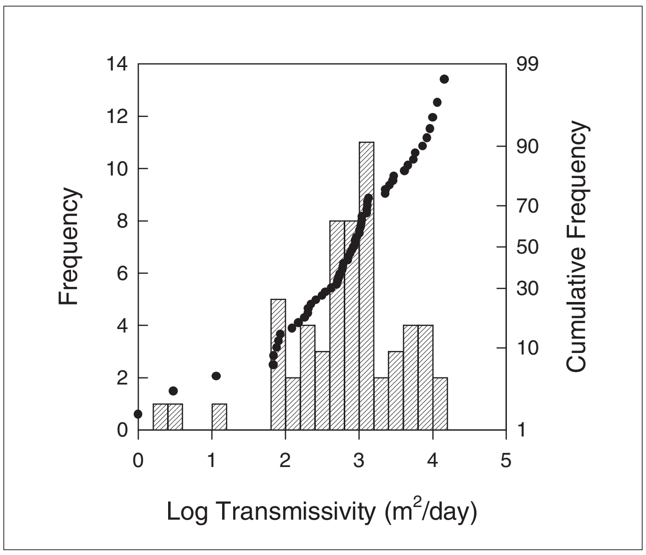


Figure 6.3.4 Distribution of transmissivity data from pumping tests in the Lincolnshire Limestone.

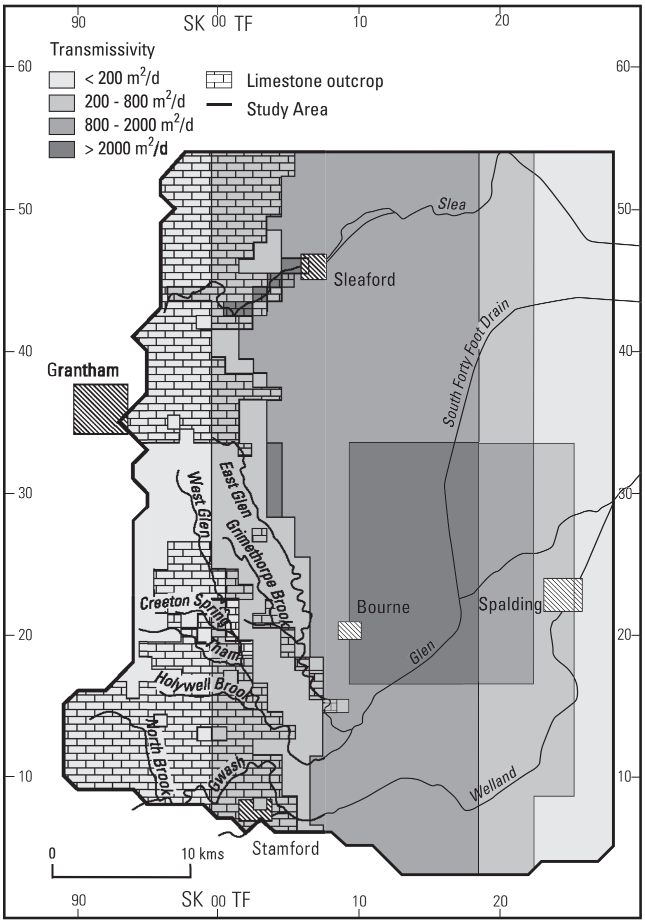


Figure 6.3.5 Distribution of transmissivity in the west–east direction in the model of the southern Lincolnshire Limestone (after Rushton et al., 1993).

porosity of the rock is of major importance in determining permeability, the mass of the rock in particular lithologies, such as the oolites, is relatively porous, and intergranular groundwater flow takes place to some extent through these deposits. The high sustained yields that are obtained from the southern Lincolnshire Limestone indicate that the fracture system is extensive and that the principal fractures are connected to smaller systems, which may be fed to some extent by slow seepage from certain lithologies through which intergranular flow occurs. However, the greatest control on the permeability and transmissivity of the aquifer will be factors affecting the development of fractures and flow horizons.

Recharge

Fractures in limestone are enhanced by solution caused by aggressive recharge water. Hence limestones in the outcrop area develop larger fractures than limestones covered by impermeable deposits. Runoff from the till which covers parts of the southern Lincolnshire Limestone may enhance the development of fractures when it reaches, and recharges into, the drift-free aquifer. Enhanced fractures may also reflect past groundwater flow regimes: the greater solutional enhancement of fractures in the southern Limestone than in the north is thought to indicate greater groundwater flows in the past.

Structure

Faults have an unpredictable effect; they may provide vertical routes between different flow horizons in the limestone, or they may act as impermeable barriers. Faults may enhance transmissivities, due to associated fractures and increased heads. No assumptions can be made on the effects of any particular fault, they will depend on local groundwater heads, stream flows and abstractions. Data on the positions of faults are also unreliable in many areas.

Lithology

Robertson and Perkins (1982) suggested that the flow horizons are stratigraphically controlled. Different parts of the succession are important for flow in different areas of the limestone. At Ashby-de-la-Launde pumping station [TF 0510 5520], the dominant yielding zones lie in the lower and central parts of the Lincolnshire Limestone, just below and above the Kirton Cementstone. The top horizons of the Upper Lincolnshire Limestone yield around 15–20% of the total volume pumped (Robertson and Perkins, 1982). However, investigations at Welton [TF 015 815] showed that the main flows in the Limestone at that site were in the top of the aquifer, with very little flow from beneath the Kirton Cementstone. An investigation in the Evedon–Willoughby area also found that most of the groundwater flow was in the Upper Lincolnshire Limestone. Peach (1984) concluded that north of Scopwick [TF 08 58] there is less flow in the Lower Lincolnshire Limestone than in the Upper; at Ashby the situation is reversed. As the Lincolnshire Limestone thins northwards, the relative importance to groundwater flow of the Upper and Lower Lincolnshire Limestone alters. In the south, the Lower Lincolnshire Limestone has a relatively constant thickness of around 13 m. Further north, this thins to less than a metre, and the Upper Lincolnshire Limestone (Hibaldstow Beds), with a thickness of up to 15 m, is more important. Transfer between flow horizons occurs as the water table crosses stratigraphic boundaries.

High transmissivities in the confined aquifer south of Sleaford contrast with lower transmissivities to the north. Downing and Williams (1969) suggested that this is due to differences in the lithology of the aquifer which becomes more argillaceous north of Sleaford.

Over- and underlying deposits

Glacial sand and gravel overlying the Southern Lincolnshire Limestone may increase the calculated transmissivity and storage of the aquifer.

Where the Rutland Formation is more permeable and there is a small degree of hydraulic interconnection between the Lincolnshire and Blisworth limestones, the Blisworth Limestone does not greatly increase the transmissivity of the Lincolnshire Limestone.

In south Lincolnshire, hydraulic continuity between the Northampton Sand Formation and the Lincolnshire Limestone can increase the transmissivity. This occurs where the Grantham Formation is thin or in quarry workings. Where the Northampton Sand is 6 m thick and fully saturated, it is likely to have a transmissivity of around 60 m^2/d; this is unlikely to be significant in the confined area, where the transmissivities of the Lincolnshire Limestone are above 1000 m^2/d, but at outcrop, where transmissivities are lower, this contribution from the Northampton Sand Formation is more significant.

Glacial action

The fracture pattern has been enhanced by frost action, particularly during the Pleistocene. This is particularly true at outcrop, as where the Lincolnshire Limestone is relatively thin the entire thickness is likely to have been affected by permafrost.

Storage coefficient

As mentioned above, Downing and Williams (1969) considered that certain facies have a relatively porous rock mass, which supports storage, although the storage capacity is mainly dependent on fractures and micro-fractures. These authors considered that the aquifer has a considerable storage capacity, reflected by the delayed response of water levels to infiltration and the corresponding relatively slow decline in storage during dry periods in some areas. However, others (e.g. Anglian Water Services, personal communication) consider the Lincolnshire Limestone shows a rapid response to recharge, and storage coefficients are generally considered to be low. The collected data (Table 6.1.2, Figure 6.3.6) of 37 values shows a range of storage coefficients from 2×10^{-7} to 0.58, with the majority being between 10^{-5} and 10^{-3}. Downing and Williams (1969) quoted pumping test derived values of storage coefficient from 10^{-5} to 10^{-3} for the confined aquifer, despite suggesting that the Limestone is a high storage aquifer. These authors used information on the lithology of the formation, the characteristics of the aquifer and water level fluctuations in response to infiltration to imply an unconfined storage coefficient of around 0.05.

The collected data from pumping tests do not show such a clear distinction between storage coefficients for the unconfined and confined areas. Values derived from pumping tests are generally less than 0.01. However, the validity of storage coefficients derived from pumping tests are questionable for an aquifer such as the Lincolnshire Limestone. The few pumping tests which exist for the unconfined aquifer indicate a range in storage coefficients from 4×10^{-5} to 2×10^{-3}, similar to that for the confined aquifer.

The model of the southern Lincolnshire Limestone (Rushton et al., 1993) defined three main zones in which the storage coefficient has different values (Figure 6.3.7):

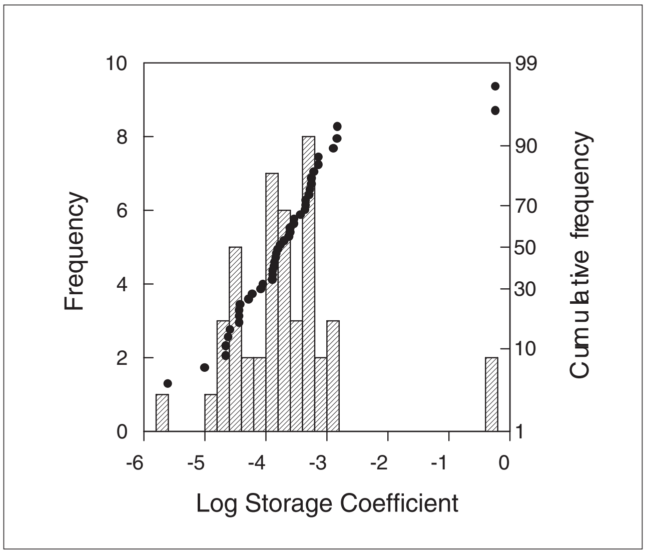


Figure 6.3.6 Distribution of storage coefficient data from pumping tests in the Lincolnshire Limestone.

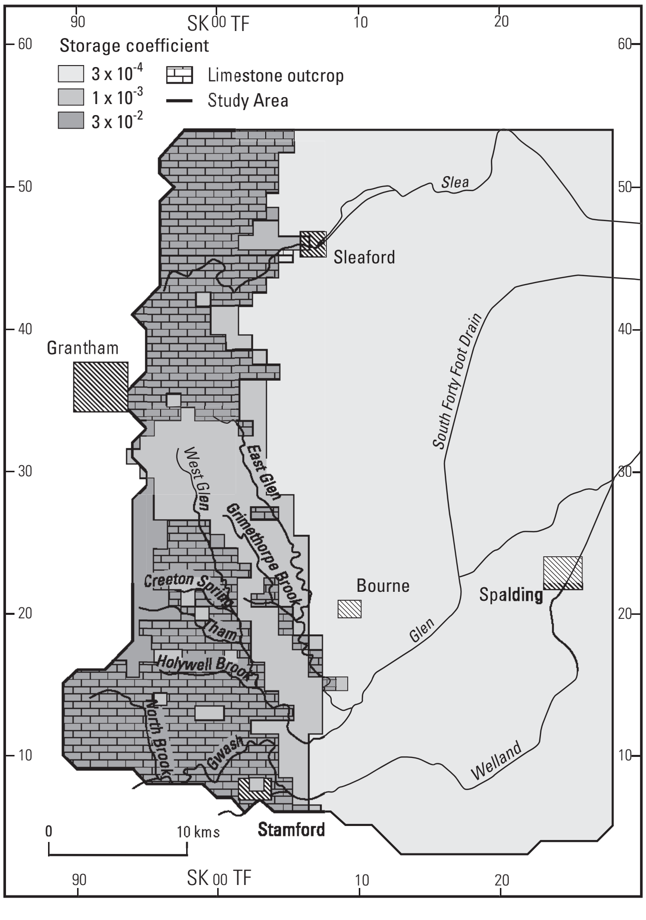


Figure 6.3.7 Distribution of storage coefficients in the model of the southern Lincolnshire Limestone (after Rushton et al., 1993).

Unconfined zone with no overlying beds: in these areas the fractures and bedding planes have been enhanced by weathering and the development of solution channels. The specific yield is in the range 0.01 to 0.05.

Unconfined zone with overlying beds: the presence of the overlying beds restricts the enhancement of the fractures and bedding planes by solution; storage coefficients are in the range 0.001 to 0.01.

Confined zone: the confined storage coefficient applies, with values in the range 1×10^{-4} to 9×10^{-4}.

The model of the Slea Catchment in the central Lincolnshire Limestone (Rushton et al., 1994) set storage coefficients as follows:

0.01 for the unconfined area
0.001 for the unconfined zone with overlying beds
2.5×10^{-4} for the confined area

No correlation between storage coefficient and transmissivity was obtained; if there had been one this might indicate that both are controlled by the same factors (fractures, micro-fractures or pores).

6.3.3 Great Oolite Group

In this area the Great Oolite Group can be subdivided into the Rutland Formation at the base, overlain by the Blisworth Limestone, Blisworth Clay and Cornbrash formations.

The Blisworth Limestone is absent north of Brigg. It thickens gradually southwards until in South Lincolnshire it comprises 7–8 m of soft limestone with marly partings. In Northamptonshire it comprises 4.5–7.5 m of shelly and oolitic limestones; while from Towcester south-westwards into Bedfordshire and Buckinghamshire it becomes a 20 m thick peloidal micrite, called the White Limestone and lithologically similar to the same formation in the north Cotswolds. The overlying Blisworth Clay (silty clay with silty sandstones and sandy limestones) passes laterally into the upper part of the White Limestone (Bladon Member) near Buckingham.

Shaw (1976) described the hydrogeology of the Middle Jurassic in the Great Ouse, Ray, Cherwell and Evenlode catchments. In the south-west of his area the Chipping Norton Limestone (Great Oolite Group) is in hydraulic continuity with the underlying Clypeus Grit (Inferior Oolite Group) as the Lower Estuarine Series is absent; the combined aquifer is 25–30 m thick in the Great Ouse catchment and 45 m in the Evenlode. Shaw (1976) quotes effective porosity values of 10 to 20% and specific yields (from centrifuged samples) of 2%. Overall porosities are highest in the zones of aeration and water level fluctuation, decreasing with depth in the saturated zone and downdip into the confined aquifer. Field values of hydraulic conductivity are hundreds of times higher than those measured in the laboratory, indicating the importance of fissure flow.

Offodile (1972) noted that the equipotential lines in the Blisworth Limestone were further apart in the area around Wappenham [SP 62 45] between the rivers Tove and Ouse, indicating that the limestone is more permeable in this area. He described a pumping test at Gawcott [SP 684 322], for which the time-drawdown plot had three sections. The transmissivity decreased and the storage coefficient increased with time, presumably indicating a confined aquifer which becomes semi-confined as it dewaters and induces leakage from the overlying beds.

There are 9 recorded values for the transmissivity of the Great Oolite in this area, ranging from 0.5 to 2800 m^2/d with an interquartile range of 105–1430 m^2/d; these values are about half those found further south-east in the Cotswolds where the aquifer is considerably thicker. There are only two storage coefficients, these are 5×10^{-3} and 5×10^{-4}.

6.4 THE COTSWOLDS

This is the area between the Vale of Moreton and the Mendips axes. The sequence is summarised in Table 6.4.1. The principal aquifers within this area are the Upper Lias Sands, Inferior Oolite and Great Oolite. Less important aquifers are the Marlstone Rock Formation, Cornbrash, Corallian and Portland and Purbeck beds. Where present, the Upper Lias Sands are in hydraulic continuity with the overlying Inferior Oolite limestones.

Richardson (1946) described the main aquifers in the Cotswolds and the interconnection between them and the springs and streams. This was followed in the seventies with the hydrogeology of various surface water catchments described in a series of theses. Reed (1975) studied the Windrush and Leach catchments, Al-Dabbagh (1975) the Coln, Churn and Frome catchments and Bromley (1975) the Bristol Avon in the south Cotswolds. More recently Atkins (1994) studied the Avon in the Malmesbury area with particular reference to river augmentation.

Properly constructed wells and springs from the oolites can yield 5000 m^3/d if they intersect a good fracture system (Al-Dabbagh, 1975). However, Bromley (1975) concluded that at flows in excess of 12.6 l/s (equivalent to 1089 m^3/d) turbulent flow can occur leading to significant well losses due to the aquifer being inefficient.

Birmingham University (1987) produced a model of the Great Oolite and the Inferior Oolite aquifers in the Cotswolds. This models the variations in transmissivity and storage coefficient with saturated depth and includes various flow boundaries to represent perennial and non-perennial streamflows. There is good agreement between the model and field values for both streamflows and groundwater heads at low flows; agreement is less good, particularly between the streamflows, at high flows, due to the extreme flashiness of the streams. Further modelling work of the Great Oolite in the Thames Basin is described by Rushton et al. (1992).

6.4.1 Upper Lias Sands

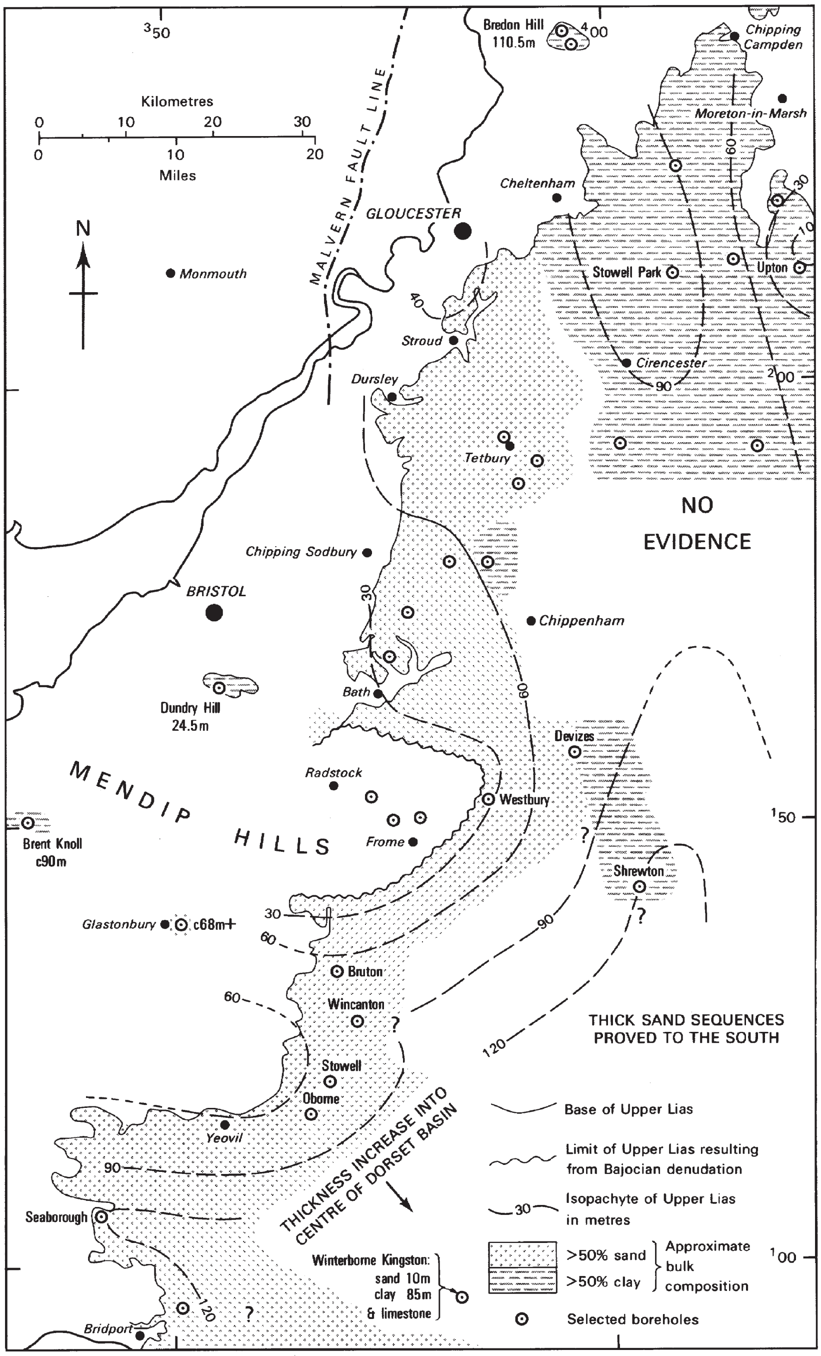
From Old Sodbury northwards the Upper Lias is represented by up to 60 m of fine, yellow sand with doggers (beds of calcareous sandstone); the Cotteswold Sands. These pass into clay between Stroud and Cirencester (Figure 6.4.1), from the base upwards. At Leckhampton [SO 94 17] the sands have practically disappeared and at Cleeve Hill [SO 98 27], the whole succession from the top of the Marlstone Rock Formation is represented by Upper

Table 6.4.1 Jurassic sequence in the Cotswolds.

	MAPPED UNIT	THICKNESS AND LITHOLOGY	
	Purbeck Group	up to 10 m	
	Portland Group	up to 13 m	
	Kimmeridge Clay Formation	up to 100 m	
	Corallian Group	25–35 m	
	Oxford Clay Formation	up to 150 m	
	Kellaways Formation	*Kellaways Sand Member* up to 9 m Kellaways Clay Member up to 28 m	
	Cornbrash Formation	up to 10 m shelly limestone	
	FOREST MARBLE FORMATION	up to 35 m	
GREAT	**SOUTH-WEST**	**CHIPPENHAM**	**NORTH-EAST**
	GREAT OOLITE FORMATION 20–30 m		
OOLITE	Upper Fuller's Earth Formation up to 28 m	ATHELSTAN OOLITE up to 25 m TRESHAM ROCK up to 18 m	WHITE LIMESTONE FM 20 m
GROUP		Hawkesbury Clay up to 10 m	
	Fuller's Earth Rock Formation up to 5 m		
50–100 m			
oolitic limestone	Lower Fuller's Earth Formation 10–15 m		Hampen Formationup to 10 m TAYNTON LIMESTONE FORMATION up to 12 m Fuller's Earth/Sharp's Hill Formation up to 25 m CHIPPING NORTON LIMESTONE FORMATION up to 12 m
	INFERIOR OOLITE GROUP	10–110 m oolitic limestones	
Upper Lias	COTTESWOLD/MIDFORD SANDS	up to 75 m	
	mudstones	up to 80 m	
	Junction Bed	0.5 m	
Middle Lias	*Marlstone Rock Formation*	up to 7 m	
	Dyrham Siltstone Formation	up to 50 m	
Lower Lias	mudstone	200 m	
	mudstone with limestone bands	up to 100 m	

CAPITALS = main aquifers
Italics = other aquifers

Figure 6.4.1 Isopachytes and lithological variations for the Upper Lias of southern England (from Green, 1992).



Lias clays (Green 1992). Southwards between Old Sodbury and the Mendips the Midford Sands occur, they are equivalent in age to the upper part of the Cotteswold Sands and comprise up to 20 m of uniform, fine-grained sands with occasional layers of doggers. In general, the sandy facies of the Upper Lias is older in the north than the south. Current nomenclature places all the the Upper Lias sands from the Cotswolds to Dorset in the Bridport Sand Formation.

There are springs at the junction with the underlying clays; some are significant such as the Bath Low Level Springs.

6.4.2 Inferior Oolite Group

Geology

Lithology

The Inferior Oolite Group comprises a sequence of shallow-water marine limestones, which reach their maximum thickness in the Cotswolds. The various formations are described in detail by Green (1992), Sumbler (1996) and Barron et al. (in press).

The Lower Inferior Oolite comprises the basal Scissum Beds, overlain in turn by the Lower Limestone, Pea Grit, Lower Freestone, Oolite Marl and Upper Freestone. The Harford Sands, Snowshill Clay and Tilestone outcrop over a restricted area in the north Cotswolds between Winchcombe and Broad Campden.

The Middle Inferior Oolite comprises various ironshot, oolitic and shelly limestones (Lower Trigonia Grit, Buckmani and Gryphite Grits, Notgrove Freestone, Witchellia Grit, Phillipsiana and Bourguetia Beds).

The Upper Inferior Oolite comprises the Upper Trigonia Grit, and between the Mendips and the south Cotswolds, the Doulting Stone-Anabacia Limestone which passes laterally into the Clypeus Grit north of Horton [SU 04 63].

In the Cotswolds the thickness of the Upper Inferior Oolite (which is present from the Mendips right across the Vale of Moreton axis) is relatively constant, thus variations in thickness (Figure 6.4.2) mainly reflects changes in the thickness of the Lower and Middle Inferior Oolite, which are only present from Old Sodbury to Stow-on-the-Wold. They reach a maximum at Cleeve Hill, where the Inferior Oolite Group exceeds 100 m in thickness. The limestones are predominantly oolitic and shell-fragmental; each of the three subdivisions are separated by well-marked unconformities. They were deposited in a generally shallow-water, high-energy environment.

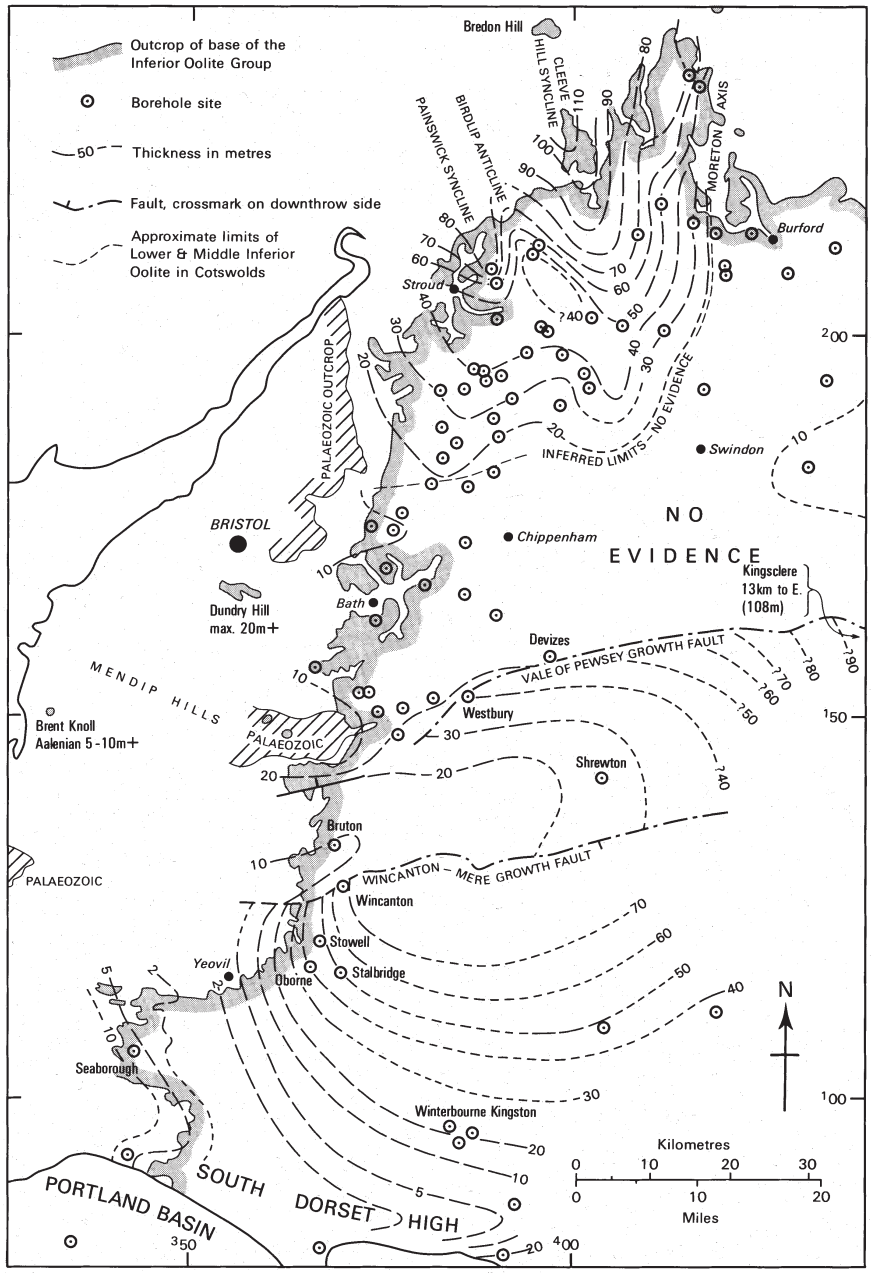
Structure

Figure 6.4.3 shows the variations in sedimentation during the Inferior Oolite within this area. During the Bajocian, the Cotswolds were affected by two main periods of intraformational erosion and transgression which separate the Lower, Middle and Upper Inferior Oolite. Sedimentation occurred without major interruption from Scissum Beds to Upper Freestone times, with subsidence being greatest in the Cheltenham–Cleeve Hill area. Erosion after deposition of the Middle Inferior Oolite resulted in its removal in many areas, and eastward overstep of the underlying Lower Inferior Oolite by the Upper Inferior Oolite.

The Chipping Norton Limestone at the base of the overlying Great Oolite Group in the north-eastern part of the area, is in hydraulic continuity with and considered to be part of the Inferior Oolite aquifer. In the area west of Stow-on-the-Wold, where there is no Fuller's Earth, the Great Oolite (above the Chipping Norton Limestone) and the Inferior Oolite are locally in hydraulic continuity.

In the north Cotswolds the overall drainage is southwards towards the Thames. In the central and south Cotswolds, drainage is also towards the Thames, with streams rising on the Upper Lias clays, then losing water, as they cross the Inferior Oolite (where the dip of the strata is greater than that of the valley profile), until they reach the Fuller's Earth Formation (Richardson, 1946). In the north Cotswolds the streams are generally effluent although

Figure 6.4.2 Isopachytes for the Inferior Oolite Group of southern England (from Green, 1992).



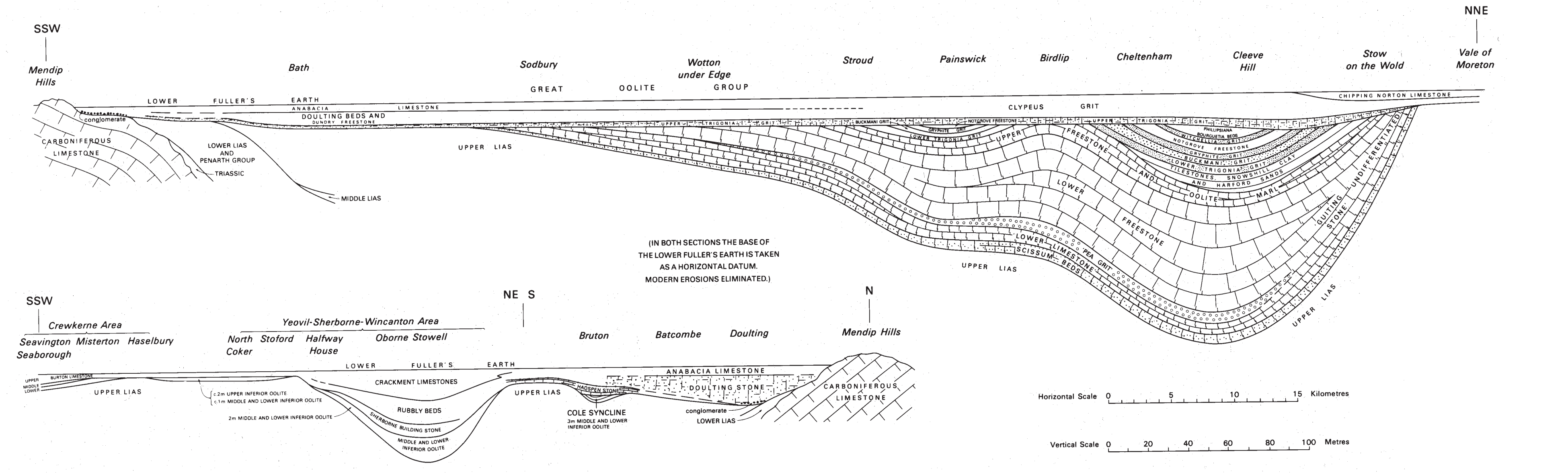


Figure 6.4.3 Horizontal diagrammatic section through the Inferior Oolite of southern England (from Green, 1992).

locally they lose water to the aquifer, particularly at times of low flow. The infiltrate from the Inferior Oolite reappears again further downstream often at specific large springs (e.g. East Leach [SP 196 068]) (Reed, 1975). Water in the Inferior Oolite aquifer on the scarp slope flows downdip beneath the Fuller's Earth and Great Oolite, from the Windrush and Coln catchments, beneath the surface watershed into the Leach catchment. Water also drains subsurface from the Churn catchment westwards into the Frome and eastwards into the Coln.

Aquifer properties

Core data

A total of 36 porosity and permeability analyses from the core of 5 boreholes are available for the Inferior Oolite. Although three of these boreholes were located on an outlier (Breedon Hill), the porosity and permeability values obtained lie within the range obtained for the other two boreholes located on the main outcrop.

The bulk of Inferior Oolite porosity values fall in the range 12 to 24% (Figure 6.4.4a), with an interquartile range of 15.7 to 21.3% and arithmetic mean of 19.1% (Table 6.1.3). Al-Dabbagh (1975) quoted a laboratory value of 4.3% and a value of 19% derived from resistivity logs for the porosity at Meysey Hampton [SU 1179 9903]. Reed (1974) estimated the linked porosity of the Inferior Oolite in the Windrush catchment to be 12.1% and the specific yield 1.8%. Hydraulic conductivities between 4×10^{-4} m/d and 6×10^{-4} m/d predominate (Figure 6.4.4b), being reflected by the interquartile range of 3.1×10^{-4} to 4.9×10^{-4} m/d and geometric mean of 5×10^{-4} m/d (Table 6.1.3). Although there is a general trend of rising porosity being matched by an increase in hydraulic conductivity, it is not as well defined as the trend for the Great Oolite in this area or the Lincolnshire Limestone further north.

Pumping test results

There are three storage coefficients for the Inferior Oolite, 7×10^{-5}, 1×10^{-4} and 8×10^{-2}, the first two representative of the confined and the last the unconfined aquifer. The 14 transmissivity values vary from 3 to 11 000 m^2/d (Table 6.1.2), with a geometric mean of 139 m^2/d. They are very variable but generally increase westwards reflecting the increase in thickness of the aquifer. Well efficiencies are very low, even after acidisation, suggesting that the real values of transmissivity could be significantly higher than those quoted. In the south Cotswolds transmissivities are less than in the overlying Great Oolite, but are generally between 200 and 700 m^2/d. However near Oldford [ST 7856 5063] a value of 1900 m^2/d was obtained from the early data. The later data is atypical of the Inferior Oolite aquifer because it is recharged by the Carboniferous Limestone with which it is in hydraulic continuity 1.5 km away, despite the two formations being separated by 33 m of Lias clays at this site.

Well behaviour

At Baunton [SP 019 048], the borehole overflows naturally whenever the maximum water levels are attained (Al-Dabbagh, 1975). The main inflows into the borehole occur from 23.5 m (base of the casing) to 27.4 m and at 35 m; minor inflows occur from 35 m to the base of the borehole at 40.8 m. Water levels fluctuate by about 10 m, responding to rainfall within a few days. When the borehole was pumped at 17 000 m^3/d, the drawdown was small indicating that most of the yield is likely to be at the expense of the River Churn. A tracer put into the river was seen in the borehole within minutes, so pumping evidently captures some of the flow in the river as well as natural discharge towards the river.

Aquifer behaviour

Abstraction from the main Inferior Oolite public supply sources at Baunton [SP 019 048], Meysey Hampton [SU 113 988] and Bibury [SP 112 071] have a rapid and significant effect on river flows.

During the 10 000 m^3/d pumping test on the Inferior Oolite aquifer at Meysey Hampton [SU 1134 9885], in 1973, the Swan springs at Bibury [SP 1142 0699], over 8 km to the north and originally thought to issue from the Great Oolite aquifer were depleted by between 1700 and 1900 m^3/d, equivalent to 20% of the flow. The springs are now thought to rise from the Inferior Oolite; water being forced up along a fault where the Fuller's Earth is downfaulted to the valley bottom. The Inferior Oolite test at Meysey Hampton also had an effect on the Great Oolite borehole at Ampney St Peter [SP 078 011], but no

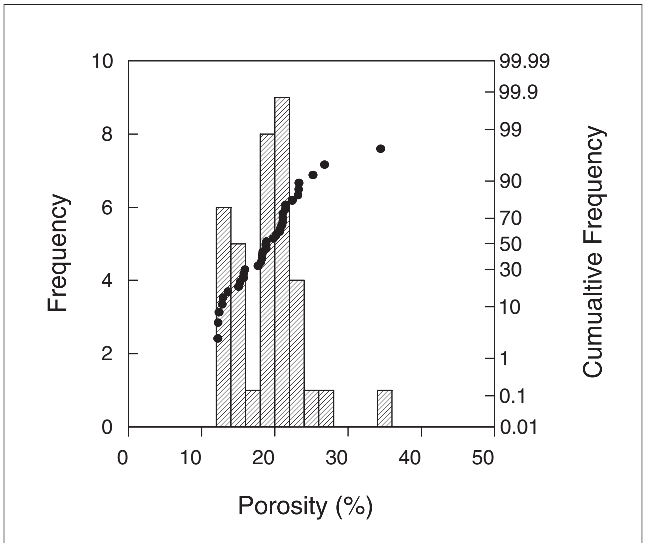


Figure 6.4.4a Distribution of porosity data for Inferior Oolite samples from the Cotswolds.

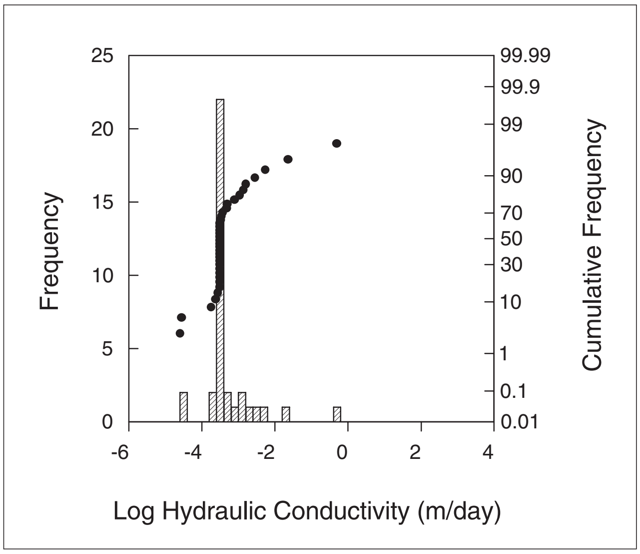


Figure 6.4.4b Distribution of hydraulic conductivity data for Inferior Oolite samples from the Cotswolds.

reduction was seen in the flow of the Great Oolite springs at Ampney Park [SP 0618 0233]. These results were used to infer the presence of a zone of low transmissivity associated with the decrease in aquifer thickness along an east-west fault between Ampney St Peter and Ampney Crucis (Birmingham University, 1987).

6.4.3 Great Oolite Group

Lithology

Detailed descriptions of the Great Oolite Group are given by Green (1992) and Sumbler (1996). Lithological and thickness variations are shown in Figures 6.4.5 and 6.4.6 respectively.

Between Cirencester and Moreton-in-the-Marsh, the Lower Fuller's Earth is progressively replaced by limestone units. The Chipping Norton Limestone (a sandy oolite) reaches a maximum thickness of 12 m in the Snowshill (or Hornsleasow) Quarry. The Fuller's Earth comprises from 0 to 25 m of mudstones with thin shelly limestones and the overlying Taynton Limestone Formation comprises up to 12 m of cross-bedded oolites. The Hampen Formation consists of 5–10 m of mudstones and marls with interbedded silty and sandy, oolitic limestones. The overlying White Limestone Formation, is about 20 m thick and includes

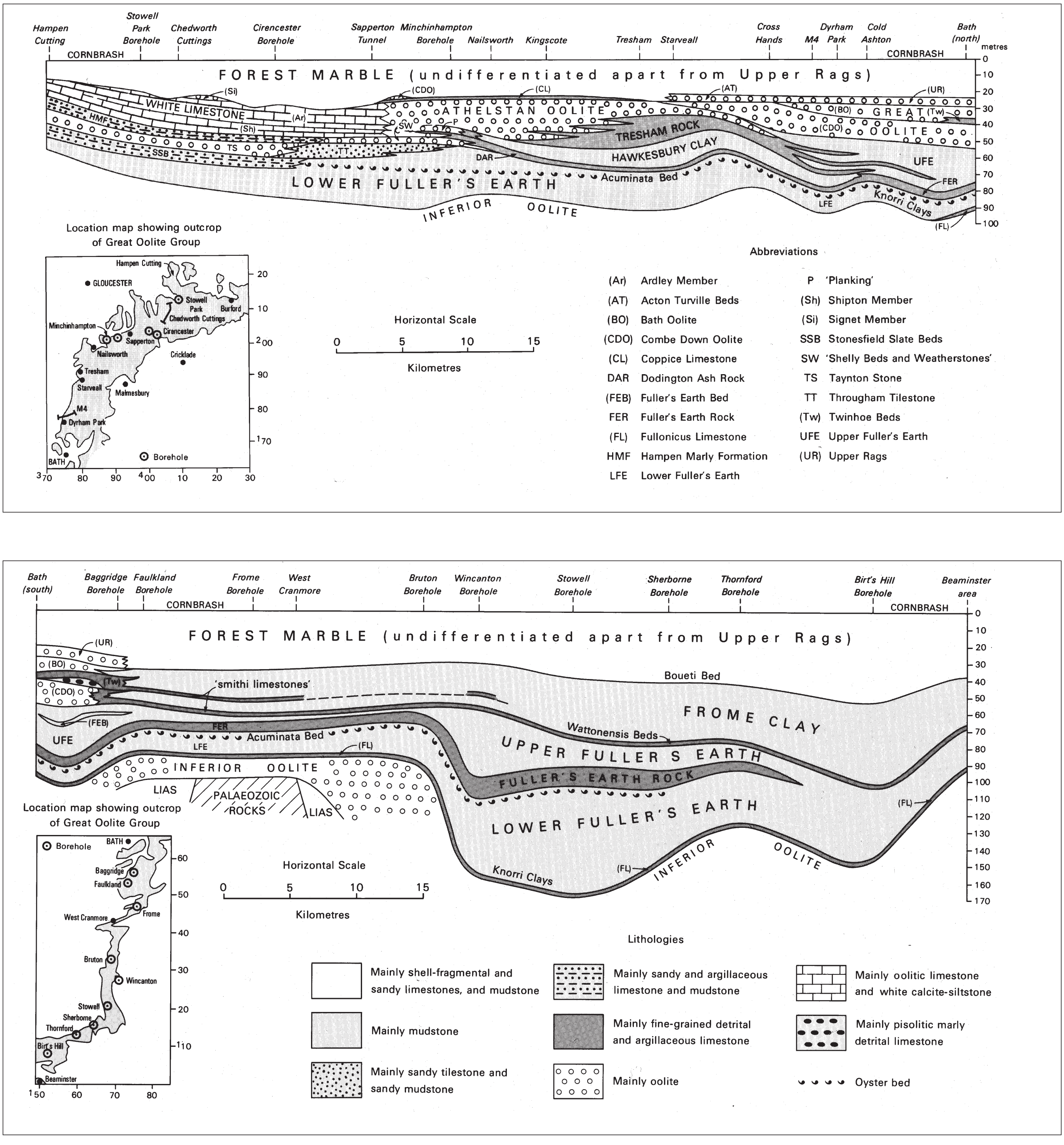
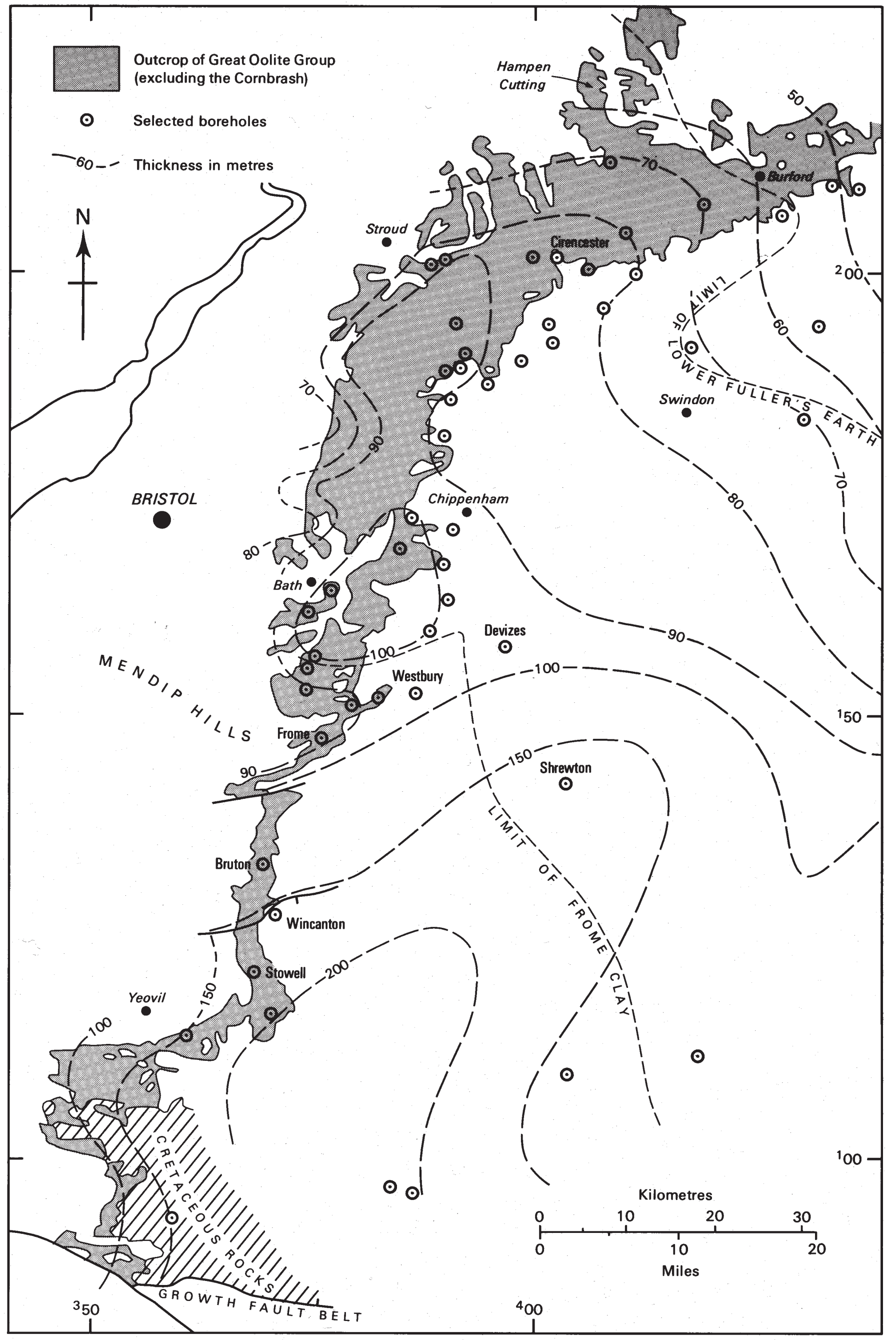


Figure 6.4.5 Diagrammatic section showing lateral variation of the Great Oolite Group in southern England (from Green, 1992).

Figure 6.4.6 Isopachytes for the Great Oolite Group of southern England (from Green, 1992).



calcite mudstones, peloidal limestones and cross-bedded oolites. In the area around Barnsley and towards Winterwell, small solution features are present which tractors have broken into.

South of Cirencester the sequence is similar but the formations have been given different names. In the area between Starveall and Nailsworth, the Upper Fuller's Earth comprises the Hawkesbury Clay, overlain and laterally replaced by the Tresham Rock. North-eastwards, both units are replaced by the Athelstan Oolite. North of Starveall, the Great Oolite Formation is absent and replaced by the Coppice Limestone.

Further south, the Lower Fuller's Earth and the Fuller's Earth Rock extend northwards over the Mendips axis into this area. The Upper Fuller's Earth comprises 0.5–28 m of calcareous mudstone and is overlain by 20–30 m of Great Oolite Formation (Combe Down Oolite, Twinhoe Beds and Bath Oolite). The Twinhoe Beds pass laterally into the Bath Oolite.

The Forest Marble is predominantly argillaceous, but the basal part is generally of limestone facies. Between Bath and Malmesbury it is 26–28 m thick. It thins to 20 m at Cirencester and 5–8 m at Burford. The overlying Cornbrash Formation, at the top of the Great Oolite Group, typically comprises about 3 to 4 m of fine-grained shelly limestone with thin clays and marls.

The Chipping Norton Limestone at the base of the Great Oolite Group is hydraulically separated from the rest of the Great Oolite aquifer by the Fuller's Earth Formation and is hydrogeologically part of the Inferior Oolite aquifer.

Recharge to the aquifer occurs through rivers and streams crossing the outcrop with any surplus water flowing downdip overflowing as springs at the junction with the underlying Fuller's Earth Formation. Some, such as the

Bath High Level Springs have significant yields. At times of high rainfall the springs move higher up the valleys.

Aquifer Properties

Core data

A total of 90 analyses from two boreholes (at depths of 4 to 39 m and 338 to 384 m), plus six from outcrops, are available for the Great Oolite. The porosity values have a normal distribution (Figure 6.4.7a) with an interquartile range of 11.2 to 17.9% and an arithmetic mean of 14.5%. The total range of values for borehole samples is about 5 to 25% whilst those from outcrop samples are higher ranging from 20 to 25%. Al-Dabbagh (1975) quoted a laboratory value of 3.7% and a value derived from resistivity logs of 19.5% for porosity at Meysey Hampton [SU 1179 9903]. Reed (1974) estimated the linked porosity of the Great Oolite in the Windrush catchment to be 8.6% and the specific yield 1.4%. Hydraulic conductivity values show a reasonable log-normal distribution (Figure 6.4.7b), they are predominantly low with an interquartile range of 2.54×10^{-4} to 2.97×10^{-3} m/d and a geometric mean of 9.8×10^{-5} m/d. The range of values from outcrop samples conforms with this range, whilst values obtained from borehole samples range from below the detection limit to a maximum of 0.035 m/d. In general terms, higher hydraulic conductivity values correspond with higher porosities but this correlation becomes less well defined as values increase (Figure 6.4.7c).

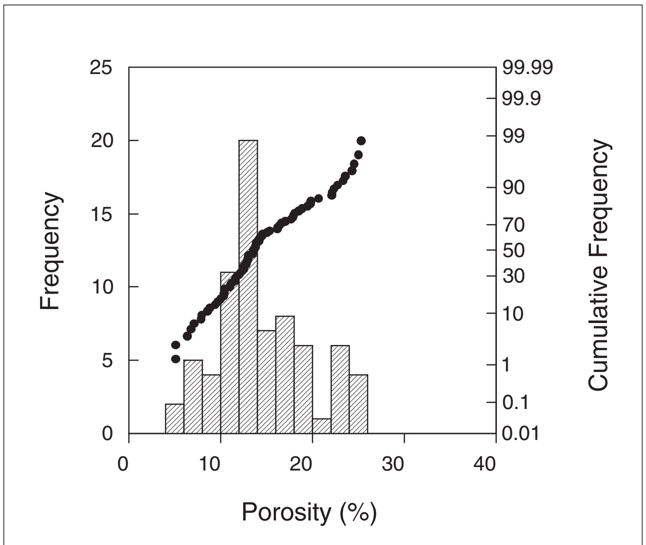


Figure 6.4.7a Distribution of porosity data for Great Oolite samples from the Cotswolds.

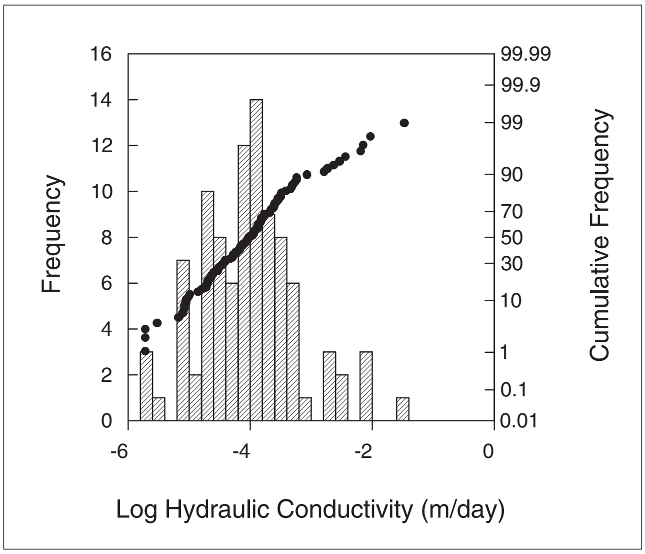


Figure 6.4.7b Distribution of hydraulic conductivity data for Great Oolite samples from the Cotswolds.

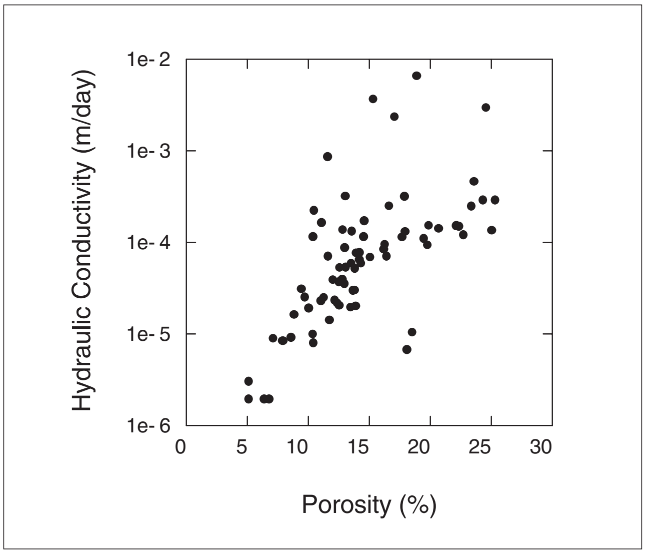


Figure 6.4.7c Plot of hydraulic conductivity against porosity for Great Oolite samples from the Cotswolds.

Pumping test results

There are 7 values for storage coefficient, ranging from 6×10^{-5} to 4×10^{-3} and their inter-quartile range is 1.0×10^{-4} to 6.8×10^{-4}. The effective fissure porosity (equivalent to specific yield) of the Great Oolite of the southern Cotswolds at outcrop was calculated as 3% by Bromley (1975), and he quoted 10^{-4} for the confined storage coefficient. There are 34 locations with recorded transmissivity data (Figure 6.4.8), ranging from 4 to 5900 m^2/d, their inter-quartile range is 37 to 825 m^2/d and the geometric mean 212 m^2/d. Rushton et al. (1992) used transmissivity values in the range 300–1500 m^2/d and storage coefficients of 10^{-5}–10^{-4} for the confined aquifer in their model of the Cotswolds.

Only the pumping tests at the Meysey Hampton [SU 113 988] and Ashton Keynes [SU 041 940] sites were carried out with sufficient observation wells to give reliable results. If the transmissivity values from these tests are plotted at the mid-point between the pumping well and the observation well from which the data was obtained, transmissivity values reach their maximum when the aquifer is fully saturated and confined beneath the Lower Fuller's Earth and gradually decrease again south-eastwards downdip (Robinson, V, personal communication). Acidisation of the borehole at Meysey Hampton [SU 1134 9885] was more successful in the Great Oolite than in the Inferior Oolite. It increased yields, and decreased drawdowns in both aquifers, but only reduced well losses in the Great Oolite.

In the south Cotswolds, transmissivities range from around 200 m^2/d across the synclines in the Holt–Chalfield area, to 1500–3000 m^2/d on the anticlines of the Lacock–

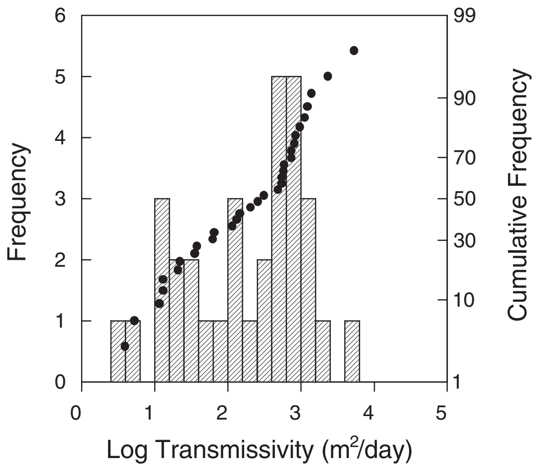


Figure 6.4.8 Distribution of transmissivity data from pumping tests in the Great Oolite of the Cotswolds.

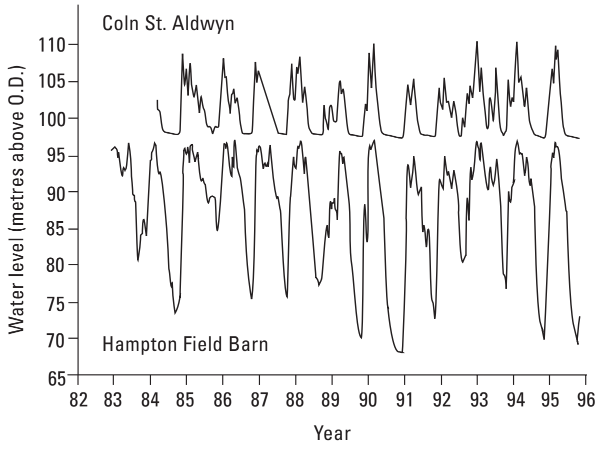


Figure 6.4.9 Hydrographs for wells in the Great Oolite at Hampton Field Barn [SP 1190 0175] and Coln St Aldwyn [SP 1450 0688].

Ivyfield area, where transmissivities are higher due to the increased thickness of the Fuller's Earth and Forest Marble limestones. Therefore although the yield of individual boreholes depends on the number of fissures encountered and their degree of interconnection, large-scale structure may also account for regional variations in transmissivity.

The jointing in the Taynton Limestone Formation separates it into clean angular blocks, while the White Limestone Formation forms silt-covered rounded blocks (Birmingham University, 1987). As the transmissivity at a particular site is the sum of the contributing saturated fissure transmissivities, faulting affecting the Taynton Limestone Formation, which provides a disproportionate amount will therefore have a significant effect on the overall transmissivity.

Aquifer behaviour

In certain situations, the Great Oolite aquifer can be considered to behave like a receptacle with a fixed volume; once water levels reach a particular height, water drains off elsewhere automatically via fractures or is discharged as springs as the aquifer cannot hold any more water. At Ampney Crucis [SP 0595 0190] the fluctuation in water levels is small because the head never goes above a certain level, excess water being discharged by the Ampney springs at the boundary of the White Limestone with the overlying Forest Marble clays. Conversely, in other localities, water levels will only drop to a certain base level and then fall no further, as they are either replenished or have reached the base of the aquifer. Figure 6.4.9 exhibits the maximum ceiling, levels rise to at Hampton Field Barn [SP 1190 0175] and the minimum levels they fall to at Coln St Aldwyn [SP 1450 0688]. Bromley (1975) noted that the minimum that water levels fell to each year at Westonbirt School [ST 8642 9030] was decreasing due to abstraction, but recharge was sufficient to replenish them to the same maximum level.

At times of low water levels the Leach disappears when it reaches the Great Oolite aquifer, emerging as a series of springs downstream at East Leach. As water levels rise, the resurgence point of the stream moves further upstream (similar to a Chalk bourne) and for a couple of months either side of the highest water levels there is a continuous stream along the Leach valley across the Great Oolite.

The principal Great Oolite public supply sources at Latton [SU 080 968], Ashton Keynes [SU 041 940] and Meysey Hampton [SU 113 988] take longer to affect river flows than the Inferior Oolite sources, although they do have a long-term effect on certain rivers. Therefore recent resource developments in the Great Oolite have attempted to utilise this delay in the response of the rivers, by devising a seasonal use of the sources that allows the major interference to occur when river flows are high while minimising the effects on low river flows (Rushton et al., 1992).

6.4.4 The Oolite aquifers

Water movement

The Inferior and Great Oolite aquifers are in varying degrees of hydraulic continuity due to the hydraulic gradients induced by pumping and variations in thickness and fracturing of the intervening Fuller's Earth clays. In the west, where the Fuller's Earth is thicker, steady state leaky conditions occur after a few days. In the east, the thinness of the clay means that the water levels are the same and the two aquifers respond as one.

Smart (1976) used dye tracing in the By Brook (a tributary of the River Avon to the east of Bath) catchment to study the flow system in the Great Oolite aquifer. Streams forming on the Forest Marble, enter the densely fractured Great Oolite at discrete sinks and reappear again further east as springs at the Great Oolite/Fuller's Earth boundary. The shape of the dye time/concentration curves indicated that the first arrival and the time to peak are both very rapid indicating that rapid fracture flow occurs with velocities of 10 000 m/day. However, the very long tail indicated that considerable dispersion and temporary storage of water in the dense network of small fractures occurs and the tracer dilution rates gave velocities as low as 2×10^{-4} m/day. Therefore the flow conduits in the Great Oolite are considerably less well defined than those of the more massive and karstic Carboniferous Limestone.

In the Bristol Avon catchment, Bromley (1975) noted that two distinct flow systems operate in both the Great and Inferior Oolite aquifers. There is a shallow flow system, where water flows down hydraulic gradient to become intercepted by and discharged rapidly to the valley streams (Avon and its tributaries) and a deeper system which recharges the confined part of the aquifer where it is mainly channelled towards the pumping stations. The Great Oolite discharges via springs thrown out at both the top and bottom of the formation at the junction with the overlying and underlying aquitards. The discharge from the Bath Upper Level Springs, at the base of the Great Oolite, increases by a factor of 15 after rain. Springs also occur on the dip slope, where the aquifer is artesian and groundwater reaches the surface via faults and fissures through the confining layer. Here many of the streams are effluent, with the head moving depending on the time of year and water levels in the aquifer. The Inferior Oolite discharges mainly via springs at the base of the Inferior Oolite/Midford Sands aquifer, e.g. Bath Lower Level Springs. These are much less responsive to rainfall (the discharge varying by only a factor of two), than those from the Great Oolite, reflecting the greater storage of the lower aquifer. There are few discharges at the top of the aquifer and no dip slope springs fed from the confined aquifer. However east of the River Avon, away from the public supply abstractions, Inferior Oolite water slowly discharges up through the cover.

In the Malmesbury area, the perennial heads of the main tributaries of the Avon are maintained by discrete springs (Atkins, 1994). The groundwater levels in the Great Oolite are up to 40 m higher than those in the Inferior Oolite, with mounds in the Inferior Oolite potentiometric surface related to the location of springs in the Great Oolite and possibly indicating zones of downward flow from the Great to the Inferior Oolite. The river augmentation boreholes into the Inferior Oolite at Stanbridge [ST 841 861], Luckington [ST 834 831] and Hullavington [ST 888 825] were located on these mounds. The annual abstraction from the Inferior Oolite is an order of magnitude greater than the direct recharge to the aquifer through its narrow outcrop area. As there is highly saline groundwater only a few kilometres downdip to the east, but no sign of increased salinity or reduced groundwater levels in the groundwater scheme boreholes, the Inferior Oolite must be recharged from the Great Oolite. This probably occurs both as seepage across the Fuller's Earth and downward flow along fractures and faults. The response of both aquifers to abstraction is heterogeneous with drawdowns not being related to yield or distance away from pumping sources. In the Great Oolite aquifer, the borehole at Cowbridge had a proportionately greater effect, causing higher drawdowns, on the aquifer along the lower Sherston and Tetbury Avon tributaries than other sources. Atkins (1994) noted that drawdowns increased as water levels fell and no by-pass flow reaches the aquifer when soil moisture deficits are high. Also stream bed losses do not increase with increased augmentation, as the losses are essentially independent of the flow rate in the river. It is therefore beneficial to transfer the augmentation water to the river as far upstream as possible.

In the Cotswolds, storage is limited in the north and northwest where the Great and Inferior Oolites outcrop, as the aquifers are dissected by deeply incised river valleys and faulting. Downdip, to the south and south-east, approaching the confined region the aquifer is more continuous and storage improves and there is potential for good yields (Al-Dabbagh, 1972; Rushton et al., 1992). Abstraction from the confined aquifer takes only a small proportion of the recharge as the rivers are more successful at obtaining water from the unconfined aquifer than boreholes in the confined region. If the abstraction from the confined aquifer is increased, some additional water comes from the unconfined aquifer but most is supplied by vertical flow through the overlying confining beds with a small contribution from confined storage.

River flows in the Cotswolds respond very rapidly to autumn rainfall, but the recession of flows in the summer months is much more gentle (Rushton et al., 1992). The response by the river flows occurs soon after recharge commences, well before aquifer storage is fully replenished indicating water is rapidly transferred laterally via highly transmissive but low storage fractures. However the response of the aquifer and river flows during a recession indicate that the bulk of the aquifer has a low transmissivity and a specific yield of 1–2 % (Birmingham University, 1987). The rapid response to recharge means that the permeability of the aquifer must increase with head, creating a non-linear increase in transmissivity. This theory is supported by higher yields being obtained in winter. Additionally the storage of the aquifers increases in the wet season as water moves from the larger fractures into the smaller ones and finally the pore spaces. When water levels and transmissivities are low (e.g. autumn 1976), the water cannot move rapidly to the rivers and a large amount of recharge can occur for only a small increase in river flows. Conversely when water levels are high, transmissivities are also high and river flows can remain high despite limited recharge (e.g. spring 1977). When this was incorporated into the Birmingham University model, groundwater variations plus spring flows in both the unconfined and confined parts of the aquifer could be reproduced.

The borehole at the Royal Agricultural College at Cirencester [SP 0048 0122] is unconfined and the water levels respond to individual storms as well as seasonal variations in recharge. Observations in the Great Oolite along the course of a pipeline at Barnsley [SP 077 041] indicate that neither the thin marl bands within the White Limestone Formation nor the Hampen Formation are likely to have an effect on the regional flow because fractures are so prevalent. However, the direction of groundwater flow in a large fracture was observed to change direction with time implying that on a local scale, marl bands do have some effect (Birmingham University, 1987).

Faults with throws of 30 to 50 m occur within the aquifers meaning that locally the Inferior Oolite and Great Oolite are hydraulically connected in a horizontal direction. Transmissivities may also be reduced due to faulting. The presence of faults has been inferred from the lack of interference between boreholes, e.g. pumping at Ashton Keynes [SU 041 940] affects different boreholes to those affected by pumping at Latton [SU 080968] (Birmingham University, 1987).

In the abstraction borehole at Meysey Hampton [SU 1134 9885], the only fractures in the Great Oolite are at 51 m and between 74–76 m. In the Inferior Oolite they occur at 116 m, 122 m, 130 m and from 131.0 to 131.8 m. In the Great Oolite when pumping at 57 l/sec, 65% of the flow came from 60–70 m and was derived from the lower fractures. In the Inferior Oolite 80–95% of the 29 l/sec overflow came from the fractures between 130–132 m depth and the artesian overflow increased significantly with depth of drilling. In the nearby observation borehole [SU 1179 9903], the fractures are at 35.5 m in the Great Oolite and 102.5, 105 and 122 m in the Inferior Oolite. Water moves from the Inferior Oolite upwards into the Great Oolite, as heads are higher in the former aquifer. The Inferior Oolite is more fractured than the Great Oolite, possibly because it has a lower clay content (Al-Dabbagh, 1975). The transmissivity of the Great Oolite is however about twice that of the Inferior

Oolite and after pumping for 200 days at 9000 m^3/d the drawdowns in the Great Oolite were smaller than in the Inferior Oolite due to the Great Oolite being unconfined while the Inferior Oolite remained confined.

Al-Dabbagh (1975) noted that plots of yield against drawdown for both the Great and Inferior Oolites at Meysey Hampton [SU 1134 9885] and the Inferior Oolite at Siddington [SU 040 999] were linear; similar plots for the Chalk are curved. This implies that the main contributing fractures are towards the base of the borehole and, unlike in the Chalk, are not dewatered by pumping.

Aquifer development and its effect on water quality in the aquifers

The Great and Inferior Oolites are both very similar hydraulically, with high transmissivities and low storage coefficients. Chemically the water from the two formations is virtually identical with variations reflecting the location of a sample within the aquifer, rather than which aquifer it is from. In both aquifers, a hydrochemical boundary marks the change from a typical calcium-bicarbonate unconfined water to a sodium-bicarbonate confined one. Development of the Inferior Oolite aquifer of the northern Cotswolds has increased the distance downdip from the base of the Fuller's Earth at which this hydrochemical boundary occurs, indicating that travel times are being reduced due to abstraction from the confined portion of the aquifer. The distance to the boundary was 4 to 8 km in the late seventies (Morgan-Jones and Eggboro, 1981) and 7 to 8 km in 1986 (Morgan-Jones, 1986). This is partly due to water moving downwards from the Great Oolite into the Inferior Oolite via faults which cross the outcrop area of the Great Oolite. Higgins (1992) only sampled within 5 km of the outcrop area and noticed no chemical changes, so the boundary could have moved even further by 1992. The confined water is low in nitrate and the tritium content indicates that there is a pre-1953 component of recharge. In the Great Oolite aquifer the hydrochemical boundary was 1 to 2 km downdip from the edge of the confined aquifer in the mid-seventies to eighties (Morgan-Jones and Eggboro, 1981; Morgan-Jones, 1986) and 2 km in 1992 (Higgins, 1992). At the present time it is not known whether increasing abstraction is also drawing water back up-gradient from the saline portion of the aquifer. However Birmingham University (1987) inferred from the shape of the groundwater level contours that the occurrence of poor quality water at Down Ampney [SU 1038 9583], Ashton Keynes Sewage Treatment Works [SU 0637 9318] and Cricklade [SU 1055 9394], close to the major abstractions at Ashton Keynes [SU 041 940] and Latton [SU 080 968] was due to this cause rather than the water being naturally of poor quality.

In the Bristol Avon catchment further south-west, Bromley (1975) noted that the total dissolved solids content of Inferior Oolite sources decreased slightly with time, due to leakage from the Great Oolite, while those in the Great Oolite increased slightly, due to downdip water being pulled in, and to leakage from the Forest Marble.

6.5 WESSEX (INCLUDING BRISTOL CHANNEL–CENTRAL SOMERSET) BASIN

This covers the Jurassic in the area between the Mendips and the south coast. A nearly complete Jurassic sequence, about 1350 m thick, is present and exposed along the Dorset coast between Lyme Regis and Swanage. The generalised succession is shown in Table 6.5.1. The main aquifers in this area are the Junction Bed, Upper Lias Sands, Inferior Oolite, Osmington Oolite (Dorset) and the Portland Stone. The less important aquifers are the Lower Lias limestones, Pennard Sands, Forest Marble, Cornbrash, Corallian (except for the Osmington Oolite), Portland Sands and Purbeck Beds.

O'Shea (1976, 1979) described the hydrogeology of the Upper Parrett basin in some detail.

6.5.1 Junction Bed

This bed comprises a basal Upper Lias limestone and the underlying Marlstone Rock. Along the coast the Marlstone Rock comprises less than 0.6 m of greenish, grey, brown-weathering limestone with limonite pellets. However, it thickens inland to up to 6 m of grey to brown ferruginous and highly fossiliferous limestone. The upper limestone consists of smoothly fracturing limestone which is locally mottled by iron and manganese oxides.

The Junction Bed is extremely well fractured and hence is highly vulnerable to pollution as water can travel rapidly through it. However due to its thinness, there are few abstractions from it and quantitatively little is known about its aquifer properties.

The Junction Bed is in hydraulic continuity with the underlying Pennard Sands in the upper Parrett catchment.

6.5.2 Upper Lias Sands

The Upper Lias Sands are now called the Bridport Sand Formation from the Cotswolds to Dorset. However, they are locally called the Bridport Sands in the south of the area and have been termed the Yeovil Sands further north. They comprise alternate beds of fine-grained sand or crumbly sandstone and sandy limestone. Their thickness variation is shown in Figure 6.4.1.

The Yeovil Sands comprise orthoquartzitic fine-grained sandstones and coarse siltstones; they become younger south-westwards. At Ham Hill west of Yeovil they contain high concentrations of calcium carbonate cement and pass laterally from sands with calcareous lenticles into 28 m of well cemented Ham Hill Stone. Davies (1966) looked at the composition of the Yeovil Sands in detail. The lower part of the Yeovil Sands is finer grained and more poorly sorted than the upper. He showed that both the amount of clay grade material and the percentage of matrix increase northwards from Yeovil [ST 55 15] to Castle Cary [ST 63 32]. The median grain size of the sand particles and the sorting of the sands also decrease northwards. Therefore the effective porosity and specific yield are likely to decrease northwards (O'Shea, 1976).

The unconsolidated nature of the sands mean that boreholes must be properly designed and constructed to minimise problems from running sands and maintain yields.

Morris and Shepherd (1982) studied the clay matrix of the very fine-grained quartz-rich Bridport Sands at Wytch Farm, to determine the effect of the clay mineralogy on the secondary recovery of oil from the reservoir. They concluded that the clay minerals had two different effects on the permeability of the reservoir. The kaolinitic clays move into the pore throats leading to dynamic permeability reduction (non-reversible), while the adsorption and expansion of other clay particles (probably illite-smectite) within the pore space was largely reversible (static permeability reduction). Overall the reduction in permeability caused by clay minerals varied from 30% in the best reservoirs to more than 70% in the low permeability sandstones.

Table 6.5.1 The Jurassic sequence in the Wessex (including Bristol Channel–Central Somerset) Basin.

	MAPPED UNIT		THICKNESS AND LITHOLOGY
	Lulworth Formation (Lower Purbeck)		up to 65 m laminated limestones with evaporites at base
	PORTLAND LIMESTONE FORMATION		up to 50 m sandy, shelly limestones
	Portland Sand Formation		up to 50 m sandy dolomite underlain by silty clay
	Kimmeridge Clay Formation		up to 500 m clays and shales
	Corallian Group		up to 90 m limestones, grits and clays
	Oxford Clay Formation		up to 150 m clays and shales
	Kellaways Formation	*Kellaways Sand Member*	up to 4.5 m
		Kellaways Clay Member	up to 21.0 m
	Cornbrash Formation		up to 10 m limestone and sandy marl
	Forest Marble Formation		up to 55 m clays with thin sandstones and thin central limestones
Great Oolite Group	Frome Clay		up to 60 m calcareous mudstones with Wattonensis Beds (up to 8 m argillaceous limestones) at base
	Upper Fuller's Earth		8–15 m calcareous mudstones and thin limestones
	Fuller's Earth Rock		4–10 m rubbly limestone
	Lower Fuller's Earth		35–55 m mudstones with thin limestones
	INFERIOR OOLITE GROUP		2–120 m limestone
	INLAND		**DORSET COAST**
Upper Lias	YEOVIL SANDS — up to 90 m sands with local limestones		BRIDPORT SANDS — up to 120 m sands Downcliff Clay — up to 21 m
	LIMESTONE up to 6 m		LIMESTONE up to 1.5 m (JUNCTION BED)
Middle Lias	MARLSTONE ROCK FORMATION up to 6 m		MARLSTONE ROCK FORMATION 0.2–4.3 m (JUNCTION BED)
	Pennard Sands Formation up to 75 m		Thorncombe Sands — up to 23 m yellow sands
			Downcliff Sands — 27 m micaceous sands and clays with sandstone bands and ironstone nodules Eype Clays 60 m
	Dyrham Siltstone Formation up to 45 m		Green Ammonite Beds — 30 m clays
Lower Lias	mudstone and shale up to 230 m		Belemnite Marls — 23 m calcareous marls Black Ven Marls — 43 m shales with impersistent limestones Shales with Beef — 22 m shales with mudstones and seams of fibrous calcite
	Blue Lias — up to 140 m interbedded limestones		*Blue Lias* 30 m mudstones and shales with limestone bands and shales

CAPITALS = main aquifers
Italics = other aquifers

Aquifer properties

Core analyses are available for a total of 135 samples from 6 boreholes and 22 samples from 3 outcrops of the Bridport and Yeovil Sands. Porosity and permeability values obtained from outcrop samples are distinctly higher than those obtained from borehole samples almost certainly due to the effects of weathering (Table 6.1.3). Porosity values have an arithmetic mean of 18.9% and an interquartile range of 13.7 to 23.1% (Figure 6.5.1a). The interquartile range of hydraulic conductivity is 1.1×10^{-4} to 2.1×10^{-3} m/d with a geometric mean of 4.9×10^{-4} m/d (Figure 6.5.1b). The maximum value recorded for an outcrop sample is 0.13 m/d whilst that for a borehole sample (from a depth of 929 m), is 0.033 m/d. O'Shea (1976) used Masch and Denny's (1966) grain size analysis curves to estimate the maximum intergranular permeability of the Yeovil Sands to be 4 m/d. There is a general, but poorly defined, increase in hydraulic conductivity with increasing porosity (Figure 6.5.1c).

The data collected for this study contained only one storage coefficient of 2.7×10^{-3}; transmissivities ranged from 1.8 to 600 m^2/d (Table 6.1.2). O'Shea (1976) concluded that the maximum transmissivity of the Yeovil Sands in the Upper Parrett basin is 500 to 750 m^2/d, but values are often less than this. Two boreholes 2 m apart at Compton Durville [ST 4175 1709], yielded over 50 l/s and had a transmissivity of 88 m^2/d.

6.5.3 Inferior Oolite

Lithology

The thickest deposits occur in south-east Somerset (Figure 6.4.2). The Upper Inferior Oolite varies considerably in thickness, mirroring the lower subdivisions. It was deposited here in deeper water and under lower energy conditions than in the Cotswolds. There is no clear distinction between the Lower and Middle Inferior Oolite. The limestones are mostly finer grained and more marly than in the Cotswolds; certain horizons are ferruginous, with abundant ferruginous ooliths, pellets and concretions. At outcrop it reaches its maximum development in the Sherborne–Milborne Port area, and the thickest sequence occurs further east downdip of the outcrop.

In the main outcrop area, just to the south of the Mendips, Upper Inferior Oolite rests on Upper Lias or older strata, except at Bruton where the Lower and Middle Inferior

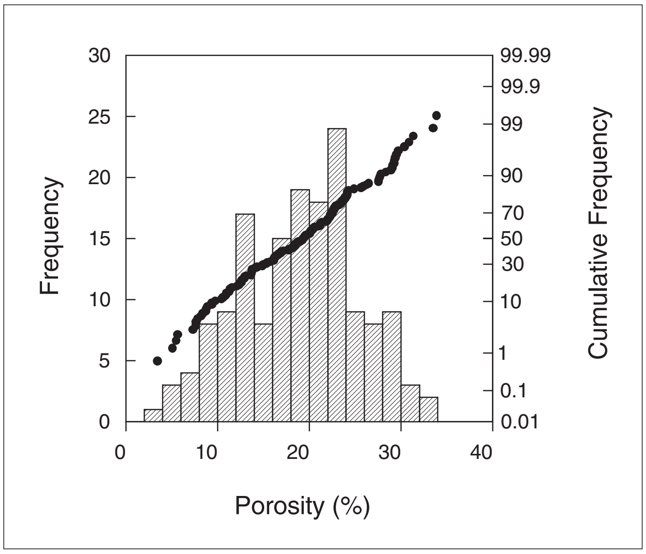


Figure 6.5.1a Distribution of porosity data for Upper Lias Sands samples from the Bristol Channel–Central Somerset Basin.

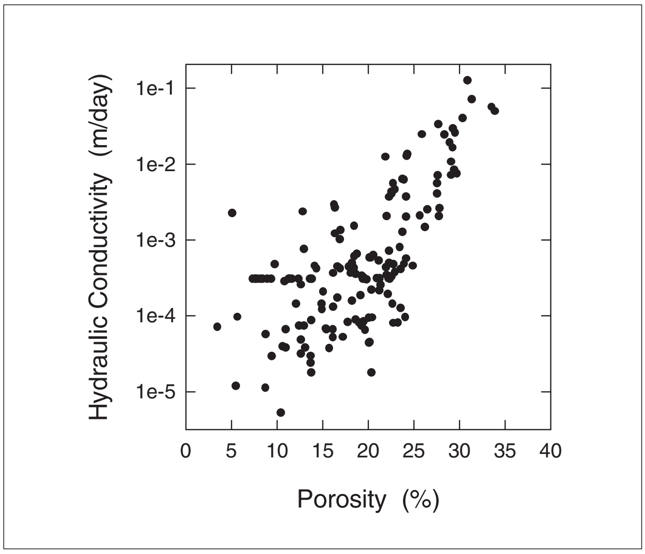


Figure 6.5.1c Plot of hydraulic conductivity against porosity for Upper Lias Sands samples from the Bristol Channel–Central Somerset Basin.

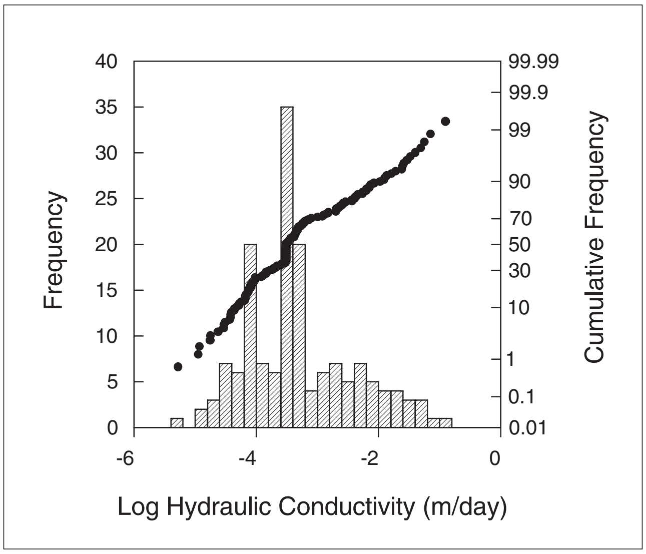


Figure 6.5.1b Distribution of hydraulic conductivity data for Upper Lias Sands samples from the Bristol Channel–Central Somerset Basin.

Oolite are preserved. The Vale of Pwesey Growth Fault (the eastern extension of the Mendips high) was active at this time, and much thicker sequences are present to the south of it than occur to the north. Further south, the South Dorset High and Mere Fault seem to have controlled sedimentation in a similar way with the succession very variable and in some places highly condensed to the north of the fault. Locally the Lower and Middle Inferior Oolite may be absent altogether. North of Wincanton and the Mere Fault, the Upper Inferior Oolite succession is more similar to that of the Cotswolds. South of Wincanton the sequence thickens dramatically (Figures 6.4.2 and 6.4.3), but all except for about 3 m is of Upper Inferior Oolite age. It thins rapidly west and southwards towards Yeovil and the coast.

Only the Doulting Stone and higher beds are present across the Mendips axis.

Aquifer properties

The collected data (Table 6.1.2) show that storage coefficients are around 7.5×10^{-5} and transmissivities range from 57 to 1400 m^2/d. At both Sherborne [ST 6384 1682] and Milborne Port [ST 676 186] abstractions had no effect on other sources only 20 m away, indicating the very localised nature of interconnected fractures. However abstractions at Lake [ST 613 143] affected another borehole over a kilometre away, due to interconnected fractures being present. This source abstracts over 89 l/s from the Inferior Oolite from two 35 m deep boreholes 3 m apart, the transmissivity is 720 m^2/d. O'Shea (1976) concluded that transmissivities range between 1000 and 2000 m^2/d where a good network of interconnected fractures are present. He derived these values from specific capacity tests, which he thought to give more reliable estimates of transmissivity than pumping tests due to the poor quality of data from the latter in this area.

The Yeovil Sands and Inferior Oolite are in hydraulic continuity and in several instances sources abstract from both aquifers. The combined use of surface and groundwater for river regulation has been investigated in the Yeo catchment whereby groundwater is abstracted in the summer to maintain river flows and this leads to reduced streamflows in winter due to the groundwater discharge is being less. Although the Inferior Oolite has a fast response time, the scheme could yield reasonable net gains, as the river flows across the Fuller's Earth for part of its length and therefore the induced recharge from the river caused by pumping should be low. However, heavy pumping of a confined aquifer leads to a rapidly expanding cone of depression reducing spring flows and lowering the net gains of the system. Some of these problems can be partially offset by boreholes also penetrating the Yeovil Sands which, with its greater thickness and lower transmissivity, has a slower response time.

6.5.4 Upper Osmington Oolite

The Oxfordian (Oxford Clay and Corallian Group) of Dorset comprises three shallowing upwards depositional cycles, each comprising a clay, a sand and finally a limestone (partly oolitic). The sequence near the coast can be summarised as follows (based on Wright, 1986):

Ringstead Clay and Osmington Mills Ironstone
Sandsfoot Grit
Sandsfoot Clay

Osmington Oolite and Clavellata Beds
Bencliff Grit
Nothe Clay

Trigonia hudlestoni Beds
Nothe Grit
Upper Oxford Clay

A fuller description is given by Melville and Freshney (1982). The Osmington Oolite comprises up to 20 m of oolites, oolitic marls, nodular limestones and pisolites and is a major aquifer in this area.

Data from 18 analyses carried out on Osmington Oolite samples from a single borehole obtained from depths of between 815 and 825 m below surface provided porosity values ranging from 3.7 to 22.6% with an arithmetic mean of 11.8%. Hydraulic conductivity values ranged from less than the minimum detectable to a maximum of 9.1×10^{-2}.

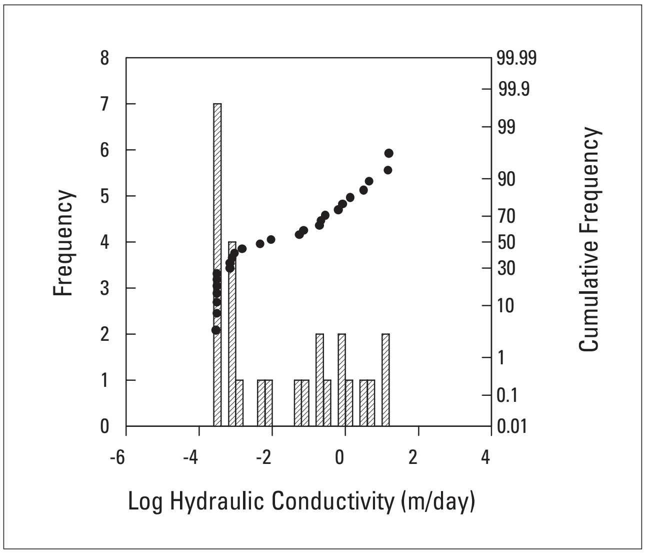


Figure 6.5.2b Distribution of hydraulic conductivity data for Portland Stone samples from the Bristol Channel–Central Somerset Basin.

6.5.5 Portland Limestone Formation

The Portland Limestone Formation comprises fine-grained white limestones overlain by coarser-grained oolitic and shelly beds.

Aquifer properties

A total of 26 analyses of core samples from five outcrops on Portland Bill are available for the Portland Stone. The frequency plot of porosity shows an approximately normal distribution (Figure 6.5.2a) with an interquartile range of 13.4 to 18.0% and an arithmetic mean of 16.4%. The interquartile range for hydraulic conductivity is 3.1×10^{-4} to 0.70 m/d (Figure 6.5.2b) with a geometric mean of 0.018 m/d. It should, however, be noted that these samples originated from outcrops subject to weathering, and are likely to have greatly increased permeabilities compared with unweathered strata at depth.

The only recorded pumping test for the formation at Friar Waddon [SY 652 570], gave a storage coefficient of 6.3×10^{-5} and a transmissivity value of 200 m^2/d.

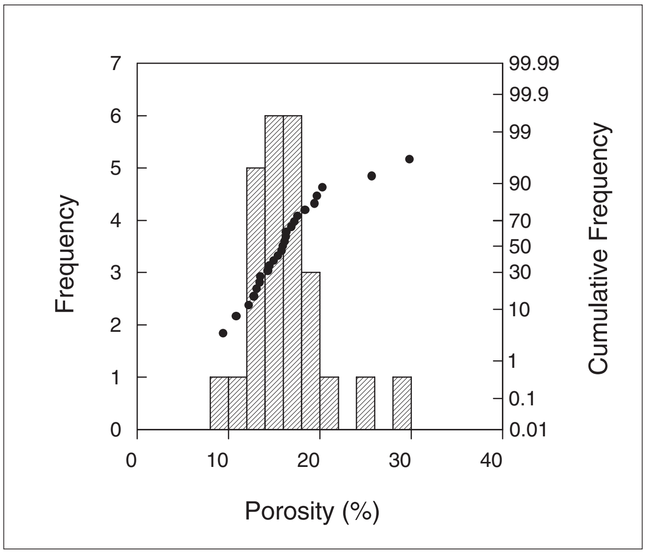


Figure 6.5.2a Distribution of porosity data for Portland Stone samples from the Bristol Channel–Central Somerset Basin.

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7 The Permo-Triassic sandstones

7.1 OVERVIEW OF THE PERMO-TRIASSIC SANDSTONE AQUIFER

7.1.1 Introduction

Overview

The Permo-Triassic sandstones form the second most important aquifer in the UK, supplying around 25% of licensed groundwater abstractions in England and Wales (Monkhouse and Richards, 1982). The aquifer provides important groundwater resources, especially in northern and central England, where the Sherwood Sandstone Group forms the most important aquifer. A number of large towns obtain their water supplies at least partly from the Permo-Triassic sandstones, among them are Manchester, Liverpool, Birmingham, Leeds, Doncaster and Nottingham. Individual well yields from the aquifer can be up to 10 000 m^3/d in the Midlands; elsewhere they are lower and Monkhouse and Richards (1982) suggest a 50% probable yield of around 200 m^3/d for the country as a whole.

The geological setting and the general hydrogeology of the Permo-Triassic sandstone aquifer in England and Wales are briefly discussed in this overview, as are the general physical properties of the aquifer and the controls on those properties. Aspects of aquifer properties measurement relevant to the sandstones are reviewed and common hydraulic effects encountered in the aquifer are discussed.

This introductory section is succeeded by regional sections, which detail the aquifer properties of specific areas of England and Wales. The Permo-Triassic aquifer has been divided into areas on the basis of their geographical outcrop, stratigraphy and the abundance of data. The following eight subdivisions have been chosen (Figure 7.1.1): the north-east, the West Midlands, Shropshire, Cheshire and south Lancashire, the Fylde, the north-west (Cumbria and Carlisle), Clwyd, and the south-west.

Geology

The Permo-Triassic sandstones outcrop in the southwest, central, north-east and north-west of England, and in the Vale of Clwyd (Figure 7.1.1). In general, they are preserved within the onshore extensions of a number of major offshore sedimentary basins. The sandstones have variable, and often substantial, thicknesses. For instance, the Sherwood Sandstone Group is up to 600 m thick in Lancashire, and around the northern edge of the Cheshire Basin the Permo-Triassic sandstones approach 1000 m in thickness. The Sherwood Sandstone Group is about 90 m thick in south Nottinghamshire, increasing to 180 m further north in Yorkshire. The combined thickness of Permo-Triassic sandstones in the Vale of Eden and along the Cumbrian coast exceeds 900 m (Day, 1986).

In the south-west and north-east of England, the sandstones dip to the east and become confined down dip by the Mercia Mudstone Group, the aquifers feathering out to the west. In the west Midlands the aquifer occurs in a number of basins and in the north west, dip beneath the Irish Sea. The aquifer properties of the sandstones are greatly affected by their sedimentary structure and by post-depositional diagenesis.

Geological history

An account of the depositional environment during the Permo-Triassic was provided by Downing and Gray (1985) from which much of the following background was obtained.

During the late stages of the Variscan (Hercynian) orogeny, in late Carboniferous times, a phase of uplift affected Britain, with consequent subaerial erosion in a desert-like environment. Simultaneously, in response to tensional stresses, local downwarps developed, (in many cases along pre-existing fault-lines), these being separated by relatively elevated terrain. Other downwarps were caused by gentle flexuring, perhaps related to crustal thinning. The Mesozoic basins so formed include the East Yorkshire and Lincolnshire Basin, the Wessex Basin, the Cheshire and West Lancashire Basin, the Carlisle Basin and the Worcester Basin. These basins continued to develop throughout the Permian and Triassic periods and they gradually filled with sediments, including the thick sandstones. Both syn-depositional and post-depositional faulting is significant.

The initial products of the erosion of the highlands were coarse breccias and sandstones, which were swept into the basins as flood deposits. These are concentrated along the basin margins but occur impersistently and variably over much of the land surface that existed at that time and recur locally throughout the Permian and Triassic sequences. Volcanic rocks are interbedded locally with these basal breccias and presumably result from eruptions associated with the tensional stress regime. The breccias are overlain by coarse-grained, well-sorted, cross-bedded sandstones such as the Bridgnorth, Collyhurst and Penrith Sandstone Formations, which have been interpreted as aeolian dunes, and which merge laterally into water-laid deposits. Together these sediments attain thicknesses of several hundreds of metres and tend to smooth out the pre-Permian topography.

Upper Permian rocks are commonly represented by marine deposits, which were laid down as a result of marine transgression across a low-relief Lower Permian landscape. The deposits comprise complex and variable formations of limestones, dolomites and evaporites, which grade upwards and laterally towards the margins of the basins into continental marls and sandstones. Analysis of these sediments suggest that they result from at least five major periods of marine transgression and regression.

The end of the Permian and the early Triassic period heralded a return to a continental environment. The basins initiated in the Permian continued to subside and thick clastic deposits accumulated which spread gradationally and diachronously across the older rocks, forming the deposits of the Sherwood Sandstone Group. They are largely of fluviatile origin, deposited by a mojor braided river system, of which a modern example is the Saskatchewan river in Canada. The river system deposited a sequence of channel sands, with basal lags overlain by overbank silt and floodplain muds. Locally, within the Sherwood Sandstone Group, wind-blown deposits, marls and breccias also occur, suggesting different local depositional environments typical of modern desert basins. The succession thins

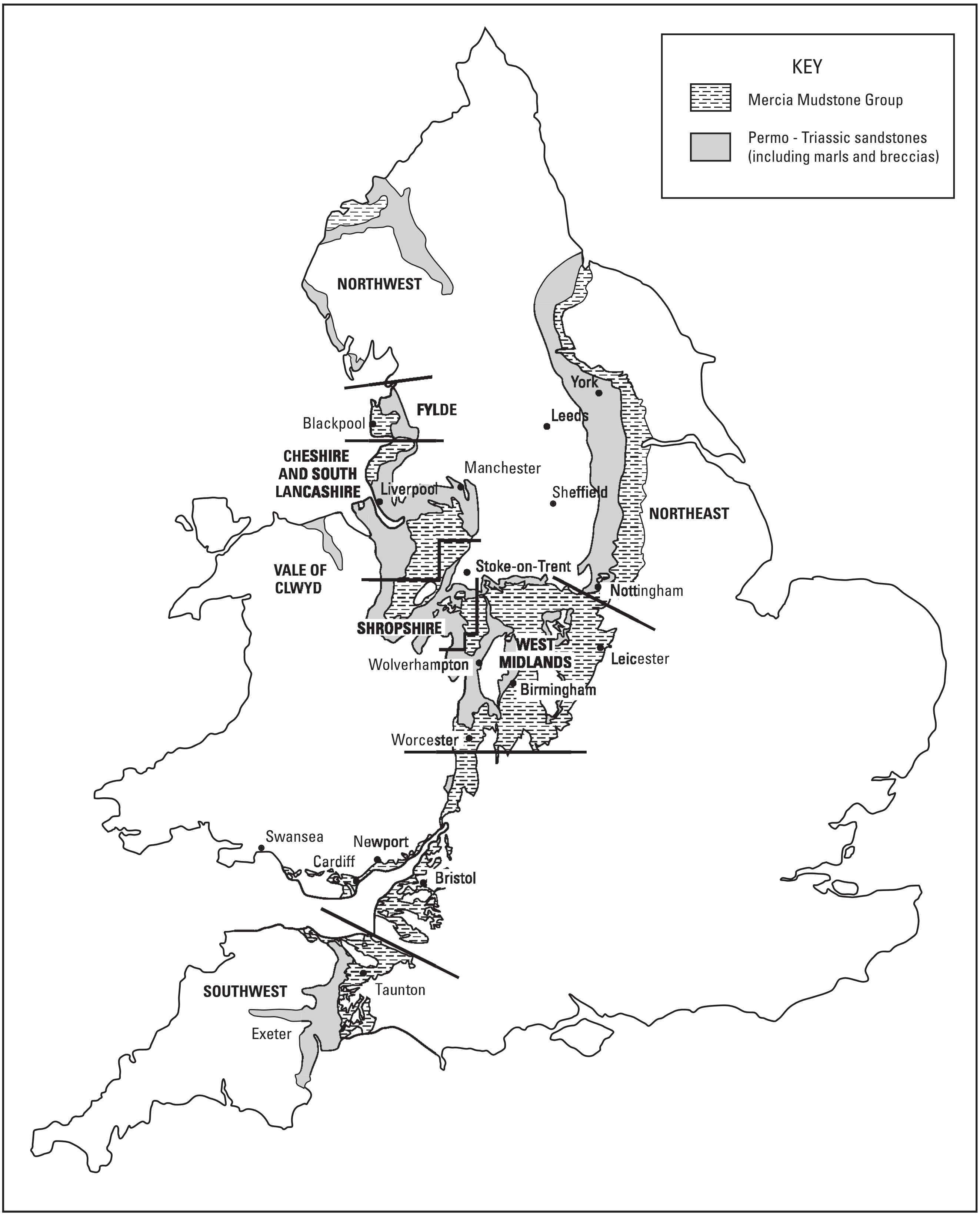


Figure 7.1.1 Outcrop of the Permo-Triassic sandstones and overlying Mercia Mudstone Group showing the regions covered in the text.

against older uplifted areas, such as the London Platform and the Pennines. A number of cycles of gradational grain-size occur within the sequence, and as a whole the grain-size decreases upwards.

Subsequently the partly marine red mudstone and silt-stone deposits of the Mercia Mudstone Group covered the Sherwood Sandstone Group. The lower beds of the Mercia Mudstone were deposited by a low-sinuosity, meandering sandy river with a wide floodplain, which became gradually gave way with time to inland and coastal playa lakes where muds and evaporites were formed. Interbeds of halite, gypsum and anhydrite are present within the mudstone, and in places there are sandstone and siltstone horizons. Disseminated evaporite minerals are also present.

Diagenesis

The absence of sedimentary compaction and relatively high porosity of the Permo-Triassic sandstones suggest that, while they were initially cemented, much of the primary cementation has subsequently been dissolved. A variety of cements are now found, including calcium carbonate, dolomite, various forms of anhydrite, halite, iron oxide and clay minerals (Strong, 1993).

Anhydrite ($CaSO_4$) is found deep in the Wessex basin (e.g. the Winterbourne Kingston Borehole) and in north-east England at Cleethorpes. It is likely that here anhydrite dissolution has formed the bulk of the secondary porosity (Strong and Milodowski, 1987; Knox et al., 1984). The presence of halite in Permo-Triassic rocks at depth in the Irish Sea Basin suggests that dissolution of a halite cement may have also contributed to the secondary porosity of the sandstone aquifers.

In the north-west and Birmingham area there is less calcite towards the top of the aquifer than at depth. Deeper flowing waters tend to be supersaturated with calcite, presumably from mineral dissolution.

In deep basins, bedding-parallel and steep-angled calcite veins are common. These mineral veins are at least partially weathered-out near the outcrop and so form open fractures along which water may flow. Hard cemented paleosols and siliceous paleosols are present in places. Many calcretes are present in Wessex, though these are often dissolved in outcrop.

Iron rich cements are seen locally. Some iron oxide coatings on sediment grains may have formed prior to deposition in a desert environment.

A variety of clay minerals may be present within pore spaces. For example kaolinite may be present as a late freshwater pore infilling. Illite can form webs across pores, reducing permeability by orders of magnitude without substantially affecting porosity, (although this mainly occurs in the saline part of the aquifer rather than near outcrop; for example the East Irish Sea Basin has an 'illite affected zone', which formed beneath a palaeo-gas–water contact [Cotter and Barr, 1975]).

Nomenclature

Variable stratigraphy across the country is caused by the nature of the fluvial sedimentation, with deposition switching to the east or west with time so that the sediments in different areas were deposited at different times, though apparently at the same stratigraphic level. The Permo-Triassic deposits in the various basins have been given different names for coeval rocks; the general usage adopted is that described by Warrington et al. (1980) (Figure 7.1.2).

Hydrogeology

The Permian sandstones and the Triassic Sherwood Sandstone Group, which together comprise the Permo-Triassic sandstones, form a major aquifer. The Permian marls, where present, form an aquitard and separate the Permian sandstones from the overlying Triassic sandstones. The Mercia Mudstone Group, which overlies and confines the Sherwood Sandstone Group is also an aquitard.

Aquifers

The fluvial sequences which form most of the Permo-Triassic sandstone aquifers fine upwards from gravels and sometimes pebbles, to sands, silts and muds. Extensive clay horizons, resulting from the settling of flood overbank deposits, also occur. Channel deposits may be continuous for significant distances: channels in the Permo-Triassic sandstones beneath the Irish Sea are traceable for tens of kilometres. The result of this deposition is that hydraulic conductivity may be directional: values are likely to be higher along and down the channels. The aeolian Permian

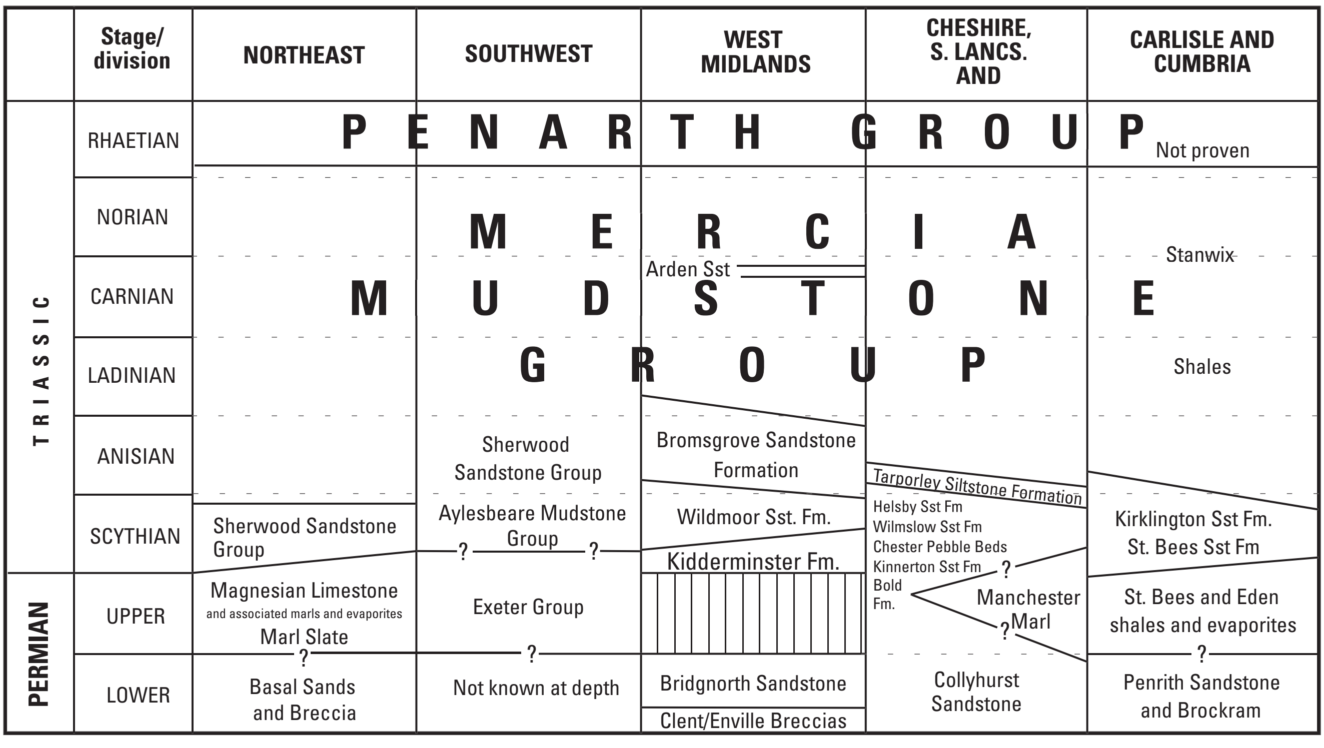


Figure 7.1.2 Generalised correlation of stratigraphical nomenclature for the regions of the Permo-Triassic sandstones covered in the text (after Warrington et al., 1980).

deposits have relatively low proportions of fine-grained material, and are cross-bedded on a metre rather than decimetre scale which is more typical of the fluvial deposits.

Fine-grained layers within the Permo-Triassic sandstone have lower permeabilities, and can act as confining layers. There is a general northerly decrease in grain size due to the fact that much of the sedimentation occurred from braided rivers flowing northwards from the Amorican massif. For instance, as one goes northwards from the Sherwood Sandstone Group of the Fylde to the St Bees Sandstone of the Lake District, the marl content increases. Correspondingly, in the north-east, from Nottinghamshire northward through Yorkshire the grain-size decreases. The lateral persistence of individual fine-grained bands can be highly variable, (for example marl layers in adjacent boreholes at Sugarbrook, Bromsgrove cannot be correlated).

Lateral facies changes can cause deposits to change from being aquifers to aquitards. For example the Bold Formation sandstones of the western Cheshire Basin become increasingly more argillaceous to the east, eventually becoming known as the Manchester Marl Formation, which hydraulically separates the Permian from the overlying Triassic sandstones. The content of fine-grained sediments also varies vertically, often increasing towards the top of the Permo-Triassic sandstones. For example the Tarporley Siltstone Formation in the Cheshire Basin consists of interbedded siltstones and mudstones and acts as a passage facies between the Triassic sandstones and the overlying Mercia Mudstone Group. In other areas such as the south-west and the north-east, the Sherwood Sandstone Group grades into the Mercia Mudstone Group via transition deposits; for example in the north-east, the Colwick Formation (formerly the Waterstones).

Aquitards

Generally the Mercia Mudstone acts as an aquitard, confining the Sherwood Sandstone Group. However locally, especially around the mudstone and sandstone junction, there is considerable interlayering of sandstones and mudstones in fining upwards cycles (as for example in the Colwick Formation of central and eastern England). These strata commonly yield up to 2 l/s for up to around 40 m drawdown, with low sustainable yields. In the south-west of England water is locally taken from the Mercia Mudstone Group with yields of less than 2 l/s from muds, marls and silts.

The Permian marls, present as the Aylesbeare Mudstone Group in the south-west and as the Manchester Marl Formation in the north-west, act as aquitards confining the Permian sandstones. Limited water resources can however be obtained locally from these rocks.

The hydraulic significance of fractures and faults

Fracture flow plays a significant role in saturated groundwater flow through the Permo-Triassic sandstones. The discontinuities include bedding-plane fractures, inclined joints of either tectonic or diagenetic (i.e. dissolution of vein infills) origin, and solution-enlarged fractures (Lovelock, 1977). They can provide preferential flow paths and have a significant effect on the physical properties of the aquifer. Adjacent to pumping boreholes fractures may be developed or enhanced by pumping sand from the fractures into the borehole.

The hydraulic effects of faults in the Permo-Triassic sandstones vary widely, ranging from impermeable features which form barriers to groundwater flow, to highly transmissive structures which may act as recharge boundaries.

Evidence for the presence of impermeable faults includes; drawdown effects during pumping tests, potentiometric head differences across the structures and hydrochemical changes across the faults, (for example the Roaring Meg Fault in Merseyside). Such faults can effectively dissect the aquifer into a number of distinct blocks. This effect is seen in the Sherwood Sandstone Group in the southwest region north of the Otter Valley in the Tone catchment, and in parts of the West Midlands, where faults effectively isolate sections of the aquifer.

Permeable faults may be revealed as recharge boundaries during pumping tests. It is possible that increased transmissivity may result from a permeable brecciated zone adjacent to a fault, (the Topcliffe fault in North Yorkshire may act in this way), but direct evidence for such an effect is sparse.

Hydrochemistry

The water in the Permo-Triassic sandstones is generally of good quality and the aquifer has in consequence been extensively exploited for a wide range of uses. Groundwater chemistry varies both with depth and laterally, towards the feather edge of the aquifer or down dip beneath the confining Mercia Mudstone Group. The high matrix porosity and the generally low natural hydraulic gradients mean that groundwater movement is slow and there is adequate time for the water to reach chemical equilibrium with the aquifer matrix. The groundwater chemistry is thus indicative of the groundwater flow regime in a region.

Unconfined aquifers

The water in the unconfined sandstones is generally oxic and of a calcium bicarbonate type with subsidiary magnesium and sulphate ions and very minor sodium and chloride ion concentrations. In general the unconfined water chemistry is not greatly altered by the aquifer mineralogy, which is mainly relatively unreactive quartz and feldspar in the sandstones. There is some limited dissolution of the carbonate cement which gives the water some degree of hardness. The age of groundwaters is generally less than one hundred years old, this being approximately the time taken from recharge to discharge at springs, rivers or by borehole abstraction.

Near the feather edge of the sandstones, for instance in the Yorkshire region, the presence of the mudstones beneath the sandstones affects the chemistry of the groundwaters. An increased sulphate (and calcium) concentration in the groundwater occurs where dissolution of anhydrite and gypsum from the underlying mudstones and marls is significant.

Confined aquifers

Groundwater in the confined part of aquifer is generally much older and has a more evolved chemistry. It has had longer to equilibrate with the aquifer material, including the fine sediments and matrix cements. Down the stratal dip, cationic exchange processes operate and the water quality eventually deteriorates to a strong impotable sodium chloride type (Day, 1986). For the purpose of this report, the aquifer limits down dip has been defined as the limit of good quality water.

In the north-east concentrations of dissolved oxygen and nitrate decrease down dip, whereas sulphate and chloride concentrations, and overall mineralisation show a corresponding increase. Low salinity water used for water supply is located mainly in the outcrop areas and up to about 10 km down dip in the confined section of the aquifer. A similar regime is seen within the Triassic Otter

Sandstone Formation aquifer in the south-west region, where good quality water is not found more than 5 km down dip. In the Worcester area ionic concentrations change with distance south from the outcrop, and groundwaters at depth around Stratford upon Avon (about 20 km down gradient from outcrop) are of the soft sodium sulphate type of good quality (Day, 1986).

The presence of evaporites such as gypsum and anhydrite alters the chemistry of any water recharging through the Mercia Mudstone Group. In the Yorkshire region anhydrite dissolution from the overlying beds of mudstone and marl contributes to the salinity in the confined aquifer. Similarly, the extent and nature of Pleistocene Drift cover are important in determining groundwater quality. In the Fylde area in Lancashire, Pleistocene zones of preferential recharge can be identified chemically by their relatively low bicarbonate concentrations (Edmund, 1986).

Variation of groundwater quality with depth

Vertical variations in groundwater chemistry can develop and be maintained, due to the layered anisotropic nature of the aquifer which minimises hydraulic interaction between horizons. These vertical chemical differences are indicative of variations of groundwater age with depth. In the south-west region the presence of the Budleigh Salterton Pebble Beds Formation beneath the Otter Sandstone Formation gives rise to chemical changes with depth; these result from the differences in lithology and cementation between the two formations.

Natural brines occur within the Staffordshire and Cheshire basins due to dissolution, by circulating waters, of beds of halite near the base of the Mercia Mudstone Group (Day, 1986). The distribution of saline groundwater bodies in the north of the Cheshire Basin is complex. The fresh/saline water interface in the Lower Mersey Basin occurs at levels of between 50 and 200 m below Ordnance Datum. The thickness of the saline/freshwater interface zone is related to natural groundwater flow and is thinnest in shallow aquifers where groundwater flow is also more rapid.

Coastal saline intrusion

Potential for saline intrusion exists in the south-west region along the coast in the southern part of the Otter Valley. In the north east of England there is some saline intrusion in the Billingham area. Saline intrusion has also occurred in the Liverpool area, along the tidal reaches of the Mersey, and to a limited extent in south Cumbria in the Furness region.

7.1.2 Controls on aquifer properties

Controls on transmissivity

Matrix hydraulic conductivity

VARIABLE LITHOLOGY

Matrix hydraulic conductivity varies according to lithology. Grain size and geometry, particle size distribution and the extent of cementation are of paramount importance, affecting intergranular hydraulic conductivity and hence the general transmissivity distribution of the aquifer, due to the variable nature of the sediments.

LAYERED HETEROGENEITY

Layered heterogeneity results from hydraulic conductivity variations between horizons within the aquifer. Individual beds making up the formation have relatively homogeneous hydraulic conductivities, but the system, when considered as a whole, is heterogeneous. This phenomenon is common in the Permo-Triassic sandstone aquifer, where fine- and coarser-grained layers are interbedded. For instance, core permeametry studies of the Bromsgrove Sandstone Formation by Ramingwong (1974) showed that the hydraulic conductivity of fine-grained layers is 0.02 m/d horizontally and 0.01 m/d vertically (i.e. approximately similar values). However this is 500 times lower than the cleaner interbedded sandstone, where horizontal and vertical hydraulic conductivity are also similar, at 8 m/d and 6 m/d respectively.

Interlayered marls can cause 'double aquifer conditions' for example at Bridgnorth, Wolverhampton, and Stourbridge in the Midlands. The Permo-Triassic sandstone aquifer horizons above and below marl layers are not in hydraulic continuity, as indicated by water quality differences. The hydraulic separation of aquifer horizons affects the aquifer response to pumping and a characteristic response to step testing.

ANISOTROPY

An aquifer is considered anisotropic if the hydraulic conductivity varies with the direction of measurement at a point. Anisotropy at the matrix scale within the Permo-Triassic sandstone layers is principally caused by fine-scale laminations or by the orientation of clay minerals. On a larger scale, there is a relationship between layered heterogeneity and anisotropy. A layered system as a whole may be considered to act as a single anisotropic aquifer. The associated horizontal and vertical intergranular hydraulic conductivities of the system may be determined by calculating the thickness weighted means of core-scale horizontal and vertical hydraulic conductivities respectively.

PREFERENTIAL FLOW PATHS

The layered nature of the Permo-Triassic sediments and associated variations of hydraulic conductivity result in changes in the direction of groundwater flow. The greater the hydraulic conductivity contrast between layers, the greater the amount of refraction. This results in strong horizontal flow in more permeable layers and slow but extensive vertical flow across less permeable horizons. Water is refracted both by fine-grained bands within a sandstone unit, and on a larger scale, across the Permian marls where they separate the Permian and Triassic sandstone aquifers.

Lower hydraulic conductivity layers influence groundwater flowpaths. Preferential horizontal flow in the sandstone horizons will occur where marl bands are laterally persistent. Where they are laterally variable and peter out, vertical flow becomes more significant. Although fine-grained layers restrict water movement to some extent, hydraulic continuity is generally maintained throughout the Permo-Triassic sandstones: the sandstones frequently effectively respond as a single aquifer.

Fracture hydraulic conductivity

In this text, the term 'fracture' includes breakages of all orientations and causes. They may have tectonic origins, be solution-enlarged features, or have been created by pumping or subsidence. Their hydraulic significance in the Permo-Triassic sandstones depends mainly on their aperture, their degree of interconnection, and on the intergranular hydraulic conductivity of the fractured strata.

On a borehole scale, fracture hydraulic conductivity is most significant where intergranular permeability is low, for instance in the north-west. Here fractures may provide the majority of flow to a borehole, and in the absence of fractures borehole yield may be very low (Peacock, A J, personal communication).

On a regional scale the significance of fractures depends primarily on the extent to which they are interconnected. Where interconnection is poor, regional hydraulic conductivity may be most closely represented by the intergranular hydraulic conductivity. Conversely where interconnections are extensive, fracture hydraulic conductivities may dominate the regional value.

Large-scale fracturing is commonly associated with faulting. Where such fracturing decreases with depth, the relative importance of intergranular flow increases as greater depths are considered (Worthington, 1977). Faulting can break marl bands, and by offsetting beds allow flow to occur between aquifer units separated elsewhere. Such intense faulting is significant in Cheshire in the basal unit of the Mercia Mudstone Group, where hydraulic connections are created between different sandstone layers of the Tarporley Siltstone, and the underlying Permo-Triassic sandstone.

Voids in poorly cemented horizons can also be induced by pumping. During borehole development, large volumes of sand may be expelled, creating cavities in poorly consolidated sandstone horizons. Bed separation and increased fracture hydraulic conductivity may also be caused by subsidence due to coal mining activities. Workings beneath the Permo-Triassic sandstone have caused subsidence for up to 5 km down-dip of the feather edge in the region between Liverpool and Manchester (Brassington, F C, personal communication).

Solution enlargement of fractures (and therefore an increase in permeability) may occur near rivers as flows become more concentrated. Fracture enhancement by solution may also have been more important during glacial times (Lloyd, J, and Tellam, J, personal communication).

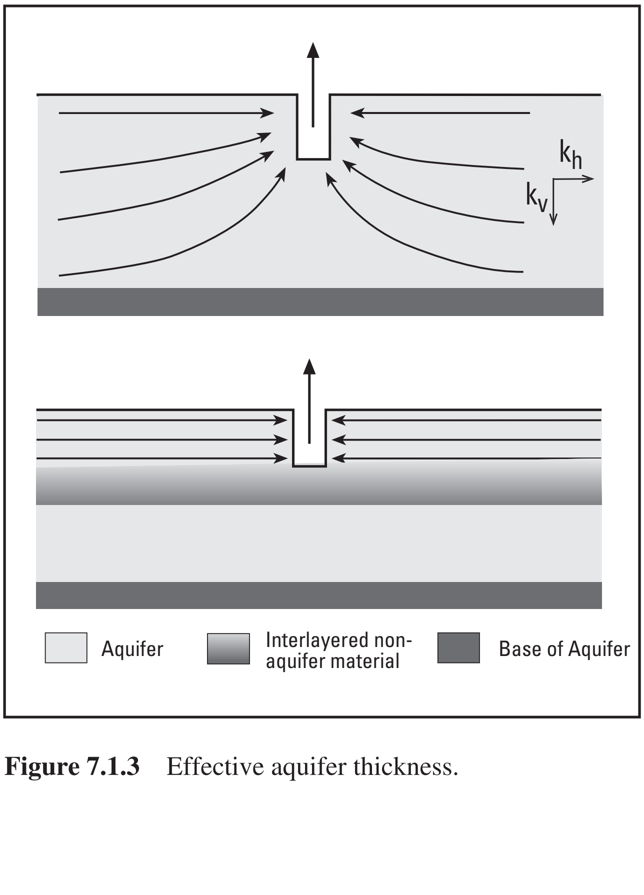


Figure 7.1.3 Effective aquifer thickness.

Effective aquifer thickness

In order to obtain an aquifer hydraulic conductivity from pumping test derived transmissivity values or to construct groundwater flow models, the 'effective thickness' of the aquifer is required. This may be considerably less than the full thickness of the aquifer (Figure 7.1.3).

Traditional pumping test analysis assumes fully penetrating boreholes. However the Permo-Triassic sandstone is often hundreds of metres thick, and most boreholes only partially penetrate the aquifer. Flow to these boreholes is three-dimensional.

Theoretically the full thickness of an aquifer should only contribute flow to a partially penetrating pumping borehole beyond a certain distance from the borehole. This distance (r) is given by:

$$r > 1.5b(K_h/K_v)^{0.5}$$

Where b is the full thickness of the aquifer and K_h/K_v is the ratio of the horizontal to vertical hydraulic conductivity (Domenico and Schwartz, 1990).

However the combination of significant aquifer anisotropy and large aquifer thicknesses means that the flow to a Permo-Triassic borehole may not come from the full thickness of the aquifer, but only from the upper layers. For practical purposes, the effective depth is often taken as the borehole depth (or the borehole depth plus 10 to 20 m, or 110% of the borehole depth). Hence, where the aquifer is thick, the effective depth of the aquifer is constrained by the depth of the boreholes and may be considerably less than the full potential aquifer thickness.

Controls on porosity and storage

Porosity

High porosities are observed in sediments which are friable, clean, have little cementation, and are well sorted. Conversely, cemented, consolidated, and poorly sorted sands have lower porosities. The original porosity of the Permo-Triassic sandstones at deposition was probably around 30%. This primary porosity has been modified by diagenesis, which started soon after deposition with initial chlorite, anhydrite, and carbonate cementation reducing the high initial porosity before compaction began. These cements are still seen deep in the Wessex, Irish and North Sea basins which have low porosities of around 10 to 15%.

In the freshwater circulation zone of aquifers where there has been recent recharge, all of the halite has dissolved, as has most of the anhydrite, although some calcium carbonate and in places iron (carbonate and oxide) cements remain. There is no observable cementation variation with depth within the top 200 m of the freshwater aquifers. Core data for these depths show a scatter range of porosity of approximately 10 to 35%.

Storage

There are a number of ways in which water can be stored in the Permo-Triassic sandstones. The compressibility of the groundwater and the aquifer matrix allow confined aquifers to store water. Specific storage is a measure of this property, (as is discussed further in Appendix 1). The dominant contribution to specific storage comes from the aquifer compressibility, which is typically 10^{-7} to 10^{-9} Pa^{-1} for sandstones. The specific storage multiplied by the aquifer depth gives the storage coefficient of the aquifer. Typical values theoretically to be expected for this sandstone are 10^{-5} to 10^{-3}. Values of storage similar to this are seen in confined pumping tests in the Permo-Triassic sandstones.

Given the porosity of the sandstones, the unconfined values of storage coefficient for the Permo-Triassic sandstones are likely to be broadly in the range 10^{-2} to 10^{-1}. It is, however, rare to obtain such values from pumping tests, even when the aquifer is unconfined. As discussed in Section 7.1.4, the explanation for this behaviour is likely to be the inhibiting effect of low-permeability layers within the sandstones on vertical flows.

In addition to these two dominant forms of sandstone aquifer matrix storage, the fractures within the Permo-Triassic sandstones also have compressible storage and drainable porosity. The timing of how these types of storage interact may depend on the permeability and the relative importance of the fracture and the matrix storage, how confined the aquifer is, and the ease with which the drainable porosity can be accessed.

Summary of controls

A number of general aquifer properties are common to all of the Permo-Triassic sandstones of England and Wales. Both matrix hydraulic conductivity and porosity are functions of cementation, compaction, and the size and degree of sorting of the grains. The nature and extent of cementation affects both porosity and hydraulic conductivity, but by differing mechanisms. Hydraulic conductivity is controlled by the size of the pore throats, and the degree of their interconnection. Thus highly porous sands only have high intergranular hydraulic conductivities if the pore throats are large.

The Permo-Triassic sediments all have some degree of interlayering, having predominantly been deposited by rivers, but also occasionally under aeolian conditions. Sands interbed with silts and muds, and in places breccias and pebbles are found. This gives the aquifers, as a whole, anisotropic permeability: the overall hydraulic conductivity parallel to the layers is dominated by the more permeable horizons, and that perpendicular to the layers is dominated by the less permeable horizons. The anisotropy, arising from the layered heterogeneity of the aquifers, affects the response of the aquifers to pumping. Vertical movement of water is impeded, leading to a delayed water table response, and the effective thickness of the aquifer is often significantly less than the actual thickness. Fine-grained layers can also cause the aquifer to act as a double aquifer, or even as a multiple aquifer system. The horizontal movement and the confined pressure response of the aquifers are less affected by the interlayering.

Fracture systems can give rise to preferential flowpaths and cause locally, or even regionally, enhanced transmissivities.

7.1.3 Aquifer properties measurements

Aquifer properties have been determined at a variety of scales in the Permo-Triassic aquifers. Permeametry is conducted on a centimetre scale, packer tests and geophysical logs provide data on a borehole scale, and pumping tests give information applicable in the range of hundreds of metres to a few kilometres. Properties have also been estimated indirectly on a regional scale by groundwater flow modelling.

Core analysis

A discussion of core analysis techniques is provided in Appendix 3. Reeves et al. (1975) describe core sampling of Permo-Triassic sandstone. They found that the core recovery was low where the sandstone was poorly cemented or where a high frequency of fractures was encountered. Thus the very features within the strata that would give a qualitative indication of high permeability may be absent from the borehole logs and cores. Extremely low values of hydraulic conductivity cannot be measured with permeametry techniques, and low permeability clays are poorly represented as a result of sampling difficulties, thus data-sets are also truncated at the low hydraulic conductivity end.

This study used primarily porosity and horizontal and vertical core hydraulic conductivity data stored on the British Geological Survey core database and the distribution of core samples by region and stratigraphical Group or Formation is shown in Table 7.1.1. Data held on the database include all of the relevant sample values used by Lovelock (1977) in his detailed assessment of the aquifer properties of Permo-Triassic sandstones in the United Kingdom. Many of the data used in this report are from borehole core samples. Outcrop data are included in the data summaries as Lovelock (1977) found that no serious difference existed between surface and subsurface data.

Borehole logging is useful for indicating significant flow horizons and clay-rich layers. It can be used to illustrate the presence and location of fracture flow, but cannot be used to quantify its lateral extent.

Temperature, conductivity and calliper logs may exhibit steps at active fractures; groundwaters may have different origins with depth, and have correspondingly different temperatures and chemical histories. Closed circuit television logs can confirm the presence and orientation of fractured horizons. Calliper logs may detect horizontal fractures, but may miss short vertical fractures, depending on the orientation of their arms relative to the fracture system (Severn Water Authority, 1972).

Gamma logs can be used to detect marly low-permeability horizons; this is because clay layers are gamma ray emitters due to the presence of potassium, uranium and thorium. However, they also detect coarse sandstones which are rich in potassium feldspar, another high gamma emitter.

Packer tests

Packer tests are used to measure the hydraulic properties of rock adjacent to isolated sections of a borehole and (particularly in conjunction with core data) can provide quantitative estimates of the contribution of fractures to total borehole transmissivity. They have been conducted at various sites in the Permo-Triassic sandstone, for instance at Kenyon Junction in Merseyside, Cliburn in the Lake District, and at Dunhampton in the West Midlands. Higher values of hydraulic conductivity are usually found to coincide with the presence of fractures. Horizons of differing hydraulic conductivity can be distinguished by packer testing, even when the Permo-Triassic sandstone, as a whole, is apparently uniform (Brassington, 1992).

Analogue modelling of packer tests by Bliss and Rushton (1984) demonstrated that the influence of packer tests may extend for only around 10 m into the surrounding aquifer. Packer testing results therefore, are a measure of local borehole properties, rather than representing the overall hydraulic conductivity of the aquifer. Unless a very small standard section interval between packers is used (less than a metre), the test is unlikely to provide reliable estimates of the hydraulic conductivity of thin marl bands. The presence of low permeability marls can have a significant effect on aquifer potentials and the pattern of groundwater flow (Salmon, 1989).

Tests must be carried out at very low excess pressures under laminar, rather than turbulent flow conditions. The

Table 7.1.1 Core analysis data for the Permo-Triassic sandstones held on the BGS Aquifer Properties Database.

Region	Group/Formation	Total number of samples (from permeability tests)
North-east	Sherwood Sandstone	2523
West Midlands	Bromsgrove Sandstone	399
	Wildmoor Sandstone	170
	Kidderminster Sandstone	251
	Bridgnorth Sandstone	76
Shropshire	Helsby Sandstone	24
	Wilmslow Sandstone	27
	Chester Pebble Beds	60
	Kinnerton Sandstone	196
Cheshire and south Lancashire	Helsby/Ormskirk Sandstone	73
	Wilmslow Sandstone	325
	Chester Pebble Beds	185
	Collyhurst/Kinnerton Sandstone	47
	Sherwood Sandstone (undifferentiated)	671
Fylde	Permo-Triassic sandstone	329
Vale of Clwyd	Permo-Triassic sandstone	57
North West (Carlisle and	Sherwood Sandstone	101
Vale of Eden)	Penrith Sandstone	2959
(Cumbria)	St Bees Sandstone	168
South-west	Sherwood Sandstone	228
	Permian sandstone	64

pressure/flow relationship is analysed for each isolated section, and steady-state conditions are assumed. Water can either be pumped into the packer system (inflow test), or can be pumped out (outflow test).

Inflow tests have problems associated with the injected water. Permeabilities depend on temperature, and injected water may be several degrees warmer than in situ groundwater. Clays respond to the chemistry of the inflowing water; it is difficult to supply water of an equivalent chemistry to that of the aquifer water. Clogging may present a significant problem during inflow tests if a high imposed hydraulic gradient causes changes in the aquifer material around the borehole. Hydraulic shocks may cause illite clays to break up: resulting in the movement of small platelets around pore spaces which then become wedged at the outflow of the pores, so restricting the flow of water. By contrast outflow tests do not encounter the problems of clogging and water incompatibility shown by inflow tests, and have the advantage of permitting water samples to be obtained for analysis.

Pumping tests

Aquifer properties values are obtained by the analysis of pumping test data obtained from boreholes. The advantage of using large-scale (mainly constant rate) pumping tests is that they provide an estimate of the in-situ properties of a relatively large volume of the aquifer. Unfortunately the interpretation of the observed response can be ambiguous. There are numerous combinations of aquifer properties and associated boundary conditions which could produce any particular observed response.

Short-term pumping tests lasting a few days on single boreholes are largely influenced by the local rather than regional aquifer characteristics of the sandstones. The local vertical and horizontal inhomogeneity and anisotropy of the aquifer arises principally from sedimentological variability, the fracture distribution, and saturated thickness variations. As well as responding to the pumping rate and aquifer characteristics, the potentiometric levels around the pumped borehole reflect interactions with local boundary conditions and local point sources and sinks. Long-term tests lasting for several weeks or months on a number of wells are necessary to directly determine the regional characteristics of an aquifer. In practice however, these are very rare due to the high costs involved (Reeves, 1991).

An important aspect of the analysis of the pumping test data is the recognition that all apparent anomalies on hydrographs and drawdown-time graphs have some significance, and in a well conducted test they need to be understood in order to gain a full understanding of the aquifer system. For example water levels can rise during a pumping test: this paradoxical situation can occur when, for example, the drawdown is less than the rise due to sea tides (Campbell, J E, and Walthall, S, personal communication).

Large vertical hydraulic gradients may be present within the Permo-Triassic sandstone aquifer and are seen in boreholes, in the Lake District for example. Here, borehole rest water levels (or hydraulic head) are a function of borehole depth (Peacock, A J, personal communication). Downward flow occurs through the sandy Manchester Marl, this is seen at Halewood, near Liverpool, where the head in the Collyhurst Sandstone Formation is 40 cm lower than in the overlying strata (Brassington, 1982).

Observation boreholes

The Permo-Triassic sandstone pumping test data in the Aquifer Properties Database is derived from both abstraction borehole and observation borehole analyses. Observation boreholes monitor the hydraulic response to the aquifer properties of a much broader area, effectively averaging the aquifer properties over that area. Storage coefficient values can also be deduced from the observation borehole response to pumping.

The depth and position of observation points relative to the abstraction borehole can strongly influence the drawdowns observed. For example a shallow observation borehole penetrating only above a semi-confining layer may underestimate drawdown and therefore overestimate transmissivity. A system of nested piezometers, which monitor the piezometric response at different depths at a given site, can be used to evaluate such effects, as well as determining the presence (or absence) of aquifer layering (Rushton and Howard, 1982).

The use of orthogonal lines of observation points during pumping tests to investigate lateral aquifer anisotropy is more likely to be influenced by local heterogeneity than regional anisotropy. For example one piezometer may sample a permeable zone which the abstraction borehole also penetrates, but which the other piezometers may not sample (Eggboro and Walthall, 1986).

The calculation of dewatering requirements for excavations is dependent on the site specific knowledge of local aquifer parameter variations. Pumping tests can be conducted using an array of perpendicular wellpoints to act as observation holes. From the analysis of this pumping information, the number of boreholes required for dewatering can be accurately ascertained (Campbell, J E, and Walthall, S, personal communication).

Abstraction boreholes

Frequently, the drawdown and recovery in abstraction boreholes only is measured. This can give an estimate of transmissivity, but is less accurate than observation borehole data for a variety of reasons. Flow into and within the borehole may be non-laminar, poor borehole construction may result in significant well losses, and the actual pumping water level in a borehole may be dominated by only a single fracture. Water level readings from an abstraction borehole may therefore not accurately reflect the head in the aquifer.

Clogging and encrustation is frequently a problem in boreholes in the Permo-Triassic sandstones and can result in underestimation of transmissivity values and deterioration of borehole yields. Drilling mud and cuttings need to be removed from newly constructed boreholes by appropriate cleaning techniques. Many boreholes in the UK, especially those drilled before the 1960s were drilled with non-biodegradable muds.

Step tests can give transmissivity information if enough steps are used to define a clear trend of specific drawdown against discharge. The transmissivity measured reflects only the properties of the borehole and its immediate surroundings, unlike constant rate tests which sample a significantly larger aquifer volume. Step tests also measure borehole efficiency but, unlike packer tests, yield no information about the distribution of the hydraulic conductivity. Their results are therefore more dependent on fractures encountered by an individual borehole, than the regional hydraulic conductivity of the aquifer.

Step tests carried out at Halewood, Merseyside illustrate the effect of clogging on aquifer properties; a significant improvement in step test transmissivity was observed after each of two cleaning operations. This is illustrated in the Table 7.1.2 (Brassington and Walthall, 1985). Similarly, borehole development can increase the apparent transmissivity due to the removal of fines and a consequent local increase of fracture size in the vicinity of the abstraction borehole.

Data

Information from pumping tests is stored on the Aquifer Properties Database, and is considered on a regional basis in the following sections. It includes transmissivities, storage coefficients and some specific capacities. The specific capacity data provides information about borehole productivity but caution should be exercised when comparing the values because they have not been standardised or corrected for different borehole lengths, borehole diameters, pumping rates or pumping durations.

Groundwater models

Regional values of transmissivity can be ascertained by groundwater flow modelling. Normally in such models, aquifer properties values, recharge and boundary conditions are chosen to simulate the observed piezometry. When compared with values obtained from hydraulic tests, such as pumping tests, model values can provide much useful information on the possible controls on aquifer properties (this is discussed in Section 7.1.4).

Table 7.1.2 The effect of cleaning a borehole in the Permo-Triassic aquifer on apparent transmissivity (after Brassington and Walthall, 1985).

Test	Transmissivity (m^2/d) and analysis method	
	Bierschenk and Wilson (1951)	Hvorslev (1961)
Before cleaning	174	157
Cleaned above 86 m (below datum)	230	207
Cleaned above base (129 m below datum)	383	346

7.1.4 Aquifer properties results and interpretation

Introduction

The Permo-Triassic sandstone aquifers comprise complex, heterogeneous systems, both lithologically and hydraulically, which frequently violate the necessarily simplistic assumptions imposed by standard techniques of analysis. However, understanding the hydraulic structure of these systems is helped by the range of data obtained from different types of measurements. The key to understanding their aquifer properties is *scale*, both spatial and temporal. By comparing the results of tests at different scales and by considering features of the aquifer which are likely to vary between these scales, insight can be gained into the controls on the aquifer properties. For example permeabilities measured at the centimetre scale may not hold true at the metre, hundred metre or kilometre scale, and *vice versa*. An important factor which varies between these scales and is likely to provide a significant control on permeability is the degree of fracturing. Similarly, values of storage coefficient measured in the sandstones can be affected by the timescale of the method used. This has led to consideration of the effects of layered anisotropy on vertical water movement.

As a result of the importance of scale effects in the Permo-Triassic sandstones the structure of the discussion below, and of those in the following regional sections, is to consider and compare the results of techniques from the matrix to the regional scale.

Matrix aquifer properties

The distribution of core porosity and permeability results for all Permo-Triassic sandstone samples is shown in Figures 7.1.4. The hydraulic conductivity data vary over six orders of magnitude from 10^{-6} to 20 m/d (10^{-2} to 10^{4} mD), with a median value of 0.56 m/d. It should be borne in mind that unconsolidated sands with very high values of hydraulic conductivity will not have been tested, nor will clays or other material with very low hydraulic conductivities. Porosity data vary from around 2 to 35%, with a median value of 26%.

Field-scale aquifer properties

Transmissivity

The general transmissivity distribution for all the Permo-Triassic sandstones (for all the sites on the aquifer properties database) is illustrated in Figure 7.1.5. There are a total of 763 sites, and the transmissivity values show a broadly log-normal distribution with a geometric mean transmissivity of 189 m^2/d (median 206 m^2/d), and an interquartile range of

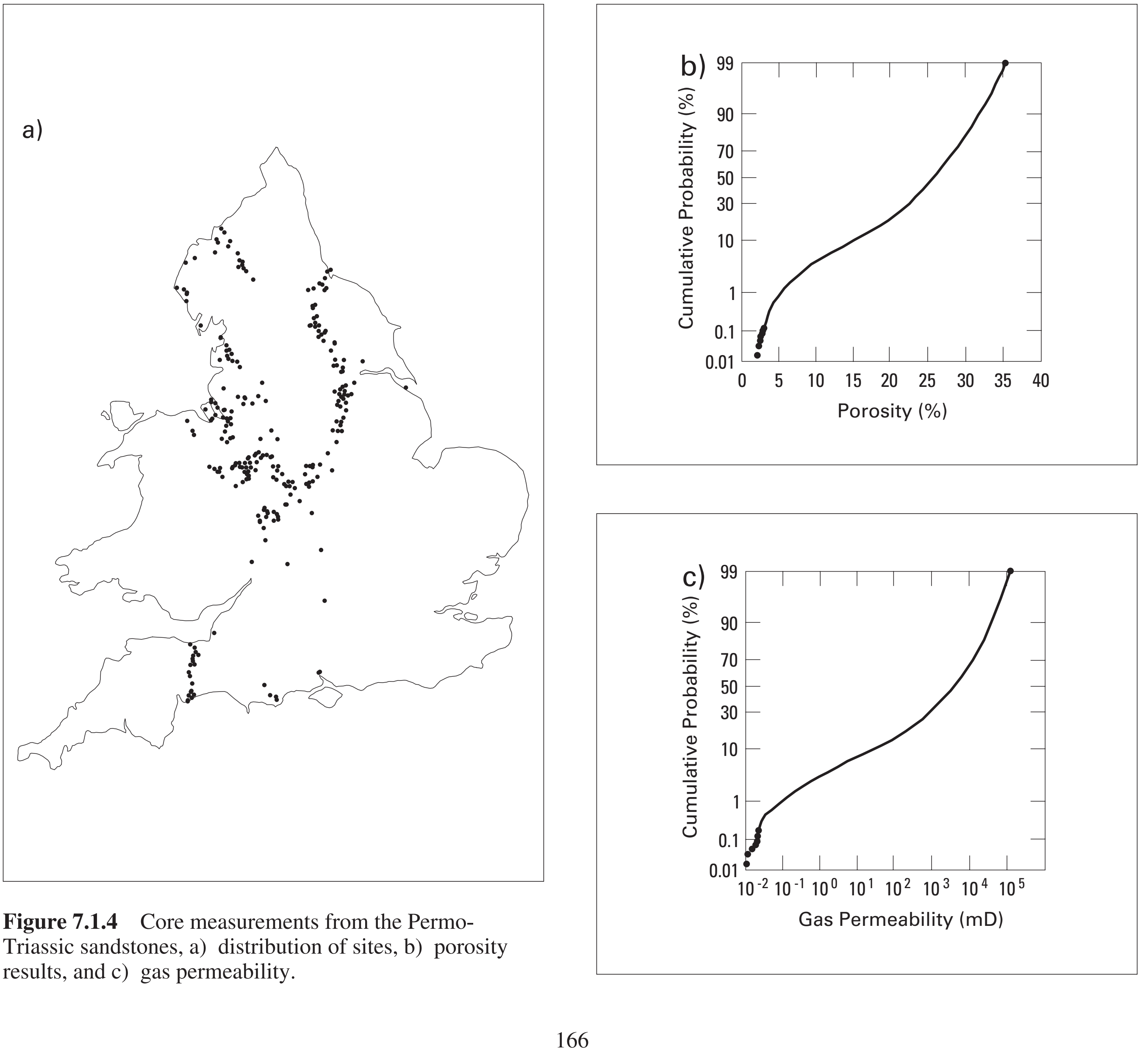


Figure 7.1.4 Core measurements from the Permo-Triassic sandstones, a) distribution of sites, b) porosity results, and c) gas permeability.

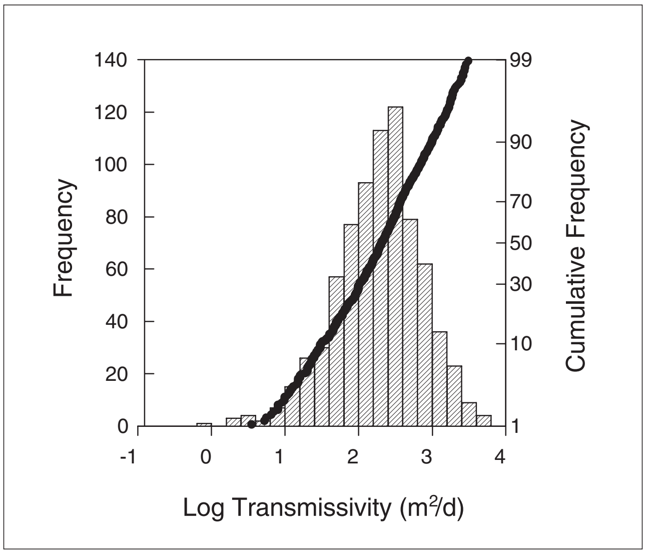


Figure 7.1.5 Distribution of transmissivity data from pumping tests in the Permo-Triassic sandstones.

90 to 436 m^2/d. The transmissivity values range over four orders of magnitude from 0.9 to 5200 m^2/d.

Transmissivity data from pumping tests can be compared with core data if sufficient core information is available to allow an estimate of an intergranular transmissivity to be made. Lovelock (1977) gave several instances of this method and found that in every case pumping test transmissivities exceeded estimates from core, indicating non-matrix (i.e. fracture) contributions to aquifer transmissivity. A similar approach has been used in various studies to compare packer test values of transmissivity for sections of boreholes with core data from the same sections. Again, important fracture contributions to borehole transmissivity estimates have often been identified.

There are unfortunately very few locations where enough core data are available to compare directly with pumping test or packer test data. However by using the concept of 'bulk hydraulic conductivity' — defined as transmissivity divided by aquifer thickness — and by comparing the distribution of borehole bulk hydraulic conductivities with that of core data on a regional basis, indications of fracture contributions to transmissivities estimated from pumping tests in boreholes may be made.

Bulk hydraulic conductivities can be calculated for a borehole site by dividing the site's transmissivity by the open saturated borehole depth. This gives a combination of intergranular and fracture hydraulic conductivity. Using the open saturated borehole depth for calculating bulk hydraulic conductivity assumes that the flow to the borehole is predominantly horizontal, and that any flow coming up from beneath the base of the borehole is negligible. This is likely to be reasonable considering the layered anisotropic nature of the Permo-Triassic sandstone aquifer. For boreholes where there is significant vertical flow, the calculated bulk hydraulic conductivities are overestimates.

The saturated borehole depth is calculated thus (Figure 7.1.6):

a) Where the casing depth is shallower than the rest water level, for instance when there is no casing, or no recorded casing depth, or when the casing terminates in the unsaturated zone, then:

   saturated borehole depth = borehole depth-rest water level.

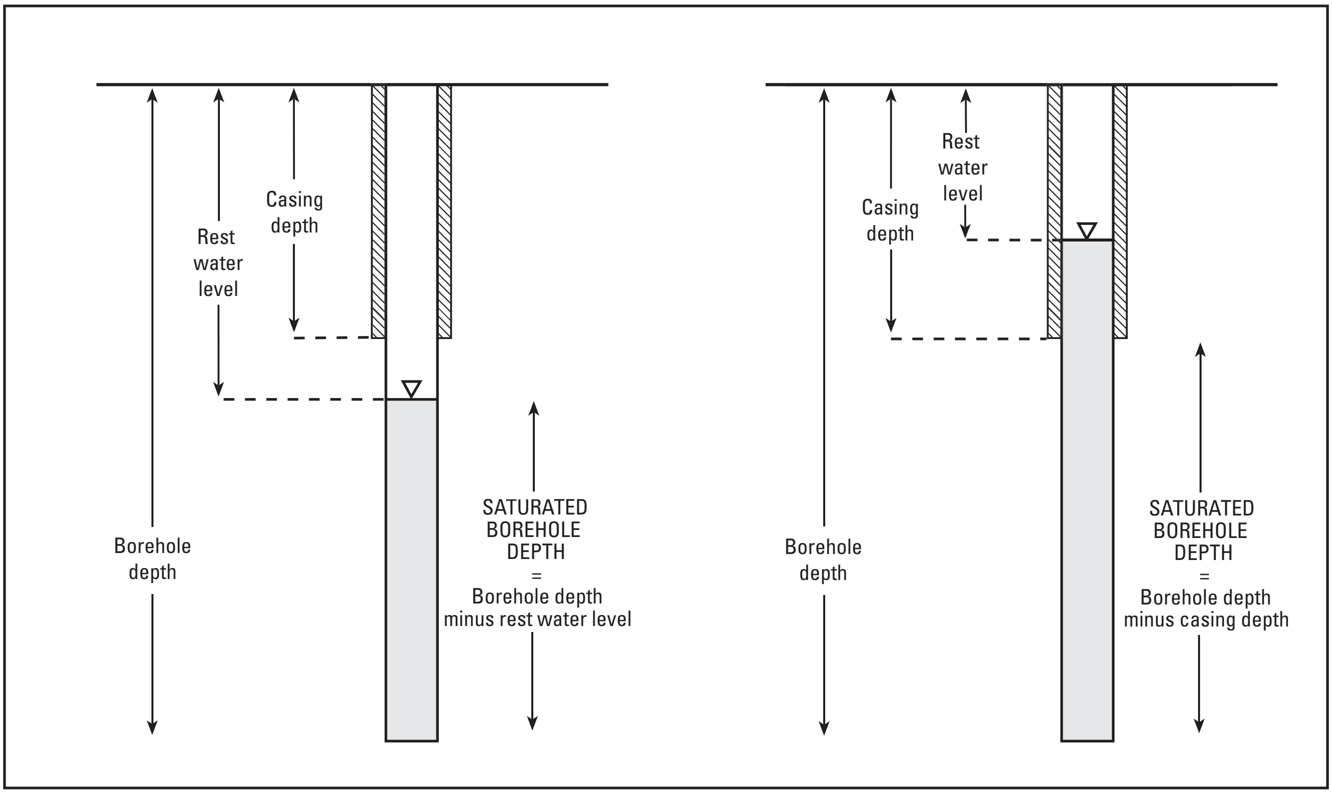


Figure 7.1.6 Calculation of the saturated borehole depth and hence bulk hydraulic conductivity, a) when casing depth is less than rest water level, b) when casing depth is greater than rest water level.

b) Where the casing depth is deeper than the rest water level, for example where the borehole is confined, or where there is no recorded rest water level, then:

saturated borehole depth = borehole depth-casing depth.

Bulk hydraulic conductivities derived from pumping tests can be compared with matrix hydraulic conductivities from laboratory core analysis to determine how significant fracture flow is at a borehole. When the intergranular and bulk hydraulic conductivities are similar, groundwater flow can be assumed to take place entirely at the intergranular level (even if most of the flow into boreholes occurs via fractures, the flow is sustained further from the borehole by matrix flow). When bulk hydraulic conductivity exceeds intergranular hydraulic conductivity, both intergranular and fracture flow are important. However when cementation is high, and the matrix is relatively impermeable, fracture flow dominates.

In the regional sections it is shown that average borehole bulk hydraulic conductivities are almost invariably larger than average core hydraulic conductivities, suggesting the importance of fracture flow in the aquifer, at least locally. In general, therefore, it seems that groundwater enters production boreholes principally through discontinuities such as bedding-plane fractures, inclined joints of either diagenetic or tectonic origin, and solution features, even when formations possess a sizeable intergranular hydraulic conductivity (Lovelock, 1977). Transmissivity and specific capacity are dominated by the number of fractures and highly permeable horizons intercepted by a borehole. Thus, adjacent boreholes can have transmissivity values which vary by one or two orders of magnitude. Well development can cause locally enhanced transmissivities, and similarly clogging and encrustation of boreholes can reduce transmissivities. These are local phenomena, and do not represent the overall aquifer transmissivity.

Given the above, the fractured Permo-Triassic sandstones can be described as a 'dual permeability' system, at least with regard to borehole behaviour. The majority of the total storage capacity of the system is provided by the rock matrix, and significant regional transport occurs in both the fractures and the rock matrix. Water flows through the matrix and the fractures towards a borehole. (By contrast, a 'dual porosity' system is one in which the fractures provide the dominant path for regional transport, and the matrix water is relatively immobile — any flow within the matrix being towards the nearest fracture, and not necessarily towards the borehole, Barker, 1991).

Storage coefficient

The storage coefficient distribution of the Permo-Triassic sandstones in the aquifer properties database for all the Permo-Triassic sites in shown in Figure 7.1.7. This indicates some very low confined storage coefficient values, a large number of intermediate values of the order of 10^{-4} to 10^{-3} and some higher unconfined values of the order of 10^{-2} to 0.1. The storage values span eight orders of magnitude, and have a geometric mean of 10^{-3} and an interquartile range of 3.6×10^{-4} to 3×10^{-3}. This distribution illustrates the great variety in storage values which are dependent on the manner in which the aquifer responds to pumping.

This distribution of data seems surprising given that most of the boreholes in the sandstones are in unconfined areas rather than in regions confined by the Mercia Mudstone Group. Drift occurs locally and is most significant in the Fylde, parts of Shropshire and over much of the north-east, but is not very significant elsewhere, including the southwest. Thus, over much of their area the aquifers would be expected to respond to pumping tests in an unconfined manner. However, the Permo-Triassic sandstones tend to behave as confined or semi-confined aquifers even when confining layers are absent: pumping test analyses yield confined storage coefficient values, and boreholes often exhibit barometric efficiency.

A typical unconfined Permo-Triassic sandstone aquifer gives a delayed yield response to pumping in which an initial confined response lasts for hours to months, followed by a transition period in which the drawdown data depart from the confined type curve, showing smaller than expected values. This is then often followed by an increase in drawdown rate towards an unconfined response after a few days, weeks or months (Figure 7.1.8). However a complete double curve, (with both the confined and fully unconfined response), is rarely seen. When analysed (using the Theis or

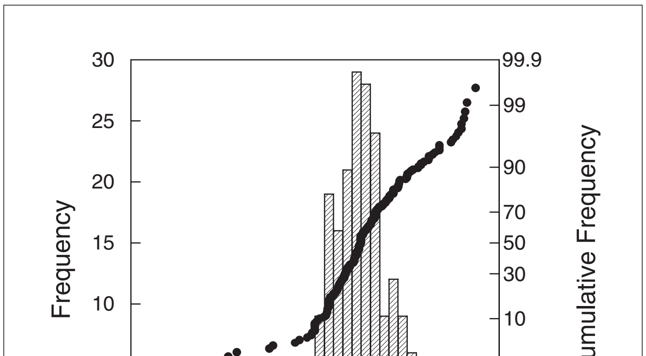


Figure 7.1.7 Distribution of storage coefficient data from pumping tests in the Permo-Triassic sandstones.

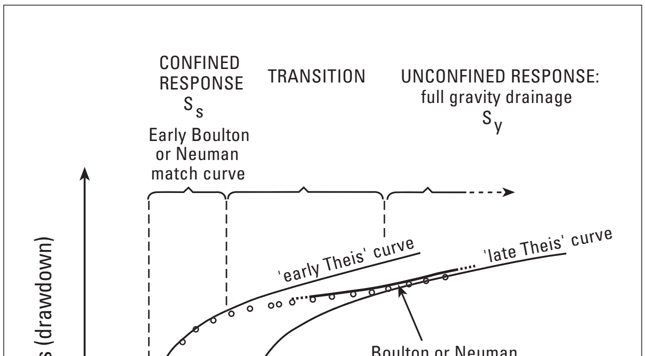


Figure 7.1.8 Characteristic response of the Permo-Triassic sandstones to pumping.

Boulton methods) a confined storage of 10^{-3} to 10^{-4} is often obtained, but it is virtually never possible to analyse the end of the curve for specific yield. Thus when even obviously unconfined Permo-Triassic sandstone aquifers are pumped, a characteristic confined response curve is seen.

Although the fully unconfined response is not observed in low stress pumping, it is often found in high abstraction dewatering; thus specific yield values are most appropriate for dewatering calculations and values of the order of 0.1 are considered to be reasonable. The dewatering response is seen in terms of days, rather than years as in groundwater supply (Campbell, J E, and Walthall, S, personal communication). Similarly, specific yield values are applicable for long-term regional computer groundwater flow modelling.

The most likely explanation of aquifer behaviour is its anisotropic nature. After the initial confined response of the aquifer, vertical hydraulic gradients are set up across the less permeable layers as more water flows out of the permeable layers so reducing their head. The propagation of this head change to the surface for an unconfined water table response is slowed down by the low vertical hydraulic conductivity layers of the aquifer. Retardation of vertical flow by the less permeable horizons means that the interlayers effectively confine the aquifer. The drawdown response in longer tests, where the upturn of the curve is seen towards the end of pumping (Figure 7.1.8), is typical of anisotropic unconfined aquifers.

Other explanations which have been invoked to account for the confined response of the Permo-Triassic sandstones on pumping are the effects of boundaries, superficial strata and fractures. However while each may contribute to specific test responses, they cannot explain the widespread nature of the effect.

BOUNDARIES

Aquifer boundaries have been used to explain the final increase in drawdown gradient, such as in the north-west of England in the Vale of Eden (Price et al., 1982), but suitable no-flow boundaries cannot always be identified at the correct distance to give an increase in drawdown at the right time. Faults are an obvious potential boundary to flow which could increase drawdown when the cone of depression intersects them. However faults may be both impermeable (for example the Roaring Meg fault in Merseyside) and permeable (such as the Topcliffe fault in Yorkshire), but it is difficult to universally justify invoking faults when there is little evidence for their existence or properties.

SUPERFICIAL STRATA

Both the Mercia Mudstone Group and the drift confine the Permo-Triassic sandstone aquifer in places, but such confining layers are not ubiquitous and cannot explain the universal nature of the delayed water table response. In the Vale of York and Humberside, till locally acts as a confining layer and it is possible that in longer tests the cone of depression spreads beyond the till to unconfined areas so giving an unconfined storage after some time. However this explanation is not valid in the south-west of England where till cover is not significant and yet the effect is found and storage coefficient values are usually confined.

FRACTURES

The fractured nature of the aquifer is also likely to contribute to its unusual behaviour. The dual permeability nature of the system is likely to result in changes to the gradient of the drawdown curve as different components of the system come into play (for example the accessing of storage from deeper parts of the aquifer). However the characteristic times of these responses are unknown and, at present, unpredictable.

A further possibility is that dewatering of fractures could provide the low storage values, later followed by a matrix contribution. The values of storage obtained from pumping tests are however too low even for fracture storage and they can only be attributed to confined storage. However there is some component of fracture flow and this dominates the transmissivity in some areas. Fractures may contribute low storage values in pump tests especially in the breccias of the south-west. Generally, however, throughout the Permo-Triassic sandstones the annual storage of the aquifer appears to be controlled by a high-matrix specific yield, even in areas where fractures are important in transporting water and give high borehole transmissivity.

Regional aquifer properties

For the Permo-Triassic sandstone aquifers, regional groundwater models often require (in order to provide realistic head distributions) values of transmissivity which span a significantly smaller range, and are generally smaller than, those obtained from pumping tests in the same area. If the data are valid this would seem to imply that although the effects of fracturing and high permeability lenses are very significant on a borehole scale, they are less significant on a regional scale. Thus there is the implication, important for both resources and pollutant transport investigations, that fractures may not be regionally interconnected, despite being locally significant.

If fractures are not interconnected on a regional scale, then core intergranular hydraulic conductivity may most closely represent the regional hydraulic conductivities. In this situation the values of hydraulic conductivity used in regional models will be similar to those obtained from core permeametry. Where the interconnection of fractures and highly permeable horizons is more widespread, model hydraulic conductivities exceed typical intergranular values, although they are still significantly less than the high pumping test values. For instance, in the Cheshire and south Lancashire region, model values are typically 1 to 2 m/d (with associated transmissivities of about 50 to 300 m^2/d) compared with 0.5 m/d for the core-scale intergranular hydraulic conductivity.

Other factors which have a bearing on this discussion are the (unknown) extent to which the borehole data are biased towards high-yielding sites and the degree to which fractures intercepted by boreholes are real features, or are caused, or at least enhanced by borehole construction and development. It is evident therefore that the true significance of fracturing on regional flows and aquifer properties is very poorly understood in the Permo-Triassic sandstones.

Conclusions

Spatially, the Permo-Triassic sandstone aquifer is both heterogenous and anisotropic. Lateral and vertical lithological and structural variations affect both horizontal and vertical flows. The anisotropy and heterogeneity arising from the presence of fine grained layers causes deviations from ideal aquifer flow behaviour and thus many pumping test analysis assumptions concerning the 'ideal aquifer' are violated.

Temporally, the presence of interlayered sediments of variable permeability has a major influence on the short term response of the aquifer: both to pumping and to barometric pressure changes. In both cases they cause unconfined aquifers to behave in a confined or semi-confined manner but have little effect on the long-term aquifer storage behaviour. The long-term response of the aquifer systems can only be successfully modelled if the unconfined values of storage coefficient are used.

The permeabilities characterising the Permo-Triassic sandstone aquifer are strongly scale-dependent. Measurements at the core scale show the matrix properties of the aquifer, but do not indicate the effect of fractures. Packer tests indicate the sum of matrix and local fracture properties, and can be targeted on individual fractures. Pumping test data can give an average permeability of an effective thickness of the aquifer, including fractures and matrix, up to distances of the order of kilometres. However pumping test responses may be strongly affected by local fractures, (which may themselves be enlarged by drilling and testing operations). At a regional scale, effective permeabilities are often smaller than those obtained by pumping test analyses, perhaps indicating the lack of regional interconnection of fractures, (although the bias of pumping test data to high-yielding sites will also be a factor).

7.1.5 Aquifer properties data

Aquifer properties data are analysed and described in the regional sections which follow. They have been taken from permeametry, packer tests, pumping tests, and groundwater flow modelling, and were obtained from a variety of sources. Pumping test data were collected principally from the National Rivers Authority regional offices, and include information on transmissivity, storage coefficient, well depth, casing depth, and water levels. These data were entered onto the Aquifer Properties Database (Chapter 2). Core porosity and hydraulic conductivity data from the British Geological Survey's archives at Wallingford have been used. Data from packer tests and computer groundwater flow models were also collated.

In addition to collecting these basic aquifer property data, references and expert opinion have been sought in order to provide an insight into interpreting the numbers and understanding the context in which they should be used. References which have been used include: National River Authority reports, water authority reports, water company and Environment Agency reports, PhD and MSc theses, published literature, Source Protection Zone Lead proformas. The opinions and knowledge of local and regional experts from regional offices of the Environment Agency, water companies, universities and consultancy companies were sought.

Existing information and reports were compiled, and the database was interrogated on a region-by-region basis. The database was used to investigate and plot possible trends in the data. Log and linear frequency histograms of transmissivity, storage, specific capacity and bulk hydraulic conductivity, porosity and intergranular hydraulic conductivity have been plotted. Variation in aquifer properties values within each region have been compared, and statistics computed for the parameter distributions. Variations of parameters with depth and with other parameters have been investigated.

7.2 NORTH-EAST ENGLAND

7.2.1 Introduction

Geological and geographical setting

General

In north-east England, the outcrop of the Permo-Triassic Sherwood Sandstone Group aquifer extends in a wide belt from the Cleveland coast to south Nottinghamshire (Figure 7.2.1) and lies within the jurisdiction of two Environment Agency regions; Midlands and north-east. The aquifer consists mainly of red-brown, fine- to medium-grained sandstone with sporadic thin lenses of red-brown to grey-green mudstone and layers of rolled mudstone fragments; coarse-grained sandstone with common, rounded quartzitic pebbles makes up much of the Group in Nottinghamshire. The Sherwood Sandstone Group is early Triassic (Scythian) in age throughout most of the region, but in south Nottinghamshire the lowest beds are probably late Permian in age. The Group conformably overlies dolomitic limestones, mudstones and evaporites of Permian age. The aquifer generally dips gently towards the east, forming an outcrop 8 to 20 km wide before dipping beneath the confining mudstones and siltstones of the mid to late Triassic Mercia Mudstone Group (Figures 7.2.2, 7.2.3). Equivalent Triassic sandstones are proved beneath thick Mesozoic cover rocks in Lincolnshire, east Yorkshire and the southern North Sea. Thick superficial (drift) deposits of Quaternary age cover much of the outcrop in Yorkshire and Cleveland, but are much thinner and more patchily distributed in Nottinghamshire.

Regional structure and depositional environment

The structure of the Permo-Triassic rocks in the Yorkshire and Durham area is relatively simple. Beds dip gently to the east at only 1 to 2°, less commonly up to 4°. The Permo-Triassic strata have been disrupted by normal faults in several parts of the region, most of which can be related to re-activated movement on pre-existing faults affecting the pre-Permian. In the Teesside area, the Permo-Triassic strata are disrupted by several east–west-trending major faults, such as the Craven Fault, the Topcliffe Fault, the Butterknowle Fault and the West Hartlepool Fault. Farther south, faults in the Thirsk area also tend to have an east–west trend, but north-east to south-west trends are prevalent in the Knaresborough and Selby areas, with a complementary set trending north-west to south-east.

The Permo-Triassic rocks of Nottinghamshire have been subjected to faulting and minor, slight flexuring due to reactivation of underlying fractures in the pre-Permian rocks. There is a general dip to the east of around 1°, veering round to the south-east in the area around Nottingham. Undermining of the Sherwood Sandstone Group in the Nottinghamshire coalfield has resulted in subsidence and flexing of the sandstones at the edge of the worked area; several seams, each up to about 4 m thick have been worked. This results in the sandstone cracking, with fractures up to 1 m wide at the surface, and extending to depths in excess of 30 m. This fracturing is likely to greatly increase the permeability of the Sherwood Sandstone Group in affected areas. The underlying Permian mudstone formations of the Upper Permian tend to bend rather than crack, so that the hydraulic base of the aquifer remains intact (Land, 1952).

In late Permian to early Triassic times, sand deposition spread gradually north-eastwards across the region, so that the base of the Sherwood Sandstone Group is markedly diachronous, rising up the succession towards the north-east. The lowest part of the Group in Nottinghamshire is late Permian in age, and comprises both aeolian and fluvial, fine- to medium-grained argillaceous sandstones (Lenton Sandstone Formation). By the early Triassic, a major river system became established, flowing north-eastwards across the region. This deposited medium- to coarse-grained pebbly sands (Nottingham Castle Sandstone Formation)

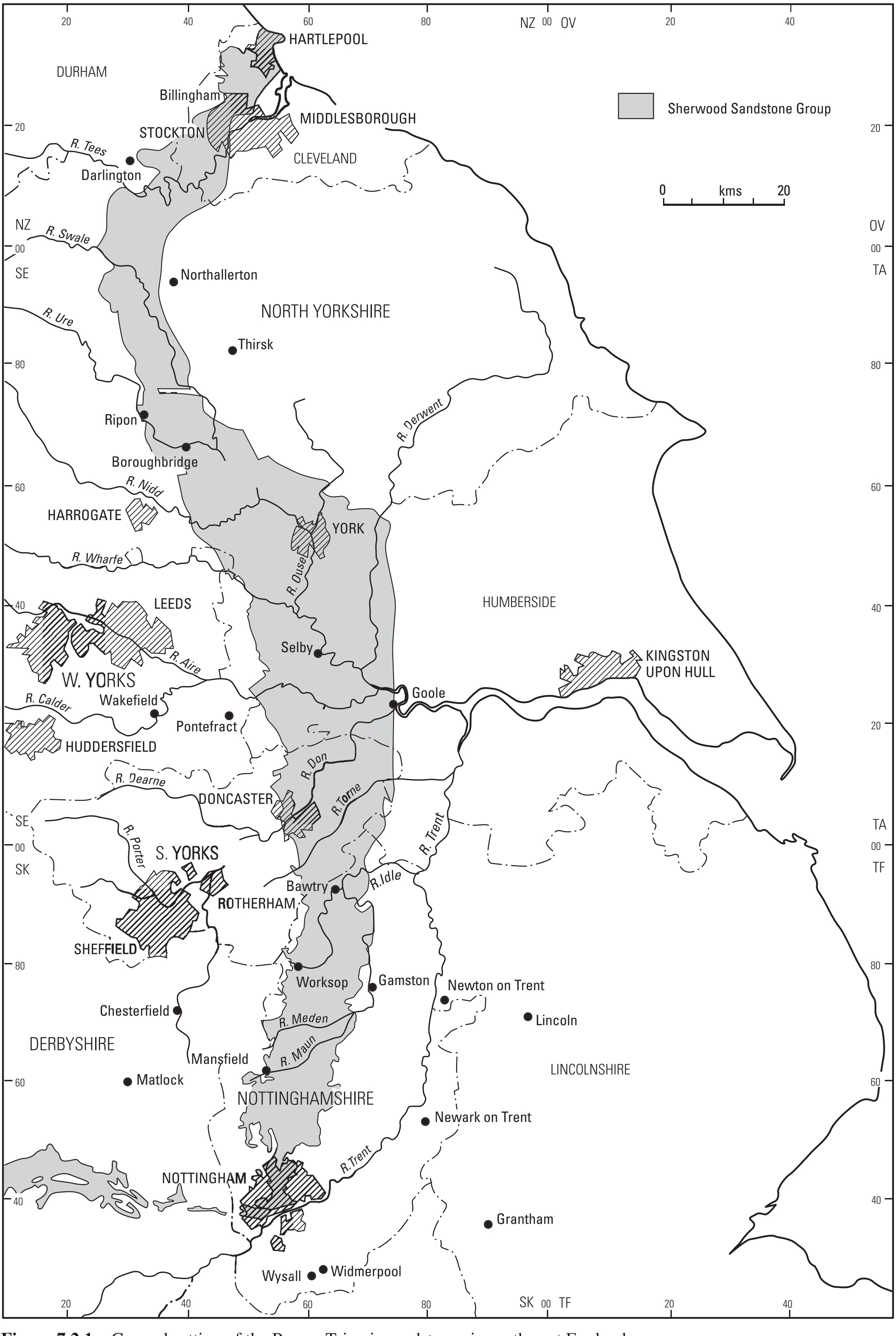
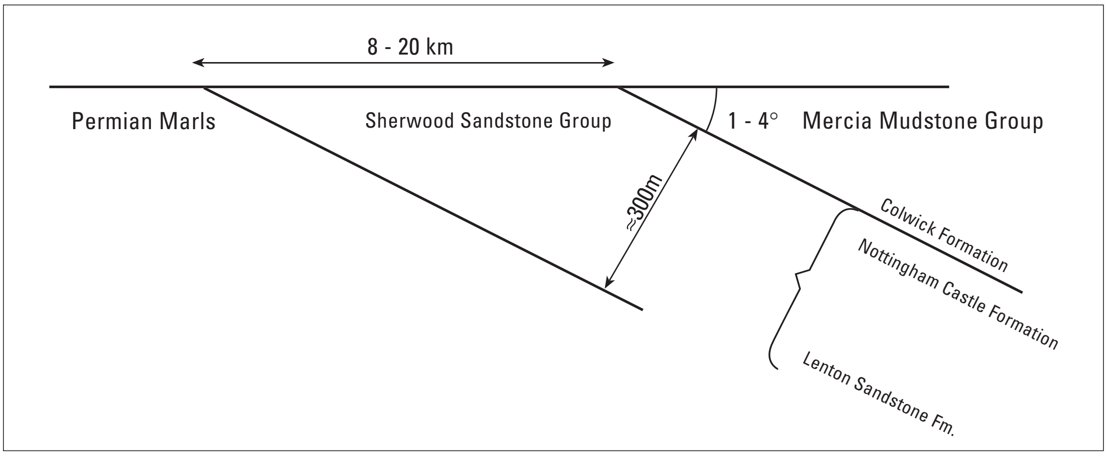


Figure 7.2.1 General setting of the Permo-Triassic sandstones in north-east England.

Figure 7.2.2 Typical section through the Permo-Triassic sandstones of north-east England.



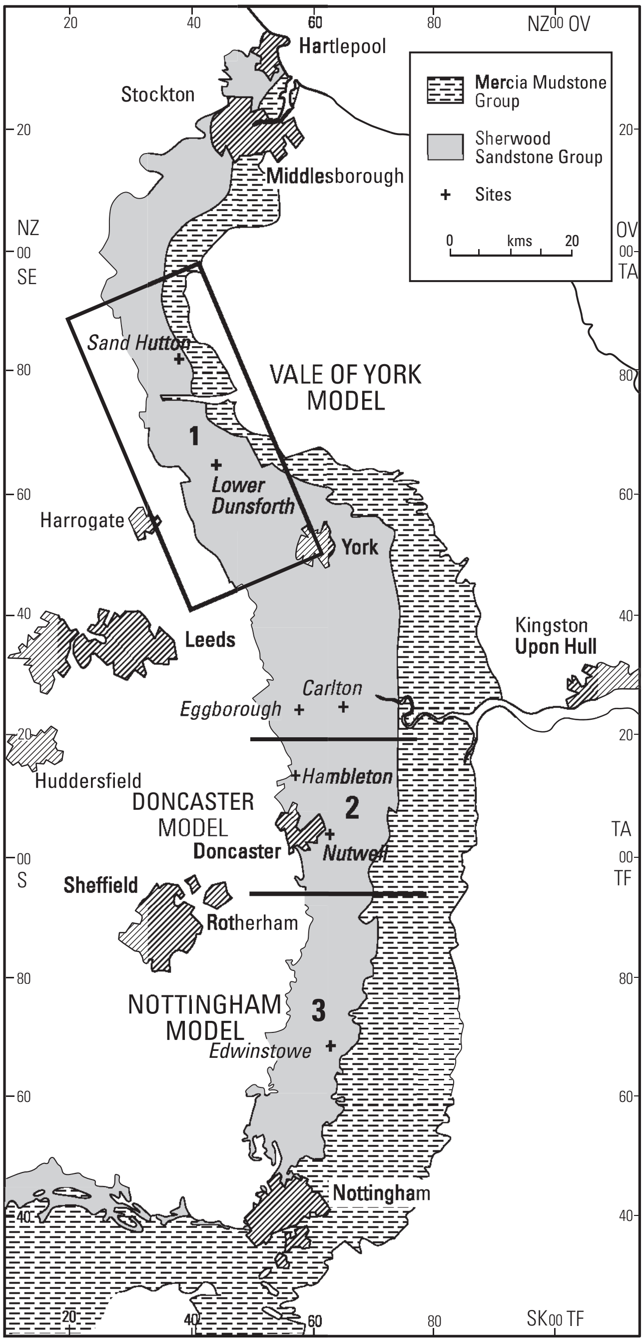


Figure 7.2.3 General geology, areas of investigations and locations of sites in the Permo-Triassic sandstones of north-east England.

in Nottinghamshire, passing into fine- to medium-grained sandstones with few pebbles in Yorkshire and Cleveland.

Following a period of uplift towards the end of the early Triassic, deposition was temporarily interrupted in the region. When deposition resumed in the early part of the mid Triassic, an arid climate prevailed, and muds, silts and evaporites were deposited on alluvial or coastal mudflats with temporary, saline lakes. These sediments now form the red and green mudstones, siltstones and thin sulphate rich evaporites of the Mercia Mudstone Group. Fluvial sand deposition was restricted to the south-west of the region, leading to deposition of the interbedded siltstones and sandstones of the Sneinton Formation, which forms the base of the Mercia Mudstone in Nottinghamshire.

Due to the regional differences in the stratigraphy of the Permo-Triassic sequence, Nottinghamshire is discussed separately from Yorkshire and Cleveland in the following section.

Stratigraphy

General

The Permo-Triassic strata of the Yorkshire and Cleveland region have been described for the Goole, Doncaster and the Isle of Axholme area by Gaunt (1994), the Harrogate area by Cooper and Burgess (1993), the Thirsk area by Powell et al. (1992), and the Durham and West Hartlepool area by Smith and Francis (1967). Smith and Warrington (1971) describe the petrology of Mercia Mudstone Group strata above the Sherwood Sandstone Group. Koukis (1974) described the petrology of the Sherwood Sandstone Group in the Vale of York.

In Yorkshire and Cleveland, the Sherwood Sandstone Group aquifer consists of a thick sequence (up to 450 m) of fine- to medium-grained sandstones with common argillaceous beds and lenses. The aquifer is confined below by the mudstones and siltstones of the Roxby Formation (formerly Upper Permian Marl), and above by the mudstones and siltstones of the Mercia Mudstone Group (formerly Keuper Marl) (Table 7.2.1). In contrast to Nottinghamshire, the Sherwood Sandstone Group is not divided into formally recognised formations, but three informal subdivisions are recognisable on lithological grounds. The aquifer crops out in the catchments of the rivers Went and Don in South Yorkshire, the Ouse and Swale in North Yorkshire, and the Tees in Cleveland (Figure 7.2.1).

The Permo-Triassic of Nottinghamshire is described from the Ollerton area by Edwards (1967) and from the Chesterfield, Matlock and Mansfield areas by Smith et al.

Table 7.2.1 Permo-Triassic stratigraphy in the north-east of England.

System	Group	Formation		Former name	Dominant lithologies	Thickness (m)	Aquifer unit
		South Notts	North Notts				
TRIASSIC	Mercia Mudstone Group			Keuper Marl	mudstone and siltstone	180–210	Aquitard
		Sneinton Formation		Colwick/ Waterstones Formation	siltstone and fine sandstone	40–80	Minor aquifer
				Retford Formation/ Green Beds			
	Sherwood Sandstone Group	Nottingham Castle Sandstone Formation		Bunter Pebble Beds	coarse, pebbly sandstone	50–200	Aquifer
		Lenton Sandstone Formation		Lower Mottled sandstone	fine sandstone	10–50	
			Roxby Formation	Upper Permian Marl	mudstone and siltstone	0–40	Aquitard
PERMIAN			Brotherton Formation	Upper Magnesium Limestone	dolomitic limestone	0–10	
	'Upper Permian'	Edlington Formation		Middle Permian Marl	mudstone and siltstone	0–50	
		Cadeby Formation		Lower Magnesian Limestone	dolomitic limestone	0–50	
	'Lower Permian'	Basal Breccia			dolomitic breccia	0–2	

(1967). Land (1966) and Charsley et al. (1990) describe the hydrogeology of the area around Nottingham.

The Sherwood Sandstone Group aquifer of Nottinghamshire crops out in the catchments of the rivers Trent, Leen, Maun, Meden, Poulter, Ryton, Idle and Torne. The Group consists of up to 300 m of sandstone, varying from fine to coarse grained and with abundant pebbles in the upper two thirds. Two constituent formations are recognised (The Lenton Sandstone Formation and the Nottingham Castle Formation — Table 7.2.1) although in aquifer terms the group behaves as a single unit. The base of the Group is diachronous, and lies on successively older strata towards the south of the county. The Sherwood Sandstone Group aquifer is generally confined below by mudstones and siltstones of either the Edlington Formation (formerly Middle Permian Marl) or, in the northern part of the outcrop and in the subsurface to the east, the Roxby Formation (formerly Upper Permian Marl) (Table 7.2.1). The Sherwood Sandstone Group is overlain by the Mercia Mudstone Group, the basal formation of which, the Sneinton Formation, forms a minor but significant aquifer. The remainder of the Mercia Mudstone Group is relatively impermeable.

Upper Permian

Yorkshire and Cleveland area

In much of Yorkshire and Cleveland, the Sherwood Sandstone Group aquifer is underlain by the Roxby Formation (formerly Upper Permian Marl). Although traditionally included in the 'Upper Permian' sequence, much of the formation is probably of early Triassic age. The Formation consists predominantly of reddish brown mudstone and siltstone with beds of gypsum and anhydrite. It effectively forms an impermeable base to the Sherwood Sandstone Group aquifer and dips at 1 to 4° towards the east. Recharge to the Sherwood Sandstone Group at its western feather edge appears to run down the top of the Roxby Formation. Dissolution of gypsum within the upper Permian succession in parts of North Yorkshire can cause formation of cavities and fractures in the Sherwood Sandstone Group close to the western edge of the outcrop (Cooper, 1989). The Roxby Formation is locally absent in South Yorkshire where the Sherwood Sandstone Group directly overlies the Brotherton Formation (formerly Upper Magnesian Limestone).

Nottinghamshire

In the north of the area (as in Yorkshire), the Sherwood Sandstone Group overlies the Roxby Formation, the uppermost division of the Permian. However, south west of a line between Worksop and Newark (Figure 7.2.1), the Roxby and Brotherton (formerly Upper Magnesian Limestone) formations are absent, and the Sherwood Sandstone Group lies mainly on the Edlington Formation (formerly the Middle Permian Marl). Both the Roxby and Edlington Formations consist of red-brown mudstones, siltstones and subordinate sandstones, forming an effective base to the Sherwood Sandstone Group aquifer. Locally, in Nottingham, the Sherwood Sandstone Group lies directly on the dolomitic limestones of the Cadeby Formation (formerly the Lower Magnesian Limestone). South of a line between Nottingham and Grantham, the entire Upper Permian is absent, and the Sherwood Sandstone Group lies directly on Carboniferous rocks.

SHERWOOD SANDSTONE GROUP

Yorkshire and Cleveland area

The Sherwood Sandstone Group aquifer thickens north-eastward from 250 to 450 m, its top dipping eastward at 1 to 4°. No formally defined formations are recognised within the Group in this region, but three informal units can be differentiated on lithological grounds. All three units thicken and become generally finer grained towards the north-east.

The lowest unit is 18 to 44 m thick. It consists of sandstones that are variably coloured red, brown, orange, grey, buff and white, and that are micaceous, clayey, silty, well sorted and fine grained. The grains are mainly subangular to subrounded, with some layers rich in rounded grains. Much of this sequence is cemented by a white, slightly calcareous and locally gypsiferous clay matrix. Thin beds of red, gypsiferous mudstone occur throughout, becoming thicker and more common towards the east.

The succeeding middle unit thickens northwards from about 230 m to nearly 400 m and is distinguished from the underlying beds by being dominantly red, less argillaceous, and generally coarser grained. In general, the sandstones vary from fine to coarse grained and from poorly to well sorted, with grain shapes ranging from subangular to rounded. A white, slightly calcareous clay matrix is locally present but much of the rock is uncemented, unconsolidated, friable, porous and permeable. Some beds are reported to be calcareous, gypsiferous or dolomitic. Pebbles are reported from most of the south-western boreholes, but clearly are not abundant. Some records suggest that pebbles are scattered throughout the middle part of the unit, but others imply concentrations at or near the base and at a level near the middle of the unit. Pebbles diminish markedly in abundance to the north of Doncaster. A few thin beds of red and green mottled silty mudstone are present, mainly in the higher part of the unit. Mudstone lenses, representing abandoned fluvial channel fills, are documented in the Doncaster area, where they reduce the saturated thickness of the aquifer.

The upper unit thickens northwards from 5 to 45 m. It consists dominantly of white, grey or buff, fine- to medium-grained, micaceous, argillaceous silty sandstone; typically loosely cemented, friable and largely free of pebbles. The grains range in shape from subangular to rounded. Numerous thin beds of red and grey silty mudstone and siltstone are also present.

The sediments are generally finer in the north and coarsen towards the centre and east of the region. Grain size varies on a scale of a metre or so, whilst the proportion of marl and silt changes within a cycle of deposition. However in general there appears to be a relatively constant proportion of sand, silt and clay throughout the strata penetrated by the cored boreholes, the majority of grains being 0.12 to 0.25 mm in diameter, within the range of a fine sand (Aldrick, R J, personal communication; Leeds and Dodds, 1986). In the Vale of York the sandstone ranges from friable to well cemented, the cementation consisting mainly of secondary quartz with some carbonate.

Nottinghamshire

The Sherwood Sandstone Group comprises the Lenton Sandstone Formation (formerly Lower Mottled Sandstone) and the overlying Nottingham Castle Sandstone Formation (formerly Bunter Pebble Beds). The thickness of the group varies from about 250 m in north Nottinghamshire to about 60 m around Nottingham, dying out farther south in Leicestershire.

The Lenton Sandstone Formation is 10 to 50 m thick. It is a fine- to medium-grained, poorly consolidated argillaceous sandstone, dominantly deep red-brown in colour with buff yellow mottling. Thin beds of red and green-grey mudstone and siltstone are common towards the base. Pebbles occur sporadically and are generally more angular in shape than in the overlying Nottingham Castle Sandstone Formation.

The Nottingham Castle Sandstone Formation is 50 to 200 m thick and comprises friable, medium- to coarse-grained sandstone with abundant pebbles. Thin beds and lenses of red and grey-green mudstone and siltstone occur but are uncommon. The topmost beds are notably paler in colour with a greater concentration of pebbles; the very top of the formation is commonly calcreted. At depth much of the formation is calcareous or less commonly pyritic. The pebbles are typically 1 to 5 cm across, being well worn and smooth, with flattened spheroidal shapes. Most consist of quartzite or vein quartz but a range of other, mainly igneous lithologies also occur. The Nottingham Castle Sandstone becomes finer grained and less pebbly northwards, and cannot be differentiated from the Lenton Sandstone Formation to the north of Doncaster (see above).

Clay mineral distribution varies within the Sherwood Sandstone Group with more illite and montmorillonite type clays in the north of the region and at depth in the aquifer. There is thought to have been a sequence of diagenetic events, as illustrated by the following diagenetic sequence identified in the sandstones of the Gamston borehole [SK 703 766].

1) Early precipitation of iron oxide grain coatings, oxidisation of biotite and precipitation of intergranular and replacive dolomite.
2) Burial and concomitant compaction.
3) Precipitation of illite and minor feldspar dissolution.
4) Precipitation of quartz and feldspar overgrowths.
5) Extensive dissolution of K-feldspar and dolomite with abundant precipitation of kaolinite and minor co-precipitation of silica. A minor amount of calcite was present.

The resultant porosity in the aquifer seems mainly to be due to the preservation or rejuvenation (by dolomite removal) of primary intergranular porosity, supplemented by the development of secondary porosity by K-feldspar corrosion and dissolution. The precipitation of authigenic clays, in particular abundant kaolinite, reduces the secondary porosity and may reduce the permeability of the sandstone (Bath et al., 1987).

MERCIA MUDSTONE GROUP

Yorkshire and Cleveland area

The Mercia Mudstone Group overlies the Sherwood Sandstone Group with a small unconformity. It consists mainly of reddish brown and, to a lesser extent, greenish grey, dolomitic mudstone with anhydrite or gypsum. There is no minor aquifer equivalent to the Sneinton Formation of Nottinghamshire at the base of the Group.

Nottinghamshire

The Mercia Mudstone Group overlies the Sherwood Sandstone Group with a small unconformity. The basal part of the Group, the Sneinton Formation, varies from 40 to 80 m thick and combines the Green Beds and Keuper Waterstones (or Colwick Formation) of earlier terminology. It crops out along the eastern edge of the Sherwood Sandstone Group outcrop as far north as East Retford. In the Nottingham area, the formation consists of 40 to 50 m of interbedded red-brown mudstones and red-brown or buff, fine-grained micaceous sandstones. North-eastwards, these sandstone-rich beds are split from the underlying Sherwood Sandstone Group by a gradually increasing thickness of grey-green and red-brown silty mudstones, these being up to 40 m thick in the East Retford area. Although not in itself very transmissive, the formation is hydrogeologically significant because it provides additional outcrop through which recharge can occur to the underlying pumped sandstone aquifer (Fletcher, S, personal communication).

The overlying remaining part of the Mercia Mudstone Group is 180 to 210 m thick and is composed of relatively impermeable red-brown and green-grey mudstones with siltstones. Thin beds of pale grey or greenish grey, fine-grained dolomitic siltstone or very fine-grained sandstone occur throughout the sequence. These are commonly aggregated into groups up to 2 m thick, forming the so-called 'skerries'. These may form local, minor aquifers. The higher skerries are siliceous whereas the lower ones are dolomitic. Economic deposits of gypsum are found towards the top of the Group.

DRIFT

In Nottinghamshire, Quaternary superficial deposits (drift) are thin and patchily distributed. Significant drift cover begins just south-east of Doncaster around Bawtry [SK 465 393] and generally increases in thickness northwards through Yorkshire. In the Doncaster area the drift is very variable in composition and contains a high proportion of sand, through which limited recharge appears to occur.

North of the river Don, there is little recharge through the thick cover of mainly lacustrine, clayey drift deposits. These lacustrine clays stretch from Doncaster to York and were deposited in pro-glacial lakes towards the end of the last (Devensian) ice age. However, just north of the river Aire in the Selby area, there is localised drift-free outcrop of the Sherwood Sandstone Group. North of York the deposits are more variable, consisting mainly of glacial till (boulder clay). In some areas, where there are sandy deposits within the drift, there is limited connection between the drift and the underlying sandstone aquifer and therefore some recharge potential. Sandy drift is frequently found on higher ground, with more clayey drift in the river flood plains. Within the Vale of York, drift cover of around 15 m in thickness extends from the River Aire in the south to Northallerton in the north (Gray et al., 1965). North of Northallerton there is a further increase in drift thickness to over 40 m.

General hydrogeology

Water resources

NOTTINGHAMSHIRE

In Nottinghamshire the Sherwood Sandstone Group is an important source of water for Nottingham and Mansfield. Much of the water resources development of the area began in the last century when many large diameter wells were constructed. These are often very high-yielding public supply boreholes, but no pumping test data are available. The aquifer is highly abstracted to the north of Nottingham and over abstracted further to the north in south Yorkshire. Water is abstracted for public supply north and east of Nottingham, and industrial abstraction (mainly used for laundries, bleaching and dying, pharmaceuticals and brewing) is concentrated in the urban Nottingham area. Spray irrigation in rural areas uses water from the Sherwood Sandstone Group aquifer.

The high quantities of abstraction mean that the aquifer is not in equilibrium, as the rate of recharge is less than the rate of abstraction (Fletcher, S, personal communication). The Triassic sandstones form one aquifer unit with infrequent marl bands and there is generally hydraulic continuity throughout the unit. The aquifer generally responds to pumping in a fairly intergranular manner as a result of its relatively uncemented nature, although fractures are frequently very significant. Permeabilities (both fracture and intergranular) are high in the generally coarse friable sandstones, fracture permeability being enhanced in areas where the outcrop has been undermined by coal workings. This leads to higher well yields than in the finer-grained sandstones further north. The aquifer is also usable to the east beneath the Mercia Mudstone outcrop to a greater degree than in the north.

YORKSHIRE AND TEESIDE

In Yorkshire most of the outcrop area is low lying in the valley of the river Ouse. This results in low hydraulic gradients in the aquifer and only small seasonal fluctuations in water levels (typically 2 to 3 m). Much of the area is covered in glacial till, causing local artesian heads, and a complex hydrogeological relationship between the sandstone and the drift. Both fracture and intergranular flow are important methods of groundwater movement. The aquifer is extensively developed south of the river Wharfe for both public and private water supplies. Borehole yields are mainly good and may be in excess of 10 000 m^3/d.

In the north around Teesside the Sherwood Sandstone Group becomes increasingly fine grained away from its source area to the south. This results in low permeabilities, with transmissivities generally less than 80 m^2/d. There are no public water supplies from the Sherwood Sandstone Group in the north-east, though industrial licensed abstractions amount to approximately 12 500 m^3/d.

Small amounts of water are also found within the upper Colwick Formation (formerly the Keuper Waterstones) and 'skerries' within the Mercia Mudstone Group (formerly Keuper Marl). In general, however, the Mercia Mudstone Group deposits are impermeable, confining the Sherwood Sandstone Group aquifer down dip.

Borehole problems

The sandstone is generally cemented sufficiently for boreholes (typically drilled to depths of up to around 250 m) to be unscreened with only the Mercia Mudstone Group cased out. Locally however boreholes may pump sand and therefore require screening. This has been a particular problem in variably cemented, unconsolidated to friable horizons within the Vale of York. Generally, in Yorkshire large abstraction holes which are heavily pumped (i.e. 6000 to 10 000 m^3/d) have a 25% chance of encountering a sand problem. Boreholes in which sand is a problem are screened with a gravel pack to control sand ingress. Due to the uniform nature of the grain size of the aquifer material, (over the scale of several metres), a standard design of screen and single size gravel pack can be used. In South Yorkshire iron and manganese precipitation in boreholes is also a problem in the areas where Sherwood Sandstone Group is confined (either beneath the Mercia Mudstone Group or beneath drift).

In Nottinghamshire the main problems are high levels of nitrate and over abstraction. Some boreholes regularly pump sand. However, if new holes are pumped for a few days at around $1^1/_2$ times the intended pump rate they may yield large quantities of sand, but subsequently pump very little or no sand at the lower rate (Fletcher, S, personal communication).

Fractures

Generally in this region fractures contribute significantly to transmissivity, though intergranular flow is important, especially in the south, and intergranular storage is high. Regionally, fractures are not thought to be interconnected, but are possibly often filled with sand and only developed near boreholes (Fletcher, S, personal communication). Such fractures are thought to only extend for up to tens of metres but this distance is thought to be sufficient to provide a similar transmissivity to that obtained from packer tests over the fractured interval (Price, 1994). Borehole logging indicates that fractures are present and responsible for much of the flow of water into the borehole when it is pumped.

High transmissivity values are found where fractures are encountered by boreholes. This may be the cause of high transmissivities found in Nottinghamshire, which may be of the order of 1500 m^2/d, of which only 300 m^2/d may be accounted for by laboratory permeability values.

In the Yorkshire region it is considered that most of the fracture flow occurs in the top 100 m of the aquifer (Aldrick, J, personal communication). Beneath this depth fractures are thought to be closed. In contrast, in the west Midlands, fractures are open for at least 200 m and borehole yields can increase beneath this depth in faulted and fractured areas (Fletcher, S, personal communication).

Fractures are also hydraulically important in the north of the region where the intergranular permeability is lower, and the contribution of intergranular flow to the total is low.

Fracture systems are particularly important in areas which have been undermined or where there has been mineral dissolution at depth. Mining of the underlying Carboniferous strata is mainly of importance to the west of the Nottinghamshire outcrop and in the south in Nottinghamshire where subsidence has affected much of the sandstone (for example there are large subsidence fractures in the area of Boughton [SK 466 368] — these interfere with local surface water and periodically cause streams to vanish underground). Mining in the Doncaster area is not thought to have had an important influence on the aquifer.

The association of fractures with deep mining means that they originate at depth. In consequence the number and size of these fractures does not necessarily decrease with depth, (as is usually assumed), and may in fact increase (Fletcher, S, personal communication).

Fracturing due to the rehydration of anhydrite in the underlying Permian beds is only a significant effect for a few kilometres down dip (along the feather edge of the aquifer where the water circulation is good), but does not appear to be important where the sandstone has a greater thickness.

FAULTS

Faults are present throughout the Permo-Triassic sandstones, but due to the limited outcrop and the soft nature of the rock, are difficult to detect at the surface. The most detailed information on faults is provided by Coal Board exploratory boreholes and investigation mapping, but these are not necessarily near pumping boreholes for which there are transmissivity values.

Faults are sometimes permeable and sometimes impermeable, depending on the lithologies that are juxtaposed and the degree of cementation and secondary, (for example clay), mineralisation of fault zones. The effects of faulting disrupting the bedding and aquifer thickness are not well known. Although very important locally, the hydraulic effects of faults are not necessarily important on a regional scale, or in aquifer modelling. For example faulting is present in the Gainsborough area [SK 482 390], but does not cause effects which need to be accounted for in models (Fletcher, S, personal communication).

Some faults appear to act as highly transmissive zones, in that cones of depression caused by pumping do not extend across them. This may be due to brecciation of the aquifer around large faults or simply a very high permeability along the fault.

In Yorkshire, faults with recognisable hydrogeological effects are present. The Topcliffe fault, in North Yorkshire, and a fault near Eggborough No. 3 borehole [SK 459 423] in South Yorkshire, seem to be able to supply water and do not allow the extension of cones of depression beyond them. The aquifer is thought to be brecciated in the area of the Topcliffe fault. Pump testing at Eggborough No. 3 borehole suggested that a fault was acting as a recharge boundary. In the Doncaster area faulting offsets the aquifer vertically and so locally changes aquifer depth, but this does not appear to influence the effective depth or thickness of the aquifer.

Groundwater flow

Natural groundwater flow is generally eastward from the feather edge of the aquifer in the west towards the confined aquifer in the east. The low topographic variation of the aquifer in the north is likely to have resulted in very low natural hydraulic gradients. The slightly greater topographic variation of the sandstone in the south may have resulted in increased flow. High abstraction rates now dominate groundwater flow, with flow directions concentrated towards pumped wells (Parker et al., 1985). In Yorkshire and Northumbria there is apparently less water circulation with depth (as indicated by poor quality water at depth); this may suggest a general decrease in fracture frequency with depth. Most flow is likely to occur in the upper 100 m of the aquifer where the best yielding boreholes occur (Aldrick, J, personal communication).

RIVER/AQUIFER INTERACTION

In general there is limited interaction between the aquifer and rivers in the region because the rivers are in contact with the aquifer in only a few places.

In Nottinghamshire, in the Midlands Environment Agency region, outflow from the aquifer supports watercourses and lakes. Extensive abstraction has however lowered water levels, altering the natural hydraulic gradient. Rivers also supply some recharge to the aquifer, although there is some uncertainty about the amount of recharge from influent rivers. Rivers generally gain in their upper reaches, (in the west of the aquifer), and lose in the middle of the aquifer outcrop where most of the pumped boreholes occur (Bishop and Rushton, 1993).

In South Yorkshire only the River Torne interacts with the aquifer in the central Doncaster area. The aquifer loses water to the river in its upper reaches and gains lower downstream. In the Vale of York the rivers are only locally in contact with the aquifer, for example just down stream of Boroughbridge and on the Swale above Topcliffe, the aquifer is naturally effluent (Gray et al., 1965). Elsewhere the rivers flow over alluvium and till.

Water balance studies of the aquifer (Bishop and Rushton, 1993; Brown and Rushton, 1993) indicate that some 13% of the groundwater resources of the Sherwood Sandstone Group aquifer cannot be accounted for and leakage from above has been inferred. In South Yorkshire there is uncertainty regarding the amount of recharge occurring through the drift. Geochemical evidence does not however suggest that leakage is an important phenomenon, as Mercia Mudstone Group water does not yet appear to effect pumped borehole water quality significantly (Edmunds and Smedley, 1992).

Effective aquifer thickness

The effective aquifer thickness is probably equal to the borehole depth, as the ubiquitous interlayering of sediments reduces the input from any horizon beneath the borehole. This has been modelled using a vertical flow model (Dodds, 1986). Partially penetrating boreholes do not appear to access the transmissivity of the whole aquifer. The effect of argillaceous layers means that vertical flow is restricted and therefore boreholes with a longer total open section give higher transmissivities than those with shorter open sections. At best the effective aquifer thickness is the borehole depth if the whole borehole is screened beneath the water table. If only part of the borehole is screened then the transmissivity sampled is less. The actual open section length rather than the range of depths over which there is some screen is important, even if the same range of depths is covered. Bulk hydraulic conductivity (transmissivity/open section length) remains fairly constant (Brown and Rushton, 1993).

Water quality

Three main zones of chemically distinct groundwater are seen in the east Midlands around Worksop (Edmunds and Smedley, 1992). Recent groundwater is seen in the unconfined aquifer. This water is mainly younger than 1000 years. It is aerobic, saturated with calcite and affected by industrial or agricultural pollution, (such as high nitrate and sulphate from agriculture, and high chloride from mine drainage or atmospheric inputs). Older groundwater is seen just within the confined zone. This water has a high Mg/Ca ratio from reaction with dolomite, and the redox boundary of aerobic/anaerobic conditions exists in this region. The effects of pollution are not seen and low chloride and sulphate in this water indicate pre-industrial chemical baseline concentrations. Further into the confined zone of the aquifer, to the east, the groundwater is typically older than 10 000 years and has reducing conditions, with high sulphate values from gypsum dissolution.

The transition from fresh, good quality water to older water of increased salinity varies in position from south to north along the eastern outcrop area. In the Nottingham area salinities remain low for over 10 km beneath the confining Mercia Mudstone Group. A borehole at Newton on Trent, 10 km from the aquifer outcrop, yields good quality water but 20 to 30 km east at Lincoln, the water is older and saline (Edmunds et al., 1982). The chemical transition moves from 30 km from outcrop in the Nottinghamshire area to only a few kilometres from outcrop in North Yorkshire. The groundwater quality deteriorates markedly towards the eastern edge of the outcrop where high hardness and high sulphate concentrations are associated with the Mercia Mudstone Group or with thick drift. Down dip the water becomes non-potable, (Na-Cl type influenced by the Mercia Mudstone Group chemistry).

In areas of exposed outcrop and little drift, high concentrations of nitrate also pose problems for potable water supplies. Correspondingly, in confined areas or regions of extensive drift cover, reducing conditions may result in iron and manganese solution, causing fouling in boreholes.

Within the Mercia Mudstones Group, some groundwater is obtained from thin sandstone bands and within zones of partial dissolution of gypsum bands to form cavernous horizons, (e.g. at Thirsk). Correspondingly, at the western outcrop edge subsidence has occurred due to the dissolution of gypsum within the underlying Permian Roxby Formation.

Nottinghamshire

In the Severn Trent region around Nottingham there are no major salinity problems associated with the feather edge of the aquifer. In general salinities are lower than those further north, perhaps indicating greater natural water circulation beneath the drift (Aldrick, J, personal communication). High nitrate values are a major problem in the drift-free outcrop areas of the sandstone (mainly in Nottinghamshire). Nitrate reduction seems to occur mainly in the parts of the aquifer which have heavy drift cover or down dip, as anaerobic conditions are developed in these confined areas. Nitrate levels are generally lower in the confined parts of the aquifer. The whole area of the outcrop is designated a nitrate vulnerable zone.

Yorkshire

In Yorkshire salinities are generally higher than in the south, the water is harder and water quality deteriorates rapidly once the aquifer is confined. This may be due to reduced natural circulation of water and less recharge through thick drift cover and the confining Mercia Mudstone Group than is the case further south. High sulphate concentrations are associated with underlying Permian evaporite deposits at the feather edge of the outcrop. In the eastern confined area, a similar effect is seen, and may be due to disseminated gypsum and anhydrite from the top of the aquifer or the feather edge of the Mercia Mudstone Group. These high concentrations are a problem in the Doncaster area, and water quality along the feather edge is generally poor to the north in the Yorkshire region. In south Yorkshire, in the Selby area [SE 62 32], there is a sharp transition in chemistry seen between high nitrate levels in the drift free areas and iron and manganese in solution in the confined areas (Aldrick, J, personal communication).

Northumbria

In the Northumbria region the water quality is poor. It is relatively saline with total dissolved solids of around 1500 mg/l, it is very hard with $\leqslant$1000 mg/l $CaCO_3$, and is of $CaSO_4$ facies. Saline intrusion has occurred in the coastal region and along the Tees estuary in the area of Billingham and Middlesborough causing increased salinity (Day, 1957). In the Stockton area [SE 45 18], further up the river Tees from the coast, the water is very hard and has very high sulphate values due to gypsum and anhydrite deposits.

SUMMARY

The groundwater chemistry is generally good in outcrop areas and deteriorates down dip. Salinities are lower in the south and increase to the north. High nitrate concentrations are a problem in the outcrop areas of the south.

Previous hydrogeological investigations

A significant amount of work has been done in this region as groundwater has been extensively developed for much of this century. Many investigations have been carried out by the NRA, the Environment Agency, and the water companies and previously by the regional water authorities. Lovelock's work (1977) on the aquifer properties of the Permo-Triassic sandstones of the United Kingdom sets a general background to the area as does the hydrogeological map (IGS, 1981). The general extent of groundwater development and modelling is indicated in the NRA regional appendices for the Policy and Protection of Groundwater.

The most comprehensive study of the southern part of the region is the water resource study of the Nottinghamshire Sherwood Sandstone Group. The resulting model of the Nottingham and Doncaster areas (Bishop and Rushton, 1993 and Brown and Rushton, 1993 — Figure 7.2.3) summarises the current state of knowledge in the area. Previous work includes comprehensive hydrochemical studies of the East Midlands (Edmunds et al., 1982) and Edmunds and Smedley (1992). Downing et al. (1970) gave a general overview of the hydrogeology and groundwater resources of the Trent River Basin.

There is considerable development of the Sherwood Sandstone Group aquifer in South Yorkshire, and there have been hydrogeological investigations at Carlton (Parker et al., 1985) and Edwinstowe (Satchell and Edworthy, 1972; Lovelock, 1969).

Further north, in the Vale of York in Yorkshire, matrix aquifer properties were investigated by Koukis (1974) and the general hydrogeological properties of the aquifer (including modelling) by Aldrick (1974). Recent work in this area has included pumping tests to investigate augmentation of the river Ouse in times of low flow. In addition, there are local borehole investigations such as at Nutwell Pumping Station (Dodds, 1986). In North Yorkshire and Northumbria there are some fairly old boreholes but little pumping test information and no core data.

7.2.2 Hydraulic conductivity and transmissivity

General

In general the Permo-Triassic sandstone aquifers are anisotropic; in the East Midlands vertical permeability is generally one-tenth the horizontal value often reducing to one-twentieth in the West Midlands and Shropshire. This general anisotropy of the whole aquifer (as illustrated by vertical head gradients within the aquifers) is not necessarily of the same order of magnitude as is seen in core permeabilities on the centimetre scale. In the West Midlands the sediments are more marly than in the East Midlands and north-east region, but are also better sorted, with less fine material. In the Yorkshire area the aquifers are anisotropic on the scale of metres with considerable interlayering of sands and less permeable silts on the scale of a metre in a series of fluvial cycles. This macro anisotropy is not necessarily seen at the core scale. Effective aquifer thickness is, due to macro anisotropy, approximately equivalent to the borehole depth.

Core data

Core measurements suggest that the matrix hydraulic conductivity of core samples mainly lies in the range 0.01 to 1 m/d (Figure 7.2.4). There is slight anisotropy, with the horizontal permeability twice that of the vertical. Cross-bedding is not thought to be important. The interquartile range of horizontal core hydraulic conductivity for all the region is 0.19 to 2.04 m/d (Table 7.2.2). The permeability does not appear to vary systematically with depth within the freshwater aquifer zone.

The data have been divided into a southern and northern region about the northing 400 000 (Figures 7.2.5a, 7.2.5b, 7.2.5c, 7.2.5d, Table 7.2.2). The sandstones appear to be much more permeable in the southern region, with a median core hydraulic conductivity of 2.1 m/d compared to 0.36 m/d in the northern region (Table 7.2.3). This decrease in matrix permeability is consistent with the fining of the sandstones to the north. All the plots show a negative skew to the data, with a tail at the lower conductivity values.

Although the permeability in the north of Yorkshire is generally less than in the south of the region, the average core anisotropy (K_h/K_v) is around two throughout the region. It is possible that the overall aquifer anisotropy is greater in the north than the south, as there is a greater range of matrix permeabilities in the north. In South Yorkshire at Carlton average hydraulic conductivities (arithmetic mean), from two research boreholes, are around 1 to 2 m/d with a horizontal:vertical ratio generally between 2 and 2.5, (Table 7.2.4) (Parker, 1985).

At Carlton it appears that fracture flow is important for transmitting water to the Hanger Lane borehole, whereas matrix permeabilities appear to account for all of the transmissivity at Mill Lane (Table 7.2.4). Flow logging was also carried out at these sites. This indicates little flow at Mill

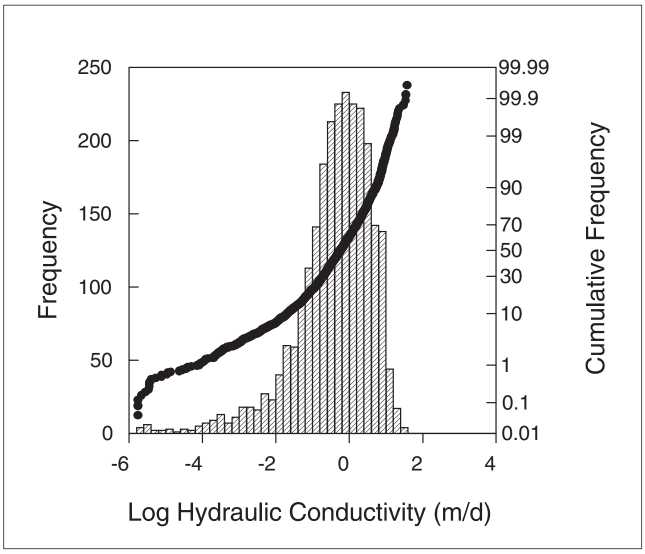


Figure 7.2.4 Distribution of hydraulic conductivity data for Permo-Triassic sandstone samples from the north-east of England.

Table 7.2.2 Horizontal and vertical core hydraulic conductivity data for the Sherwood Sandstone Group, north-east England.

Group	Orientation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Sherwood Sandstone (all)	Horizontal	1.9×10^{-6}–20.5	0.19–2.04	0.67	0.48
	Vertical	1.9×10^{-6}–22.5	0.069–1.18	0.31	0.20
Sherwood Sandstone (north)	Horizontal	1.9×10^{-6}–10.2	0.13–1.3	0.46	0.33
	Vertical	1.9×10^{-6}–6.2	0.06–0.88	0.25	0.17
Sherwood Sandstone (south)	Horizontal	3.9×10^{-6}–20.5	0.73–5.5	2.7	1.7
	Vertical	2.4×10^{-6}–22.5	0.13–3.8	1.2	0.37

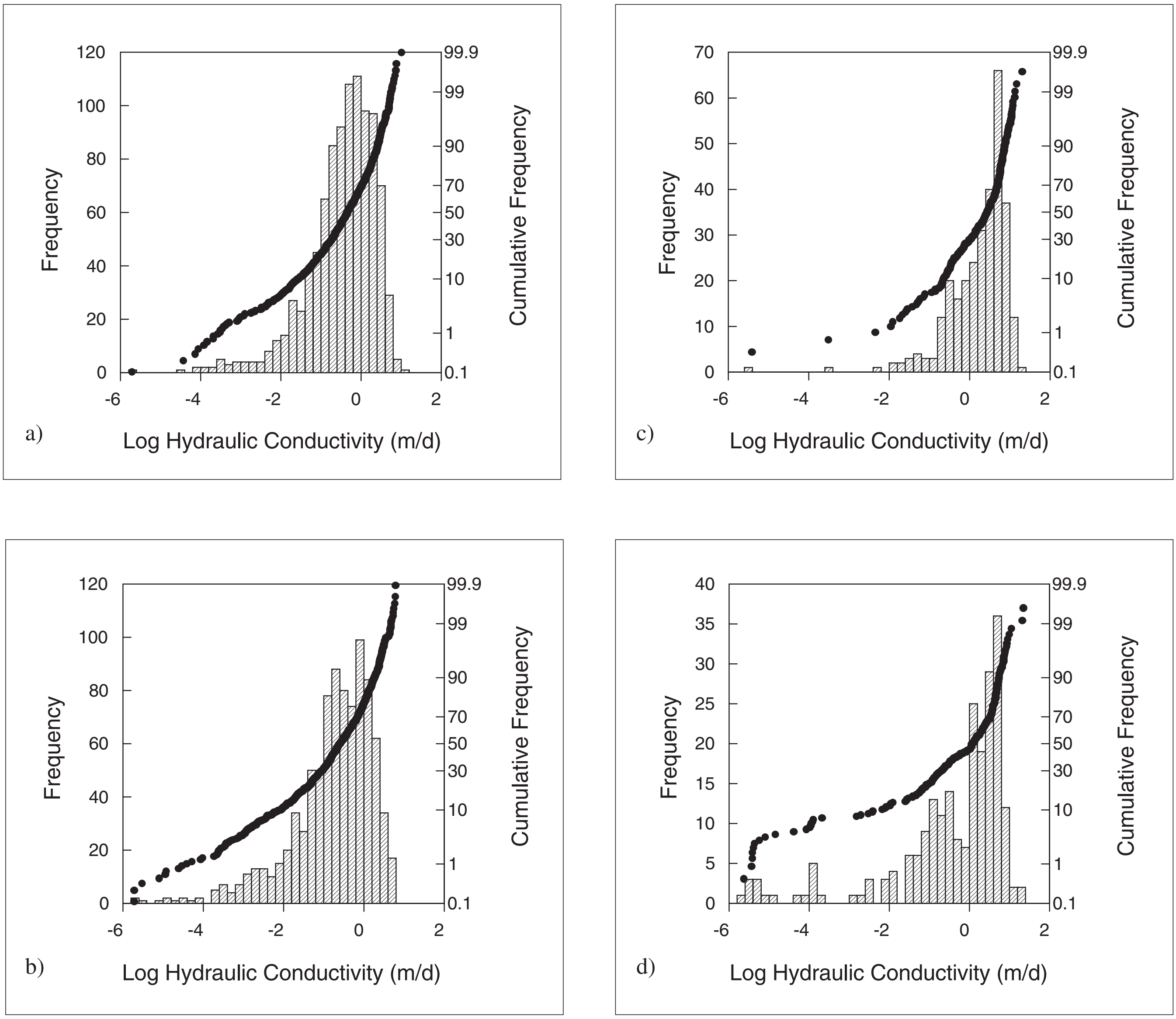


Figure 7.2.5 Distribution of hydraulic conductivity data for Permo-Triassic sandstone samples from north-east England, a) horizontal samples north of northing 400 000, b) vertical samples north of northing 400 000, c) horizontal samples south of northing 400 000, d) vertical samples south of northing 400 000.

Lane beneath 150 m bgl, although the boreholes penetrate the whole sandstone thickness to a depth of 210 m. Above 150 m bgl the flow of water increases towards the pump at 50 m bgl. Inflow to the borehole is fairly continuous as few discrete inflows were detected, however a strong inflow at 100 m bgl was detected by TV inspection. Generally the transmissivity at Mill Lane appears to be provided by matrix flow throughout the upper part of the borehole.

Further south, to the north-east of Mansfield, core data from boreholes at Edwinstowe [SK 62 67] indicate that

Table 7.2.3 General core hydraulic conductivity data for the Sherwood Sandstone Group, north-east England.

Group	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Sherwood Sandstone (all)	1.8×10^{-6}–37.6	0.14–2.12	0.58	0.39
Sherwood Sandstone (south)	2.4×10^{-6}–22.5	0.35–4.7	2.1	0.87
Sherwood Sandstone (north)	1.9×10^{-6}–10.2	0.09–1.08	0.36	0.24

Table 7.2.4 Permeability at Hanger Lane [SE 638 242] and Mill Lane [SE 655 248], Carlton (after Parker et al., 1985).

	Cored borehole 1 Hanger Lane	Cored Borehole 2 Mill Lane
K_h (m/d)	1.1	2.2
K_v (m/d)	0.25	0.43
Intergranular T (m^2/d)	115	350
Pumping test transmissivity (m^2/d)	> 400	350

vertical permeability is generally less than horizontal permeability. However for a given axis there is considerable heterogeneity in the permeability, as the vertical permeabilities obtained vary considerably with depth within one borehole. This is partly caused by cross-stratification within many of the different lithological units. The data were also biased because it was difficult to obtain porosity and specific yield measurements for silt and mudstone samples as they disintegrated on resaturation. The most permeable siltstone plug gave a gas permeability of 4.4×10^{-5} cm/s as compared with a permeability of 2.3×10^{-2} cm/s (gas) for the most permeable sandstone (Lovelock, 1969). The siltstones within the Sherwood Sandstone Group sequence at Edwinstowe are generally of the order of 2000 times less permeable than the sandstones with which they are interbedded. This demonstrates the dominance of the thin low permeable horizons in lowering the bulk vertical permeability of the whole aquifer, an effect common throughout the Permo-Triassic sandstones. At Edwinstowe, core horizontal hydraulic conductivity ranges up to 19 m/d, but is generally around 6 m/d. The ratio of core horizontal to vertical hydraulic conductivity is 5 or more.

Working on cored boreholes in the Vale of York, Koukis (1974) obtained permeability measurements based on 280 core samples. These gave a mean vertical hydraulic conductivity of $K_v = 0.257$ m/d (0.000297 cm/s) with a range of values from 8×10^{-5} to 2.19 m/d (9×10^{-8} to 2.54×10^{-3} cm/s), horizontal hydraulic conductivity averaged 0.36 m/d (0.000418 cm/s) with a range of 8.13×10^{-4} to 3.14 m/d (9.41×10^{-7} to 3.64×10^{-3} cm/s). The horizontal to vertical hydraulic conductivity anisotropy was 1.18 to 2.45, with both the vertical and horizontal permeability apparently varying together with depth. High permeability was associated with high porosity.

Pumping test transmissivity

There is a fairly good distribution of data throughout most of the outcrop area, except in the very north of Yorkshire and Northumbria where there are few data. There are only limited data for the confined aquifer in the Nottingham area, and few data for the feather edge of the aquifer in the west. As the higher-yielding boreholes are tested and analysed more fully, the distribution of transmissivity recorded may be higher than that generally found in the aquifer. For this region, best values at each borehole have been selected according to the principles described earlier (Chapter 2), so that only one transmissivity and storage coefficient is associated with each borehole.

Transmissivity results form a good approximation to a log-normal distribution (Figure 7.2.6) ranging from around 10 m^2/d to 5000 m^2/d, with a geometric mean of 201 m^2/d (median 206.5 m^2/d) and an interquartile range of 93 to 410 m^2/d. The very high transmissivities are caused by high yielding fractures while values of less than 500 m^2/d are associated with the basic matrix permeability of the aquifer.

The areal distribution of transmissivity from pumping tests shows a wide range across the aquifer. Some general trends can be distinguished, for example there is a general increase in transmissivity from the north towards the south (Figure 7.2.7). Within the North Yorkshire area there is a

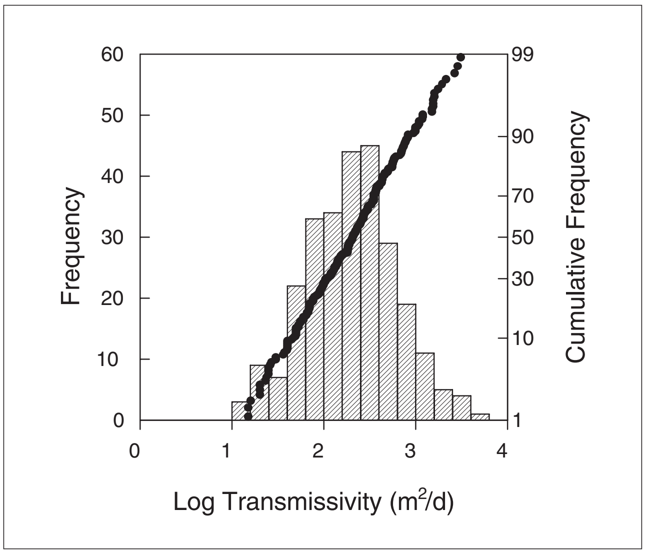


Figure 7.2.6 Distribution of transmissivity data from pumping tests in the Permo-Triassic sandstones of north-east England.

gradual increase in transmissivity southward from transmissivities of around tens of metres squared per day to the north of Boroughbridge to around 250 m^2/d around York. There are a few higher values in the centre of the outcrop which are attributable to fractures. South of York, through Selby down as far as Goole, the transmissivity is in the range of 50–400 m^2/d in the centre and east of the aquifer outcrop. In the west along the feather edge of the aquifer there is a band around 7 km wide with lower transmissivities (generally of less than 100 m^2/d) due to reduced aquifer thickness. This band continues southward towards Nottingham. The main aquifer transmissivity continues to increase to the south, ranging from 100 m^2/d to 600 or 700 m^2/d, with transmissivities for boreholes affected by fractures reaching several thousand m^2/d. The general matrix transmissivity is greatest in the centre and east of the aquifer outcrop, and increases to the south. This is due to the increasing aquifer thickness to the east, and the coarser grain size in the south which increases the permeability. There is also increased fracturing in the south (due perhaps to the harder rock being more brittle and subject to increased faulting which results in increased fracturing). A slight decrease in transmissivity from the centre of the outcrop to the eastern edge and confined area may be present and due to increased marl content of the top of the aquifer beneath the Mercia Mudstone Group (Aldrick, J, personal communication).

The presentation of transmissivity values against effective aquifer thickness (saturated borehole depth, see Section 7.1.4) (Figure 7.2.8) shows several features. A grouping of data with transmissivities below 600 m^2/d show the basic matrix permeability of the aquifer and a scatter of values depending on the precise nature of the strata penetrated by each borehole. A regression line through all the data gives an average borehole hydraulic conductivity of around 4 m/d, although there is immense variation about this figure. This figure is the average hydraulic permeability encountered by the boreholes in the aquifer, and is of the order of magnitude to be expected for permeable sandstones. From the distribution it would however appear that there are two trends. There is a very gradual trend of increasing transmissivity with borehole depth which has a gradient of about 1.8 m/d and probably represents the average matrix hydraulic conductivity. This is much less than the 'average' regression calculated bulk hydraulic conductivity based on all the data and suggests that about half the transmissivity encountered in boreholes is from fractures.

In addition to the matrix permeability, fractures are also important in the movement of water, with many boreholes having much higher transmissivities than those of the aquifer matrix. In particular, between effective aquifer thicknesses of 40 to 90 m there are many boreholes with higher transmissivity values up to thousands of m^2/d (Figure 7.2.8). This depth of aquifer corresponds to the middle of the outcrop of the Sherwood Sandstone Group, as it thickens from a feather edge in the west to being confined in the east. A zone of high

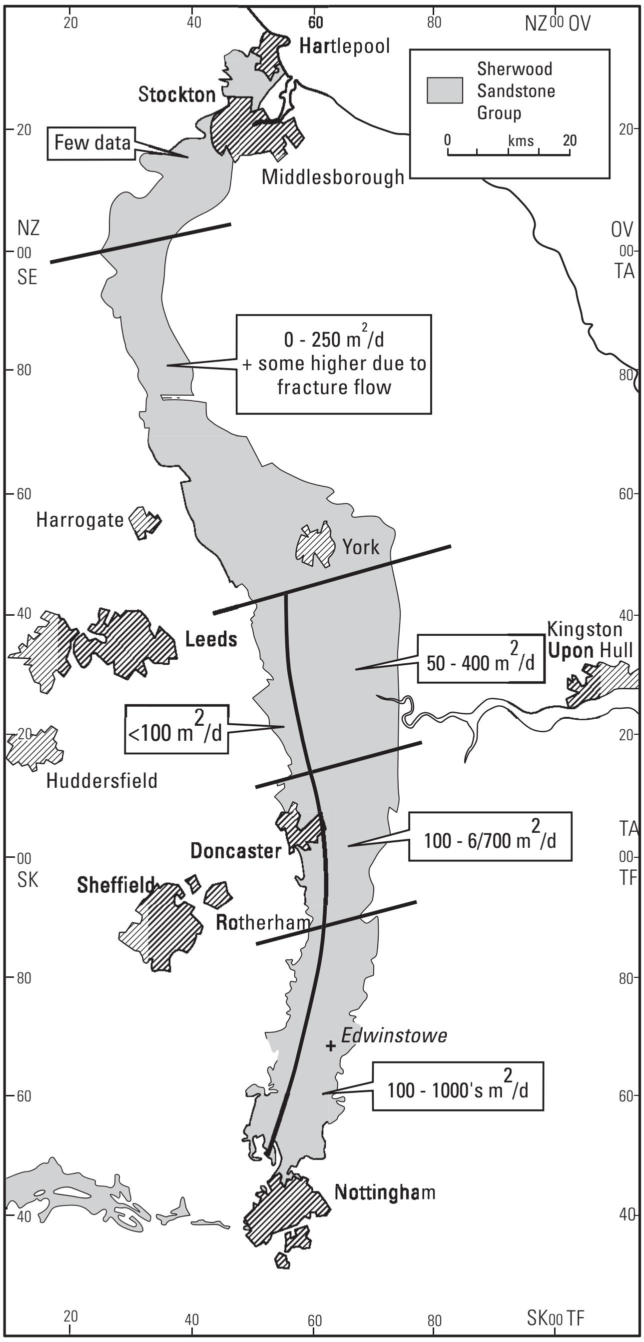


Figure 7.2.7 Regional transmissivity distribution from pumping tests in the Permo-Triassic sandstones of north-east England.

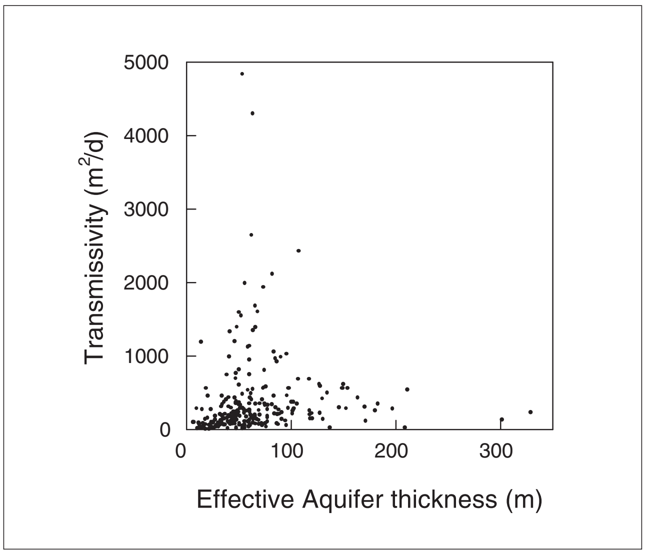


Figure 7.2.8 Plot of transmissivity against effective borehole depth for the Permo-Triassic sandstones of north-east England.

transmissivity runs down the middle to east of the sandstone outcrop. This indicates that some fracture or high permeability zones, independent of the matrix, are concentrated in this central outcrop area, or possibly that the boreholes in the east penetrate less productive sandstone, as the top of the Sherwood Sandstone Group has some marl content (Aldrick, J, personal communication).

The distribution of bulk hydraulic conductivity data, calculated for each borehole from transmissivity and effective aquifer thickness, is shown in Figure 7.2.9. The data approximate to a log-normal distribution with an interquartile range of 1.8 to 6.6 m/d and with a geometric mean and median of 3.7 m/d.

There is a general increase in transmissivity towards the south of the Nottingham-Trent area, with pumping test transmissivities up to a few thousand metres squared per day. There are also major changes from west to east in the Nottingham area, from a fairly low transmissivity along the western boundary to very high transmissivities in the central zone decreasing to low or very low values in the confined eastern area. Fractures are likely to provide most of the transmissivity above 500 m^2/d.

The confined aquifer has a generally low transmissivity of less than 100 m^2/d. This can be attributed to intergranular flow, with all the fractures having been closed by the overburden pressure of 200 m of Mercia Mudstone Group strata. Some slightly confined sources have high yields, and are likely to show a correspondingly high transmissivity, probably as a result of fracture flow.

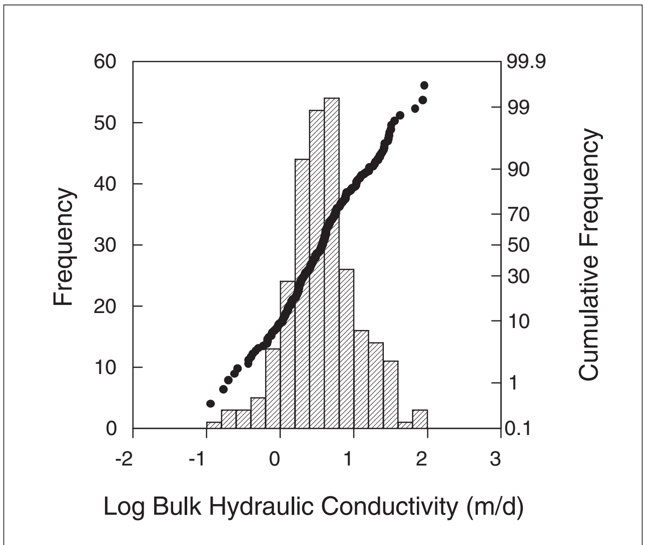


Figure 7.2.9 Distribution of bulk hydraulic conductivity data from pumping tests in the Permo-Triassic sandstones of north-east England.

Pumping test response with time

Many boreholes have a classic Theis confined response over the period of a standard test (hours to a few days). In longer tests a delayed yield effect becomes apparent, as the aquifer responds in an unconfined manner.

In Nottinghamshire, as in the other regions of the Permo-Triassic sandstone aquifer there is a fairly slow response time to pumping. Cones of depression generally do not spread very far in the unconfined aquifer. In the confined region they expand to over a few kilometres over a few months, so that drawdown cones in the confined area expand to the aquifer outcrop. By contrast, in a region such as Shropshire, where the aquifer is locally very confined, pumping cones of depression spread out very quickly and effects of pumping are seen over a few kilometres in only a few hours pumping (Fletcher, S, personal communication).

Much work has been done in the Vale of York, which indicates that many pumping tests initially show a confined response, the Theis curve levelling off after a day of pumping. Over the next week of pumping the rate of drawdown increases and the curve shows an upturn. This is the result of the aquifer initially responding in a confined manner, followed subsequently by slow vertical flow through the aquifer layers allowing an unconfined response as the top of the aquifer drains (Section 7.1.4). In addition to the confined and slow unconfined response, there is an initial response of fracture permeability and storage to pumping, which is followed by a slower matrix response. These effects are difficult to distinguish, but the general effect of an initial response with a very low storage followed by increasing storage with time is seen in many boreholes in the area. There is extensive drift in the Vale of York which acts to confine the Sherwood Sandstone Group: the water levels in boreholes penetrating only the drift are generally different from water levels in the sandstone. The sandstone water levels are often near ground level or slightly artesian in valley areas, whereas the drift water levels are usually deeper. During pump testing of the sandstone aquifer boreholes in the drift show only a small decrease in water levels indicating that there is relatively little hydraulic connection between the drift and the sandstone over much of the Vale of York.

Specific pumping tests

NORTHUMBRIA

Billingham (Figure 7.2.1)

The most northerly pumping tests in the region, at Billingham, have a mean transmissivity of 520 m^2/d. The pumping drawdown curves were analysed using Theis curve matching techniques. There is indication that delayed yield and leakage from the overlying drift layers are important but this was not analysed. It also appears that transmissivity decreases to the north-west of Billingham due to a decrease in aquifer thickness and also to a decrease in permeability (Ineson, 1957).

YORKSHIRE

Lower Dunsforth A2 (Figure 7.2.3)

This site has a number of piezometers and in consequence the aquifer properties at different distances can be measured. The sandstone lies below 15 to 18 m of drift made up of sands, clays and fine gravel. The typical lithological succession at Lower Dunsforth is:

3 m sandy clay,
1 m sand,
4 m boulder clay with stones becoming surficial deposits more sandy with depth,
⩽ 5 m sand and fine gravel,
Sherwood Sandstone Group.

Within the Vale of York there appears to be increased transmissivity in boreholes in the Lower Dunsforth area, which is a discharge area in the centre of the vale. This may be due to increased glacial erosion in the valleys and fracture enhancement in a zone of groundwater discharge.

Low transmissivity values are found in the west of the vale where the aquifer is thinner.

At Lower Dunsforth high transmissivities of 1350 m^2/d are obtained from some piezometers: this is likely to be representative of material near the borehole as more distant piezometers show relatively large drawdowns indicating the decrease in transmissivity away from the borehole. This may indicate the localised and non-interconnected nature of the fractures.

Eggborough No. 3 [SE 584 239] (Figure 7.2.3)

The pumping test on this borehole, near the village of Hensall [SE 59 23], is thought to be influenced by a local fault which was seen during drilling as a very large fracture which appeared near Eggborough boreholes No. 1 and 2. The River Aire is in the vicinity of the borehole, but it was thought to be too far away to influence the test: the fault being much closer to the borehole. The drawdown practically ceased after 12 hours pumping in borehole No. 3 and after a day in borehole No. 1 and 2. Only borehole No. 2 showed an increase in drawdown after a few days which was likely to be associated with an unconfined response as vertical flow caught up with horizontal flow. The very rapid equilibration of borehole water levels indicated that the fault was acting as a highly transmissive zone which could rapidly transport water so acting as a recharge boundary preventing the cone of depression expanding beyond the faulted zone. This effect is also seen in the Rainton test in the Vale of York where the cone of depression does not extend beyond the Topcliffe fault. This faulted and fractured zone, around half a kilometre away from the borehole, also acts as a highly transmissive zone. This may be due to brecciation of the aquifer around the fault which has considerable displacement.

Nutwell Pumping Station (Figure 7.2.3)

At Nutwell Pumping Station [SE 634 031] a number of boreholes were tested, with transmissivity results ranging from 115 to 880 m^2/d, (depending on the method of analysis and which observation borehole data was analysed [Dodds, 1986]). One monitoring borehole located between two of the pumped boreholes, showed surprisingly little drawdown, and yielded very high transmissivities. This borehole with a geometric average transmissivity of 700 m^2/d was thought to intersect a fracture system or permeable drift, so allowing the inflow of additional water. The other observation holes gave an estimated transmissivity of 350 m^2/d, with a leakage factor of 400 m.

Modelling of the pumping test, using the Rushton Radial flow model gave very similar results: a transmissivity value of 360 m^2/d. This was obtained by placing a boundary at 10 000 m from the pumping borehole, (out of range of the cone of depression), with 100% efficiency and no recharge. The model gave a hydraulic conductivity of 3 m/d and a leakage factor of 450 m. The aquifer thickness was taken as 120 m, slightly greater than the borehole depth.

NOTTINGHAMSHIRE

Edwinstowe (Figure 7.2.3)

At Edwinstowe the Sherwood Sandstone Group is 120 m thick with the water table lying at 34 mbgl. The aquifer is underlain by fairly impermeable Upper Permian strata which are 35 m thick. The Sherwood Sandstone Group is composed of the Lenton Sandstone Formation and the Nottingham Castle Formation, and is typically fine to medium grained and poorly cemented. Thin laterally impersistent mudstone and pebble beds occur in the succession. The sandstone is fractured, with frequent cross-bedding and some calcium carbonate cement and occasional barium sulphate cement.

A pumping test was carried out on two boreholes which were both pumped at 2400 m^3/d and continued for 4 days in one borehole and 5 days in the other. After one day of pumping the final drawdowns were 16 m and 17 m, indicating that, at least at this site, the aquifer is fairly uniform. This is not found throughout the Permo-Triassic sandstones, which frequently quite have variable properties over small distances. The analysis of the pumping test provided a transmissivity of 1500 m^2/d and a storage coefficient of 0.05 (Satchell and Edworthy, 1972).

It is thought (e.g. Reeves et al., 1974) that the hydraulic conductivity or bulk transmissivity obtained from a pumping test in the Permo-Triassic sandstones will vary depending on the distance at which drawdown is measured. Transmissivities calculated for observation boreholes near the abstraction borehole show greater variation in results than those further away. More distant observations provide a transmissivity which is the average of the aquifer properties over a wider area, and is thus less variable. This effect is also seen in the Vale of York.

Specific capacity and borehole yields

The distribution of specific capacity data held in the database is shown in Figure 7.2.10. The data have a geometric mean of 100 $m^3/d/m$ (median 120 $m^3/d/m$). The specific capacity data follows a similar distribution to that of transmissivity, most boreholes having values of specific capacity of under 100 $m^3/d/m$, though the higher yielding boreholes range up to 800 $m^3/d/m$ with a few higher examples.

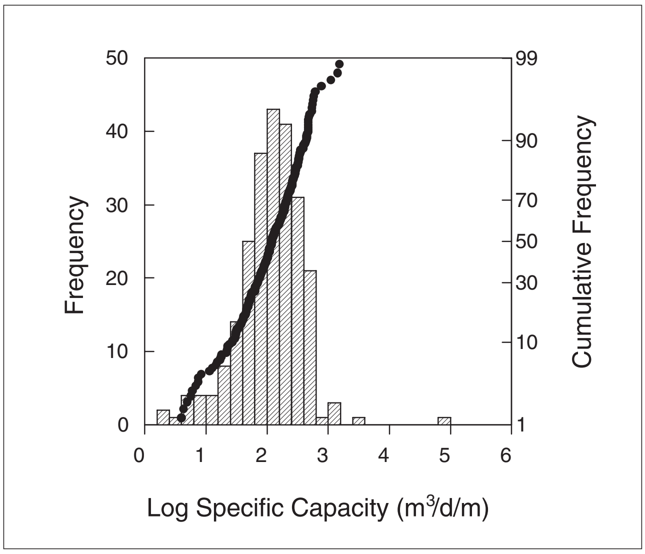


Figure 7.2.10 Distribution of specific capacity data from the Permo-Triassic sandstones of north-east England.

Geophysical logs: flow logs

There are limited data from temperature, conductivity, calliper and sonic logs (Robertson, 1983). Much logging has been carried out in the Yorkshire and the Nottingham-Doncaster area (Buckley and Cripps, 1989a,b; 1990; 1991). Flow logs generally show a gradual increase in flow up the borehole: as water flows in from the sandstone matrix.

There is little flow contribution from beneath 120 m bgl. Some horizons appear to contribute no water to the borehole and are likely to be low permeability silt and clay or have greater cementation. In places flow logs show inflows and outflows concentrated at certain depths, indicating the presence of fractures which contribute a significant proportion of water inflow to the borehole.

Yorkshire

In Yorkshire around the Cowick area [SE 650 215] most flow appears to be from the matrix rather than from fractures. Flow may occur at the same depth in a number of boreholes in the same area suggesting bedding plane fractures rather than steeply inclined fractures (Aldrick, 1984). Observation boreholes near pumping boreholes show induced inflow and outflow along fractures.

Cores at Cowick indicated that the sandstone is made up of repeated sedimentary cycles, grading from medium-grained, soft, poorly cemented sandstone through a fine-grained hard sandstone to a thin marl. The units are 0.5 to 1.5 m thick. The coarser layers are likely to be more friable, and also to transmit the most water. Sand is pumped from boreholes which is of a similar grainsize to this coarse sand. Boreholes with screen and a pack suitable for the coarse sand perform satisfactorily, after pumping a little fine sand initially. The interlayering of the sandstone is reflected in the water quality, which changes with depth. Near the surface there are higher nitrates and higher total hardness in unconfined areas (Aldrick, 1984).

At Carlton (Figure 7.2.3) in North Yorkshire there is a correlation between borehole enlargement, grain size, and horizontal permeability. This indicates preferential flow through coarse grained units, leading to the washing out of some sediment from the borehole wall. There is also a correlation of high tritium readings with larger borehole diameter (seen in calliper logs) and with values from conductivity logs. More permeable layers have a larger diameter and higher conductivity indicative of recent water, again confirming preferential flow through more permeable horizons. In one borehole the tritium reading (TU) increased with depth, suggesting greater water circulation with depth. However generally there is thought to be a trend of increasing age with depth (Buckley and Cripps, 1990).

TV logging at Hambleton borehole [SE 5580 3130] at Brayton Barff, Yorkshire showed the aquifer to be mainly sandstone with thin mudstone bands, and rip-up mud clasts which were incorporated into the sandstone. These rip-up clasts also have a higher gamma ray activity and lower resistivity. Cross laminations and current bedding are seen. There is increased mudstone content beneath 63 m as the Sherwood Sandstone Group grades into the Permian Marl. Several discrete cracks were seen in the borehole wall, both along bedding planes when they are associated with borehole enlargement, and as angular or semi-vertical cracks usually without borehole enlargement. Calliper logging did not identify all the cracks seen on the borehole video. Flow logging indicated inflow at discrete horizons. 50% of the total flow entered at 55 m depth where there is a crack, and the remainder entered over a range of depths 58 to 59 m and 32 to 55 m (Buckley and Cripps, 1991).

TV inspection and logging of boreholes in the Vale of York showed water entering the boreholes through numerous subhorizontal fractures. These fractures often coincide with soft marl flake breccia bands. At Rainton [SE 375 750] the subhorizontal fractures are thought to be linked by subvertical tectonic fractures associated with the Topcliffe fault, so forming an area of high sandstone permeability (Reeves et al., 1974).

At Nutwell pumping station [SK 634 031] dynamic flow and conductivity logs indicated cold highly conductive water entering the borehole at certain depths (Dodds, 1986]. This was likely to be recent water which had leaked in from near the surface along high permeability zones, probably fractures. This water was colder than the ambient temperature suggesting that it was moving quickly and had not had time to equilibrate with the aquifer temperature. All the boreholes in the area showed anomalies at approximately the same depth, suggesting that the fractures lie along bedding planes rather than being steeply inclined. The source of the recently recharged water is thought to be runoff from the Markham Main Colliery 3 km to the north-west of the site. The colliery lies up dip of the wells, at the outcrop of the sandstone located in the wells. Polluted drainage water from this site can infiltrate the aquifer at outcrop. This surface connection appears to be supported by the chemistry of the water. Vertical leakage occurs where there is a high drift head and permeable drift, and the water is then transmitted along bedding fractures to the pumping site (Dodds, 1986). This case study is an example of bedding plane fracture flow which is a common feature of flow in the Sherwood Sandstone Group, and it illustrates the capability of fractures to provide fast preferential pathways for flow.

Nottinghamshire

Rising chloride values in central Nottinghamshire pumped waters were investigated by Finch (1979). Surface and borehole geophysics indicated that aquifer contamination was occurring locally from acid, sometimes highly saline waters discharged from the local collieries. Near-vertical fractures induced in the aquifer by the subsidence of underlying coal mines were probably responsible for rapid movement of saline Coal Measures water into and through the aquifer. Detailed flow measurements also confirmed minewater contributions to borehole flow from mine drainage and spoil tip water (Ireland, 1978). The chemistry of pore waters in fractured horizons was seen to be much more saline (2200 mg/l Cl compared to a background value of ~200 mg/l), confirming preferential flow through fractures.

Model permeability values

Doncaster area and Nottinghamshire

Groundwater resource models of this area require transmissivity values often around half those observed in pumping tests. High and over abstraction resulting in non equilibrium water levels in the aquifer mean that steady state models such as FLOWPATH are unstable if actual abstraction and pumping test transmissivity values are used. In addition to over abstraction, the constant changing of pumping rates and pumping locations in the Nottingham and Doncaster area, combined with the slow aquifer response time, means that the aquifer is never truly in steady state; it is generally in pseudo steady state or has actual over abstraction with falling water levels. FLOWPATH protection zone modelling has resulted in all the aquifer being designated a Nitrate Vulnerable Zone (Fletcher, S, personal communication). The areas of the aquifer for which regional models have been developed is shown in Figure 7.2.3.

Permeability generally decreases south to north regionally, and this is seen within the model of the Doncaster and Nottingham area as higher transmissivities in the south of the model and the centre of the outcrop area (Figure 7.2.11). Model transmissivities decrease from Nottinghamshire north into south Yorkshire.

DONCASTER AREA MODEL

The transmissivity of the confined region is reduced due to increased cementation and overburden of the aquifer. The single layer model has transmissivity increasing from a minimum of 10 m^2/d at the feather edge to 550 m^2/d in the centre of the outcrop and then decreasing to 40 m^2/d (lowest 10 m^2/d) in the east as the aquifer becomes deeper and confined. Vertical hydraulic conductivities of 0.00005 to 0.00009 m/d are used. The sensitivity of the model to transmissivity is fairly low except in the area near boreholes (Brown and Rushton, 1993).

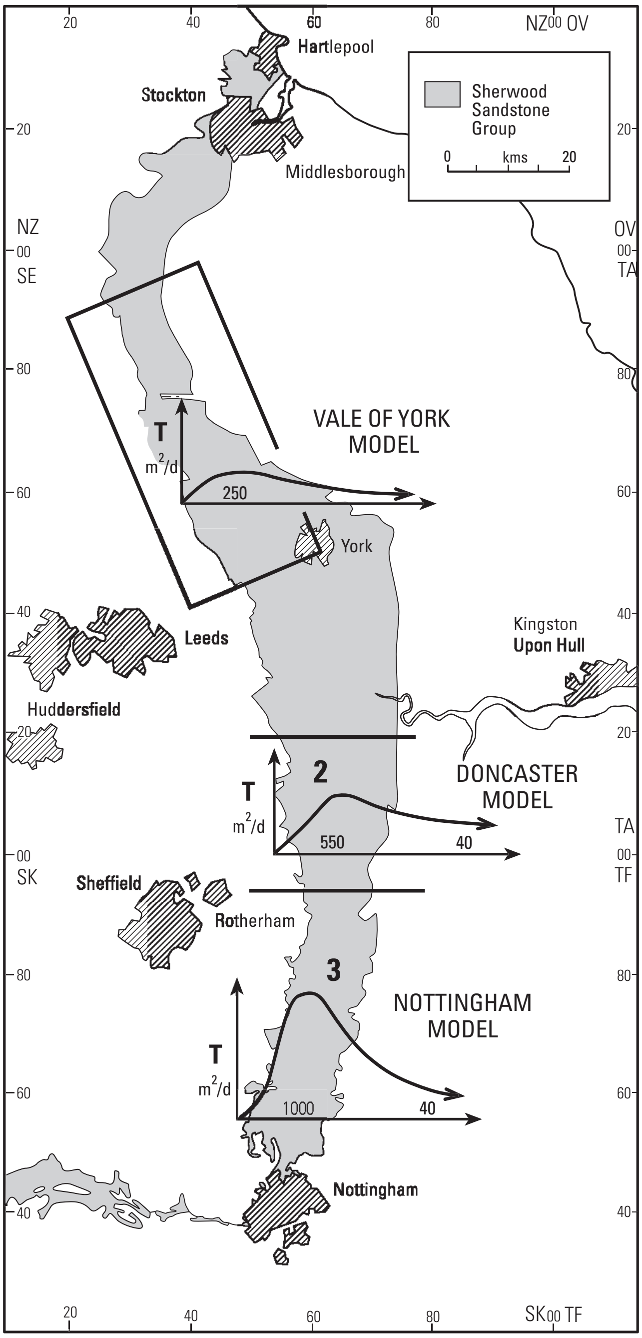


Figure 7.2.11 Variation of modelled transmissivity values for the Permo-Triassic sandstones of north-east England.

In the area of Barnaby Dun Station there are 60 m of laminated clay forming a buried channel beneath the river Don, which reduces the saturated thickness of the aquifer but has little effect on the aquifer response (Brown and Rushton, 1993).

A vertical flow model gave a transmissivity of 360 m^2/d in the Doncaster region (Dodds, 1986).

NOTTINGHAM AREA MODEL

The single layer model, which adjoins the Doncaster model to the north, has transmissivity increasing from a minimum of 10 m^2/d at the feather edge to 550 m^2/d (in the north) and 1200 m^2/d (in the south) in the centre of the outcrop. The model transmissivity then decreases to 40 m^2/d (lowest 10 m^2/d) in the east as the aquifer becomes deeper and confined (Bishop and Rushton, 1993).

The Nottingham model transmissivity value in the region of Edwinstowe [SK 635 682] (node 16 54) is on the boundary of 260–50 m^2/d (Bishop and Rushton, 1993). This is substantially less than the pumping test transmissivity of 1500 m^2/d. The pumping saturated thickness was between 42 and 25.5 m, depending on the pumped water level. The average horizontal hydraulic conductivity seen in the borehole was 1500/25.5 = 60 m/d, or taking a saturated thickness of 42 m the hydraulic conductivity is 1500/42 = 36 m/d. These figures are very large and indicate extensive fracture flow at Edwinstowe and possibly also contributions from the aquifer beneath the borehole, which is feasible given the undermining and fracturing of the Sherwood Sandstone Group in the area (Satchell and Edworthy, 1972). This site illustrates an effect seen throughout the Permo-Triassic sandstones, in that transmissivities obtained in pumping tests are much higher than those used in models.

Yorkshire

Further north in the Vale of York lower transmissivities are used in models (Figure 7.2.11); transmissivities are around 200 m^2/d (up to 250 m^2/d) except near feather edges and faults (Aldrick, 1974). Modelling of the Sherwood Sandstone Group aquifer in the Vale of York has also been described by Reeves et al. (1974). This model allows localised recharge to the Sherwood Sandstone Group in the west of the outcrop where the overlying drift consists of permeable sands rather than the clay found in the centre of the vale. Initially a uniform value of 200 m^2/d transmissivity was used, as this was the median of the pumping test results in the area, though this initial value was modified in areas with pumping test transmissivity figures and during model calibration. On the western edge of the aquifer, where the saturated thickness is much reduced transmissivities were reduced, in proportion to aquifer thickness. Along the Topcliffe fault values of transmissivity were reduced and calculated on the basis of sandstone — sandstone contact across the fault. Permeabilities parallel to the fault were the same as those in the rest of the aquifer. The bulk transmissivity value was modified locally to enable calibration with long term groundwater hydrographs (Reeves et al., 1974).

Flowpath groundwater protection zone modelling appears successful and reliable in the fairly straightforward situations to which it has been applied in the south of the region around Doncaster and Selby. The models use a regional transmissivity of 250 m^2/d with a horizontal permeability of 1 to 3 m/d for the Eggborough site and nearby sources. Groundwater movement is thought to be by fracture and intergranular flow, though this cannot be represented in the FLOWPATH models.

Summary of model permeabilities

These models seem to suggest that over a catchment area a general transmissivity can be used to represent the response of a pumped borehole (Figure 7.2.11). This may imply that although the water is moving locally mainly along discrete fractures (mainly bedding planes), regionally these fractures are not interconnected, or are so poorly interconnected as to approximate to regional permeabilities of the same order as more permeable sandstone matrix. In the Vale of York high local transmissivity, such as at Lower Dunsforth and Sand Hutton appear to be maintained over a few hundred metres (the distance to observation boreholes) however the transmissivity at Lower Dunsforth decreases when a larger area is considered (Reeves et al., 1974). This general effect of localised high transmissivities around a fracture intersecting a pumped well which is not maintained over a wide area, may account for the lower transmissivities used in models.

Summary of permeability properties

Comparison of intergranular and pumping test hydraulic conductivity

Generally in this region the range of hydraulic conductivity determined from core analyses is of the order of 0.01 to 1 m/d whereas that obtained from pumping test transmissivities is 1 to 5 m/d, on average one to two orders of magnitude greater than laboratory values. There are two reasons for this. Firstly, high permeability layers dominate the borehole transmissivities, but may not be well represented in core data as the samples may be poorly cemented and friable. Secondly fractures, which are not represented in the core data, may significantly increase the effective average hydraulic conductivity of the borehole.

Other field and laboratory data comparisons give a range of transmissivities ratios, T(field)/T(lab) of 2:1 to 27:1; the higher values are in the south, implying more fracturing in this area, and so a greater discrepancy between laboratory matrix and bulk permeability (Koukis, 1974).

In the Vale of York comparison of bulk hydraulic conductivity and laboratory values (Reeves et al., 1974) (Table 7.2.5) indicates field permeabilities that are much greater than laboratory permeabilities demonstrating the importance of fracture flow to pumped boreholes.

Comparison of field pumping test and laboratory core data at Edwinstowe (Figure 7.2.3) indicated that locally four times more water flows through fractures than by matrix intergranular flow in response to pumping. The presence of horizontal mudstone bands (e.g. 9 m bgl) hindered recharge. Artificial recharge experiments encountered fractures which suddenly opened within the Sherwood Sandstone Group outcrop on the floor of recharge basins. Permian marls, limestones and Coal Measures beneath the Edwinstowe site have been worked extensively, and this may explain the opening of these fractures. The fractures penetrate much of the Sherwood Sandstone Group and provide a rapid recharge pathway. In addition to subsidence fractures there are two sets of jointing, one with a north-north-east to south-south-west direction and the second set at 40° to this, both joints appearing to be nearly vertical. The jointing system is likely to spread artificial (and natural) recharge over a wider area; (the same is applicable to pumping cones of depression) (Satchell and Edworthy, 1972).

Over the region as a whole there is good agreement between average pumping test values of hydraulic conductivity of around 1 to 5 m/d and model values of transmissivity/aquifer thickness. Model values are lower than the very high localised transmissivities encountered by some boreholes affected by fractures. This suggests that model values represent the overall regional permeability when the effect of local fractures is not seen. This may be due to the lack of regional interconnection of fractures, and the generally well sorted nature of the sandstones. The typical radius of influence of a production borehole is thought to be around 1500 m. A typical transmissivity in the Nottingham to south Yorkshire region is in the range 500 to 1000 m^2/d, with lower transmissivities, in both models and from pumping tests, to the north.

7.2.3 Porosity and storage

Core data

Porosity values obtained from laboratory tests on core material vary from 10 to 38%, most being between 20 and 35%. There is no significant trend in the porosity with depth in the aquifer. The mean porosity is around 24%, the material having a greater porosity and larger pores in the south. Some work has been carried out on pore size distribution which varied, but which generally was around 1 to 10 μm (Koukis, 1974). The porosity data held on the BGS database have been divided into two regions: north and south of the northing 400 000. The porosity data are shown in Figures 7.2.12, 7.2.13a and 7.2.13b. The data are approximately normally distributed, with a small negative skew (particularly in the north). The porosity in the south is slightly higher on average than in the north, the arithmetic mean porosity in the south being 29.7% compared to 27.3% in the north (Table 7.2.6). However the range of porosities in the north is larger, with a greater number of lower porosity values. This is consistent with the sediment in the north having a greater fine-grained component.

In the Carlton area (Figure 7.2.3) the interconnected porosity of the Sherwood Sandstone Group (sandstone horizons) as determined from laboratory samples is in the range 28 to 35%. This reflects the poorly cemented nature of the sandstone in this area. In addition pore sizes are large; 50 to 80% of pore diameters are greater than 10 μm (Parker et al., 1985).

Table 7.2.5 Comparison of laboratory and field estimates of Sherwood Sandstone Group hydraulic conductivity in the Vale of York (after Reeves et al., 1974).

Location	NGR	Laboratory hydraulic conductivity (m/d)	Field hydraulic conductivity (m/d)
Upper Dunsforth	SE 449 632	0.77	1.9
Claro House	SE 405 600	0.33	2.1
Marton	SE 431 625	0.39	3.2
Rainton	SE 375 750	0.21	8.7
Studforth	SE 404 726	0.77	1.8
Ainderby Steeple	SE 333 925	0.31	1.9

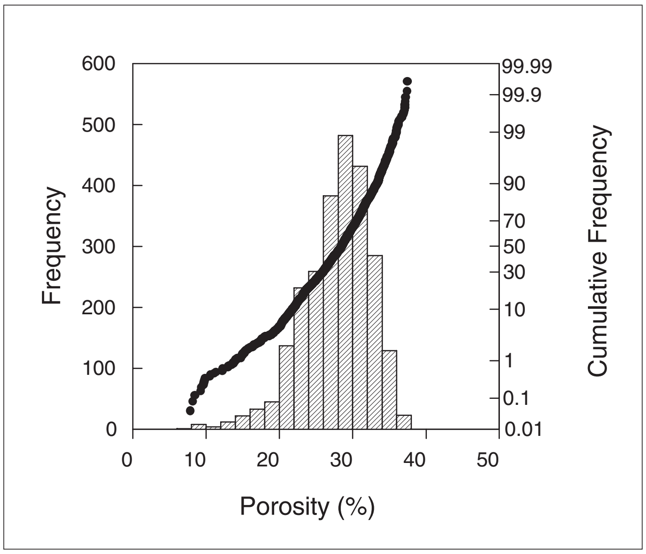


Figure 7.2.12 Distribution of porosity data for Permo-Triassic sandstone samples from the north-east of England.

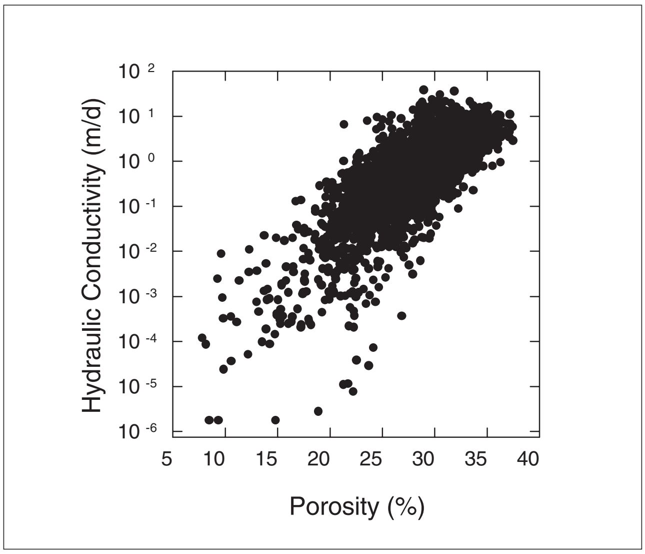
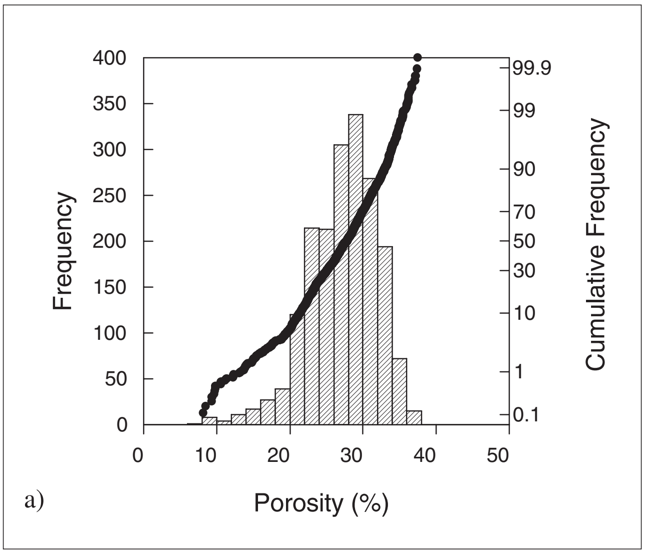


Figure 7.2.14 Plot of hydraulic conductivity against porosity for Permo-Triassic sandstone samples from the north-east of England.

Permeability and porosity

Laboratory permeability and porosity show a good degree of correlation (Figure 7.2.14), both being to a large extent determined by the grainsize distribution of the sediments. Both permeability and porosity are controlled by lithology, but the relationship of permeability and porosity is influenced by the crystallographic habit and aggregate structure of the clay minerals. The finer sediments in the north of



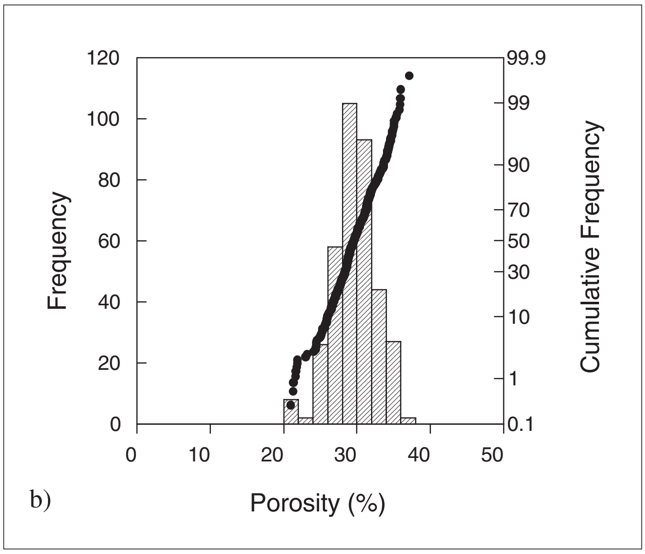


Figure 7.2.13 Distribution of porosity data for Permo-Triassic sandstone samples from the north-east of England, a) north of northing 400 000, b) south of northing 400 000.

Table 7.2.6 Core porosity data for the Sherwood Sandstone Group, north-east England.

Group	Range (%)	Interquartile range (%)	Median (%)	Arithmetic mean (%)
Sherwood Sandstone (all)	7.8–37.4	25.1–31.1	28.5	27.8
Sherwood Sandstone (north)	7.8–37.5	24.2–30.6	27.8	27.3
Sherwood Sandstone (south)	21–37.2	27.9–31.5	29.6	29.7

the region have a lower porosity than in the south, but they have an even lower permeability due to clay minerals partially filling the aquifer pores and so restricting flow in the matrix (Koukis, 1974).

Pumping test storage coefficients

Confining layers: drift cover

The depth and nature of the drift determines whether the aquifer response is confined or unconfined. In the north of Yorkshire and Durham the Sherwood Sandstone Group aquifer is generally confined west of the river Swale, and north of Northallerton and Bedale. In the Vale of York the aquifer is generally confined along the floodplain of the river, in the central part of the vale. In areas with only patchy drift cover the response of the aquifer depends on the length of the test: longer tests have a wider cone of depression are more likely to intersect an unconfined zone. This late time high storage response is then likely to mask the smaller confined response in other areas.

Pumping test data

Most pumping tests do not have a storage coefficient result; those that do mainly have a low confined storage value, with very few tests having an unconfined storage. Pumping tests appear to show the initial confined response of the aquifer rather than the long-term overall aquifer unconfined response (Figure 7.2.15).

In the south of the region unconfined storage coefficients, resulting from the delayed unconfined anisotropic response of the aquifer, have not been obtainable from the data (Fletcher, S, personal communication).

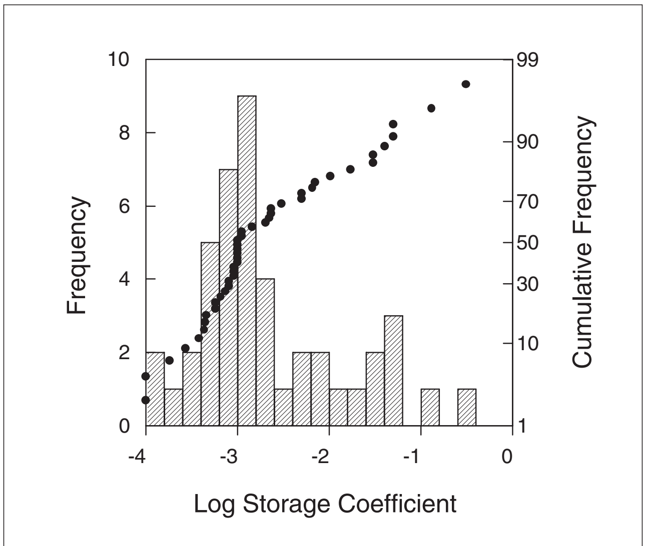


Figure 7.2.15 Distribution of storage coefficient data from pumping tests in the Permo-Triassic sandstones of north-east England.

Specific pumping tests

Billingham, Northumbria (Figure 7.2.1)

At Billingham the values of storage coefficient were of the order of 10^{-3}, with an average of 1.4×10^{-3} (Ineson, 1957), which is higher than would normally be expected for an artesian aquifer. The storage coefficient values obtained from observation boreholes near the pumping boreholes were generally greater than those obtained from more distant observation boreholes. This is thought to be because drainage effects are greatest near the pumping boreholes, with the aquifer partially dewatering in the vicinity of the pumped boreholes. This is confirmed by the recovery of pumped boreholes which is initially very fast and then much slower. It is thought that the aquifer in Billingham is naturally confined however high pumping rates result in groundwater flow that is partially confined and partly unconfined near the pumping wells.

A value of diffusivity (T/S) of 4.5×10^5 m^2/d was obtained from analysis of the reduction of the tidal effect (Ineson, 1957). This suggests that for a transmissivity of 520 m^2/d the confined storage is actually 1.2×10^{-3}, indicating that on the short timescale of tidal cycles the aquifer is responding in a confined manner.

All the boreholes in the Billingham area responded to barometric pressure: values of barometric efficiency ranged from 0.32 to 0.93 with a mean value of 0.78. The response was analysed in seven boreholes, to give a storage coefficient of $1.22–3.54 \times 10^{-4}$ with an average of 1.49×10^{-4}. This is up to ten times less than the value (about 10^{-3}) obtained from pumping tests (Ineson, 1957).

Vale of York

A borehole at Lower Dunsforth encounters a confined response followed by an unconfined response with time as the cone of depression spreads. If all the drawdown curves for the piezometers are matched for the same transmissivity then the piezometers near the borehole give very high storage values of over 0.2. This indicates that the unconfined response is first seen near to pumping boreholes, though this values is rather high to be realistic. This effect is similar to that seen at Billingham.

Group pumping tests in the Vale of York (Reeves et al., 1974) gave storage values generally 10^{-4} to 10^{-3} (confined). However two boreholes (at Marton-le-Moor [SE 371 703] and Green Hills [SE 340 910] gave values of 0.03 and 0.04 respectively. It is thought that more boreholes would show larger unconfined storage coefficient values if the pumping tests had been continued for more than a few days. The confined storage coefficient results compare reasonably with theoretical estimates from the aquifer compressibility which lie in the range 6×10^{-5} to 2×10^{-3} (Reeves et al., 1974).

Carlton (Figure 7.2.3)

Pumping tests at Carlton, in south Yorkshire, gave values of storage coefficient in the range 10^{-4} to 0.1 which reflected the degree to which different sites near Carlton were confined by drift (Parker et al., 1985). The high unconfined values of storage obtained from pumping tests in this area may reflect the large pore diameters and so the relative ease and speed of drainage of pores near the water table.

Nutwell (Figure 7.2.3)

Nutwell pumping station has finer sediment towards the top of the borehole (Dodds, 1986). When the main borehole is pumped the shallow observation holes in the drift and top sandstone and clay show a smaller water level change compared to the deep boreholes penetrating the aquifer. This suggests that the finer sediment near the top of the borehole acts as a semi-confining layer. At this site the drift is marly silt and the top of the sandstone appears to be clayey. In general the grainsize appears to increase with depth and become more uniform. These two factors being likely to increase the hydraulic conductivity with depth, leading to the aquifer responding in a semi-confined manner.

Model storage values

A value of 0.1 is used as a starting point for kinematic porosity in the aquifer used in FLOWPATH protection zone modelling, however unconfined storage coefficients (often used as a surrogate for kinematic porosity) are not obtained from pumping tests in the region (Fletcher, S, personal communication).

In the Doncaster model, values of storage cefficient of 1 to 5 × 10^{-4} were used throughout, except in the central, southern region where unconfined values of 0.15 are used. (Brown and Rushton, 1993). In the Doncaster area a specific yield of 0.15 was used for the sandstone aquifer, and a value of 0.2 was used when the water level was in permeable drift of sands or gravels; the model was not very sensitive to changes of up to 30% in these values.

Other models have used similar storage values; the Vale of York sandstone model used an unconfined storage coefficient of 0.1 for the areas with little drift cover and a confined storage coefficient of 10^{-4} in the areas with greater drift thickness (Aldrick, 1974). A general groundwater model of the Vale of York (Reeves et al., 1974) used a general value of specific yield of 0.1 in the unconfined area, and a confined value of 10^{-4}. Flowpath modelling around Doncaster also assumed an porosity of 0.1 (NRA Source protection zone modelling). A summary of the model storage values throughout the area is provided in Figure 7.2.16.

Aquifer response times

The factors effecting groundwater level fluctuations are; the aquifer boundaries, the sources of inflow and outflow and the aquifer characteristics (transmissivity and storage). In general there is only a small gradual (non-spiky) annual water level fluctuation of the order of 1 to 3 m within the Sherwood Sandstone Group.

Barometric efficiency

The aquifer exhibits barometric efficiency, some boreholes showing considerable barometric efficiency, for example a borehole at Solberge responds in a confined manner on a short timescale to barometric pressure. Thus on a time scale of days or hours the aquifer responds in a confined manner, whereas it responds in an unconfined manner regionally on an annual basis.

Groundwater levels at Edwinstowe exhibit barometric effects, with a correlation coefficient of 0.82 for an instantaneous response and a barometric efficiency of around 30% (Satchell and Edworthy, 1972).

Summary of storage coefficient values

It is useful to compare storage coefficient values that have been measured in different ways at one site. These different values have different purposes and illustrate the time and scale dependence aquifer properties in the Permo-Triassic sandstones. Thus for example at Edwinstowe porosity values range between 14 and 36%, though centrifuge specific yield values are slightly less, ranging from less than 0.11 to 0.32. This is greater than an effective storage coefficient of 0.05 obtained from pumping tests and suggests that the anisotropic nature of the aquifer dominates the pumping test storage response (Satchell and Edworthy, 1972). Edwinstowe, which is situated just north of the River Maun, falls within the Nottingham

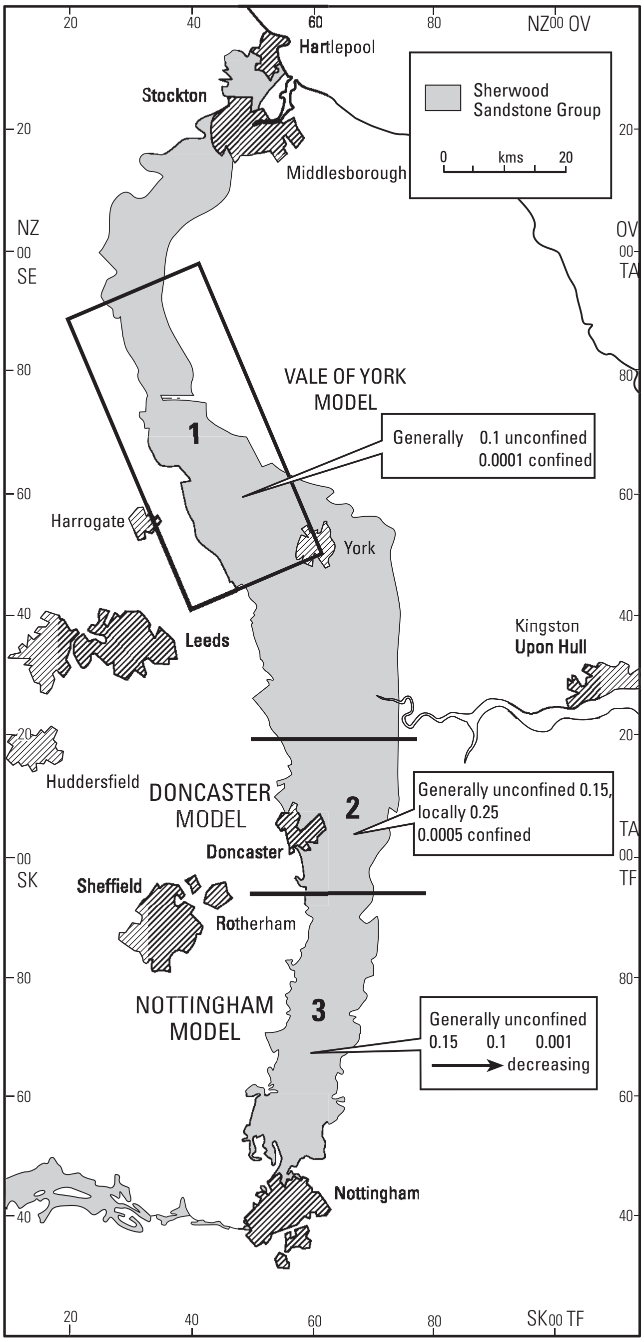


Figure 7.2.16 Variation of modelled storage coefficient values for the Permo-Triassic sandstones of north-east England.

model region which has a storage coefficient value of 0.15 in this area. This is more comparable to the porosity and specific yield obtained from centrifuging core than the pumping test storage estimates. This suggests that a high drainable porosity (of around 15%) describes the long-term water level response of the aquifer. On short time scales however, of the order of hours (barometric effects) and days (pumping tests), the aquifer in this area responds in a semi-unconfined manner, with the effective storage coefficient for this short time scale reducing to 0.05 (Satchell and Edworthy, 1972).

The values used for resource assessment and modelling long-term pumping are generally the higher specific yield values. Short term responses of boreholes to pumping tests and to barometric and tidal changes in pressure are generally confined. Typical storage coefficient values for a production borehole are a confined storage of 1×10^{-3} with unconfined values of 0.01 to 0.1. A summary of storage values for the Sherwood Sandstone Group from a variety of sources is presented in Table 7.2.7.

Table 7.2.7 Storage coefficient values for the Sherwood Sandstone Group in north-east England from various sources.

Data source	Timescale	Values	Response type
Pumping tests	hours-day long (weeks)	$\sim 10^{-4}$ < 0.15	confined unconfined
hydrographs	hours-days annual	confined 0.15	confined unconfined
models		10^{-4} 0.15	confined unconfined

7.2.4 Summary of aquifer properties

A summary of the aquifer properties data statistics from the Aquifer Properties Database is given in Table 7.2.8, and a general summary of aquifer properties data from different sources given in Table 7.2.9.

Transmissivity values determined in pumping tests have a wide range of values, with an average similar to transmissivities used in models. Hydraulic conductivity values derived from pumping tests and those used in models are generally greater than those measured in laboratory core permeametry.

Laboratory measurements indicate a range of porosities, typical of a sandstone. Values of unconfined storage used in models lie towards the lower end of the measured porosity distribution. The majority of pumping test determined storage values are in the confined storage range.

7.3 WEST MIDLANDS

7.3.1 Introduction

Geological and geographical setting

General description

The region described encompasses Bridgnorth, Birmingham, Bromsgrove, Wolverhampton, Stafford, Lichfield and Burton-upon-Trent (Figure 7.3.1). Sandstones of Permo-Triassic age form the region's main aquifer. They occur within a complex system of interconnected basins (Figure 7.3.2), and crop out around their edges. For hydrogeological purposes, the West Midlands region is better subdivided on the basis of outcrop, rather than basin-by-basin. The area lies within the Midlands Region of the Environment Agency.

The geology of the region at the 1:50 000 scale is described by a series of British Geological Survey maps and accompanying memoirs. The stratigraphical classification of the Triassic rocks is based on Warrington et al. (1980).

Regional structure

The Permo-Triassic rocks of the region lie unconformably on a surface of varied relief and geology. Phases of rifting in the Permian and early Triassic resulted in the formation of a series of rapidly subsiding, fault-bounded sedimentary basins in the region: the Stafford Basin, Knowle Basin, Worcester Basin, Needwood Basin and Hinckley Basin

Table 7.2.8 Summary of aquifer properties data for the Sherwood Sandstone Group in north-east England.

Permo-Triassic sandstones (all data)	Range	Interquartile range	Median	Geometric mean
Transmissivity (m^2/d)	12–5000	92.8–409.6	206.5	201
Bulk hydraulic conductivity (m/d)	0.11–91	1.8–6.6	3.7	3.7
Storage coefficient	1×10^{-4}–0.31	7×10^{-4}–0.0061	0.001	0.0021
Specific capacity ($m^3/d/m$)	2.3–1.3×10^5	56–245	120	100

Table 7.2.9 Comparison of aquifer properties data derived from different sources.

Parameter	Pumping test	Logs	Lab	Model
Transmissivity (m^2/d)	² 600 (locally > 600)	indicate fractures with flow	~ 200–500	(range 10–1200)
Hydraulic conductivity (m/d)	1–5+	—	0.01–1	1–3
Storage coefficient (unconfined)	0.2	—	0.1–0.38	0.1–0.15
Porosity	—	—	0.28	—
Storage coefficient (confined)	$\sim 10^{-4}$	—	—	$1–5 \times 10^{-4}$, though long term aquifer response may be unconfined

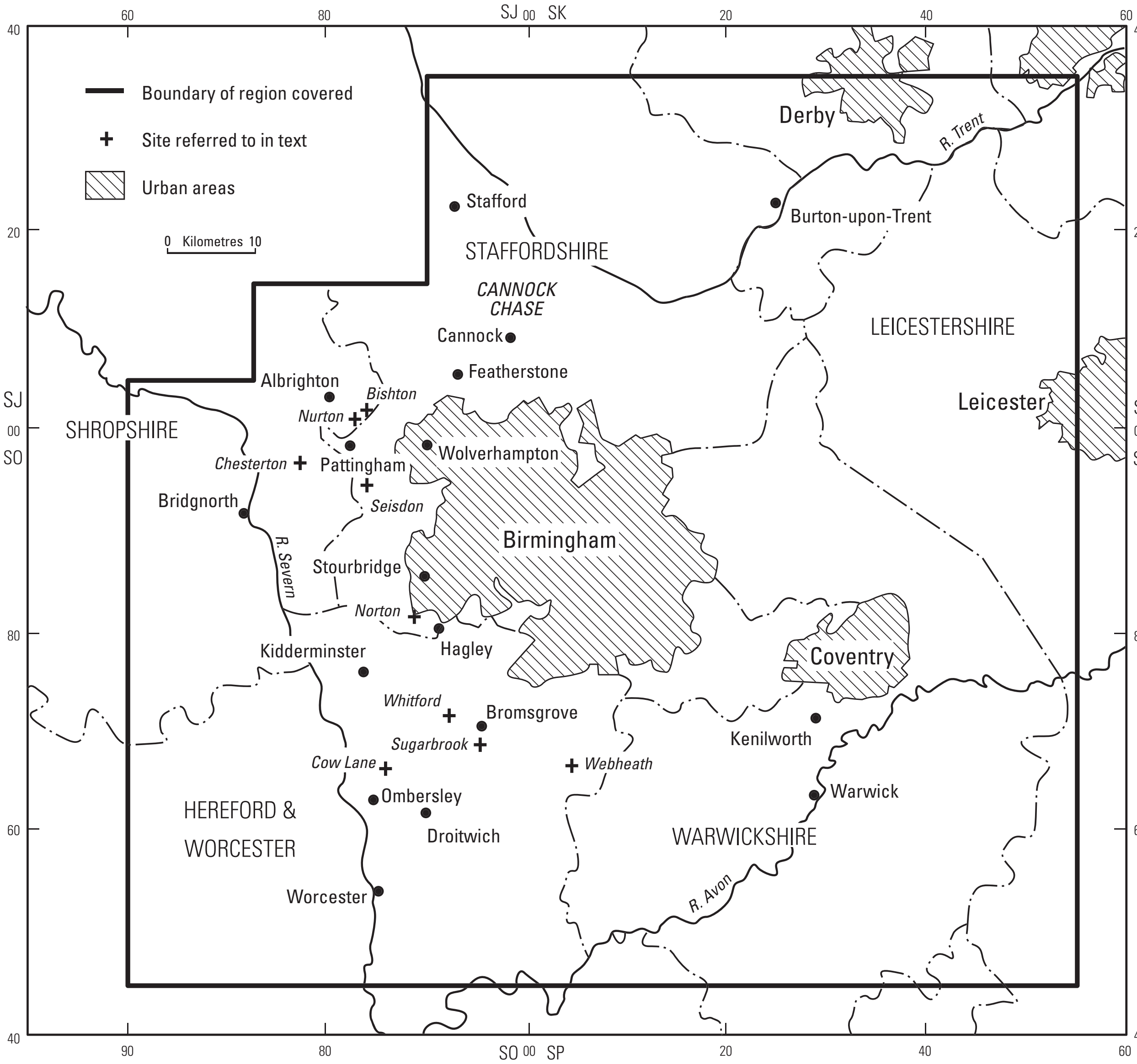


Figure 7.3.1 West Midlands — region covered and locations of places referred to in the text.

(Figure 7.3.2). Thick sequences of Permian and early Triassic sandy deposits, which now form the Permo-Triassic sandstone aquifer, are largely confined to these basins. However, as the Triassic period progressed, deposition gradually spilled over the basin margins onto the adjacent highs, so that younger formations tend to progressively overlap older ones in extent. The entire Permo-Triassic sequence is overlain to the east and south by younger Mesozoic rocks.

Stratigraphy

Thick sandstones of Permian age are largely confined to the south-west of the region and are assigned to the Bridgnorth Sandstone Formation (formerly Lower Mottled Sandstone or Dune Sandstone — Table 7.3.1). Elsewhere in the region, the Permian is represented by conglomerates and breccias of patchy distribution and highly variable thickness; a variety of local names have been applied to these deposits.

The Permian deposits are overlain unconformably by the Sherwood Sandstone Group, which consists of three distinct lithostratigraphical subdivisions. The lowest corresponds to the former Bunter Pebble Beds division. Although this unit is recognisable in all the basins within the region, lateral continuity cannot be demonstrated between some basins and local formation names have therefore been assigned (Warrington et al., 1980), namely the Kidderminster, Cannock Chase and Polesworth formations. These consist of interbedded sandstone, breccias and conglomerates. The breccias are well developed towards the margins of individual basins, and are believed to represent gravel fans at the mouths of wadis emerging from adjacent upland areas. Contrastingly, the sandstones and conglomerates with large rounded pebbles are interpreted as the deposits of a major, early Triassic river system, which flowed northwards from a source in the area presently occupied by the Britanny peninsula and English Channel.

The middle unit of the Sherwood Sandstone Group, the Wildmoor Sandstone Formation, corresponds to the former Upper Mottled Sandstone. It is absent in the east of the region. It is generally finer grained than the underlying formations and, characteristically, almost free of pebbles. It represents a gradual waning in the transporting capacity

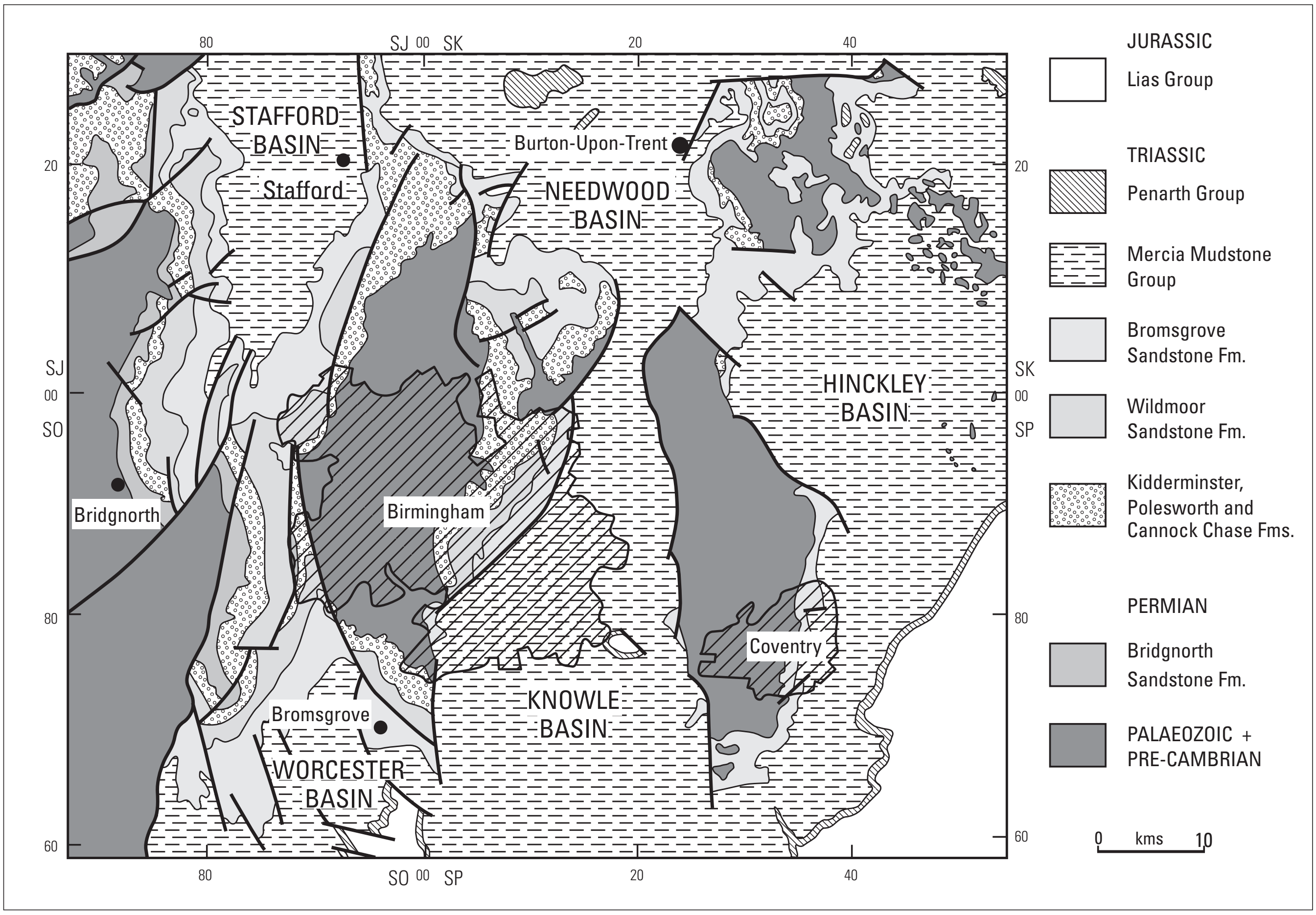


Figure 7.3.2 Geology and Permo-Triassic basins in the West Midlands (based on Warrington et al., 1980).

Table 7.3.1 Permo-Triassic stratigraphy of the West Midlands, (Worssam et al. [1989] and Warrington et al. [1980]).

System and lithostratigraphical division		Previous division	Aquifer unit	Thickness (m)
TRIASSIC Mercia Mudstone Group	Mudstone Unit	Keuper Marl	Aquitard	140–550
TRIASSIC Sherwood Sandstone Group	Bromsgrove Sandstone Formation	Keuper Sandstone	Aquifer	0–350
	Wildmoor Sandstone Formation	Upper Mottled Sandstone		0–150
	Kidderminster/Polesworth/ Cannock Chase Formations	Bunter Pebble Beds		0–200
PERMIAN	Bridgnorth Sandstone Formation (Wolverhampton and Bridgnorth areas only	Lower Mottled Sandstone, Dune Sandstone	Aquifer	0–420

and sediment load of the early Triassic river, and probably includes aeolian dune deposits.

The upper division of the Sherwood Sandstone Group, the Bromsgrove Sandstone Formation (formerly Keuper Sandstone) lies unconformably on the lower divisions. It correlates with the Helsby Sandstone Formation of the Cheshire Basin and, like that formation, consists of a series of upward-fining units, each consisting of sandstone (commonly pebbly) at the base passing up into mudstone. The lower part of the formation was deposited in braided, low-sinuosity river channels, the higher part in mature, meandering river channel and floodplain complexes. The overlying junction with the Mercia Mudstone Group is typically gradational, marked by an upwards relative increase in the proportion of siltstone and mudstone and a progressive elimination of sandstone beds (Warrington et al., 1980). The landscape during Mercia Mudstone times was probably one of arid alluvial plains, mudflats and ephemeral lakes, at times briefly connected to the sea and at other times drying out, causing salts (halite and gypsum) to be deposited.

Hydrogeology

The Permo-Triassic sandstones of the West Midlands typically act as a single hydrogeological unit. There are no major Permian mudstone aquicludes, equivalent to the Manchester Marl of south Lancashire, separating the Permian Bridgnorth Sandstone Formation from the Triassic Sherwood Sandstone Group. However, fine-grained horizons within the sandstones can cause hydraulic stratification, and result in double or multiple aquifer systems. A description of these systems follows a consideration of the formations' properties.

The Bridgnorth Sandstone Formation is poorly cemented and highly permeable. The dominant lithology consists of poorly indurated, friable, poorly sorted fine- to medium-grained sandstone with thin coarser-grained layers (Lovelock, 1977).

The Kidderminster and Wildmoor Sandstone formations are of greater importance than the Bromsgrove Sandstone Formation in terms of total outcrop area. They are fine to medium grained and often cross-bedded. The Kidderminster/Cannock Chase/Polesworth Formation consists of indurated, well-cemented breccias and conglomerates interbedded with sandstone. In the absence of fractures, it may act as an aquitard between the arenaceous units above and below it.

The Wildmoor Sandstone Formation typically consists of fine-grained laminated sands (Lovelock, 1977). The Bromsgrove Sandstone Formation is more cemented, and, in general, finer grained. It is composed of a series of fining-upward sequences, each consisting of fine-grained sandstone passing up into red mudstone (Skinner, 1977). Each fining-upward sequence is usually less than 20 m thick. Laterally variable, argillaceous mudstone beds with low hydraulic conductivity are present. These are usually less than a metre thick, but can be up to 10 m thick (Salmon, 1989).

Hydraulic significance of faults

There are a variety of records of low permeability faults in the West Midlands. Many juxtapose sandstones but nevertheless break hydraulic continuity. Evidence for them comes from water levels, pumping tests, spring lines and groundwater flow modelling. Conversely, faulting can also increase transmissivity, for instance the productive Whitford borehole [SO 935 706] is situated on the Hagley fault (Black and Barker, 1981).

Impermeable faults to the west and east of the Bishton Farm borehole [SJ 803 017], near Albrighton in the Wolverhampton to Bridgnorth area, may account for the unexpectedly low yields within the Bromsgrove Sandstone Formation there. The drawdown from boreholes in this area is therefore likely to spread to the north and south (Fletcher, 1985a; 1989). Transmissivity is also reduced across the Birmingham Fault (Figure 7.3.3), which was modelled by Knipe et al. (1993) as a zone of reduced aquifer thickness.

An impermeable fault forming the eastern boundary of a Permo-Triassic sandstone block in the Featherstone area prevents groundwater flow westwards. Local groundwater levels are 30 m higher than those in the surrounding area. A spring line falls on the north–south-trending Pattingham Fault (Figure 7.3.4), west of Nurton and north-west of Bridgnorth, which juxtaposes sandstones. The water table to its east is at about 110–115 m above Ordnance Datum (aOD) and to its west is at about 78 to 79 m aOD. The

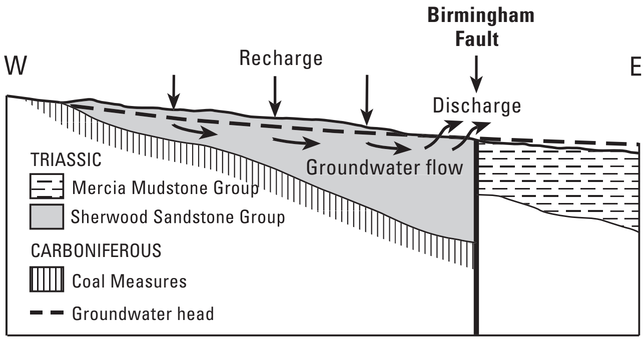


Figure 7.3.3 Groundwater flows across the Birmingham fault (after Knipe et al., 1993).

significant head difference across it of 21 to 27 m indicates that it is impermeable (Fletcher, 1994).

FAULT BOUND BLOCK AT NURTON: 'BUCKET BEHAVIOUR'

The water supplying the Nurton borehole [SJ 831 007], 5 km southeast of Bridgnorth is probably trapped within a fault block (Figure 7.3.4). The main results of a two-month constant rate pumping test on the Cannock Chase Formation, beneath the Bromsgrove Sandstone Formation, were as follows (Fletcher, 1989, 1994):

- Only the closest two of the 24 observation sites were affected by the test. Both were within 500 m of the abstraction borehole.
- Drawdown at the abstraction well increased linearly with time and did not stabilise. The water level declined at a constant rate of 0.1 m/day, when pumped at 8340 m^3/d (8 Ml/d). The initial step testing and two subsequent pump failures gave rise to short term recoveries.
- One spring-fed pond, lying on the Pattingham Fault west of the borehole, dried up. Its flow only began to return in, 1994, six years after the test. It was decided that there was little long-term future for this borehole as a public water supply and the test was finished a month earlier than planned.

The situation can be explained by considering a closed system with no lateral inflow replacing the water being removed. Radial flow modelling based on a 0.7 km^2 impermeable fault bounded block with 600 m^3/d recharge vertically through the surface layers reproduces the observed drawdown pattern. Although the presence of the impermeable Pattingham fault to the west of the borehole is known, impermeable bounding faults to the east, north and south of the borehole are only postulated.

Multiple aquifer effect

The presence of shale, marl and mudstone layers, and strongly cemented marl breccias, interbedding with the sandstones of the Bromsgrove Sandstone Formation aquifer cause it to act as a multiple aquifer system. Each unit has a different hydrostatic pressure and responds differently to pumping (Ramingwong, 1974). The effects of pumping at depth are not usually detected at the surface.

Although the effects of pumping may spread out a considerable distance horizontally at depth, they do not necessarily affect the upper aquifers. For instance, when the Bishton

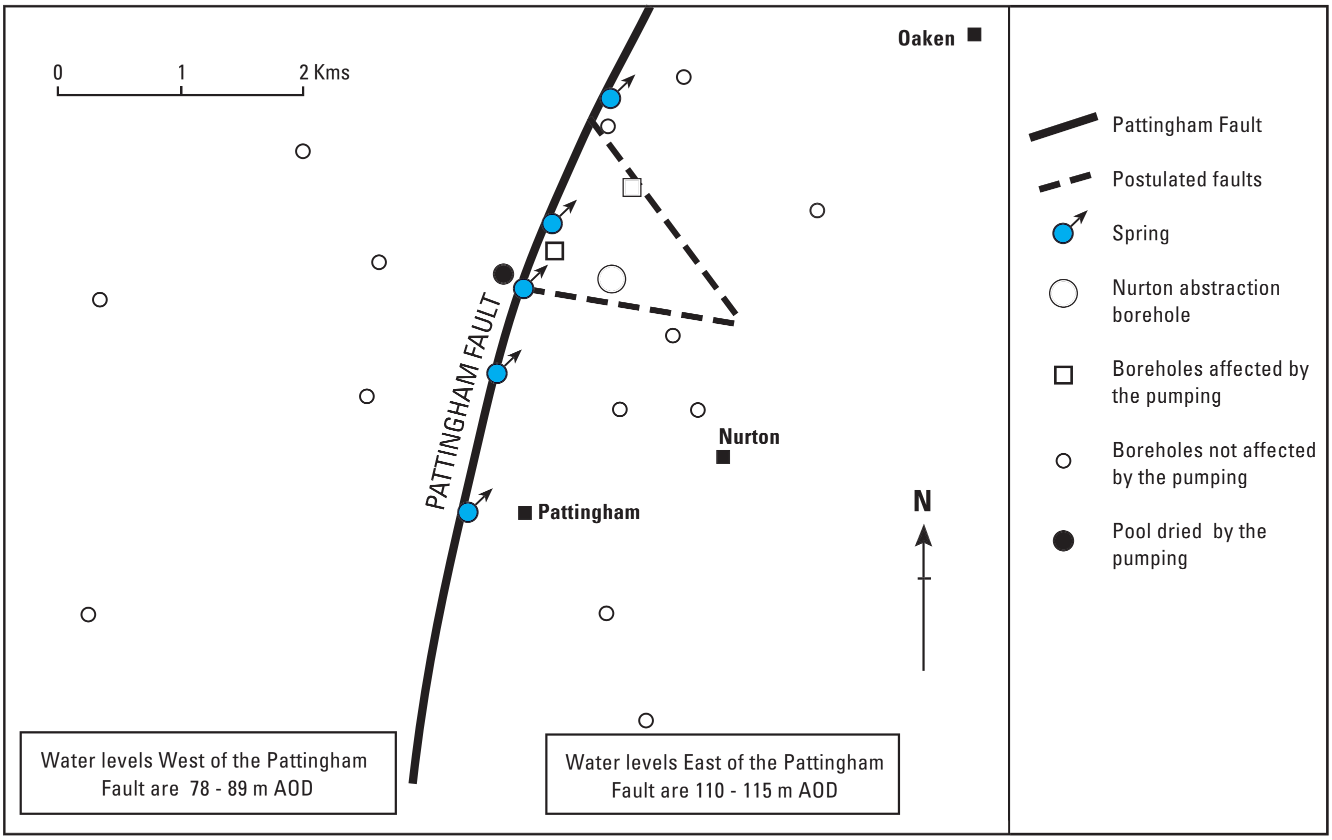


Figure 7.3.4 Impermeable faults bounding the Nurton borehole (after Fletcher, 1994).

Farm, Albrighton borehole [SJ 803 017] was pumped at 800 m^3/d, no drawdown was observed in shallow tube wells monitoring the water table [SJ 7999 0238 and SJ 8036 0237], nor at the pond [SJ 808 023] (Fletcher, 1985a). Likewise, the adjacent spring and streamflows, tube wells and observation boreholes were not affected when the Burnhill Green [SJ 774 009] borehole was test pumped (Fletcher, 1985b). In the Coalville area, interbedded marls may locally cause the Bromsgrove Sandstone Formation, Polesworth Formation and Moira Breccia to behave as multi-aquifers (Worssam and Old, 1988).

Marl bands can give rise to locally confined conditions. Artesian flows have occurred from boreholes at Cookley Pumping Station [SO 844 807], Kinver [SO 848 833], Stourport [SO 814 711] and Kidderminster [SO 825 772] (Djaeni, 1972).

Double aquifer effect

In the Bridgnorth to Wolverhampton area, around Chesterton, and at Seisdon and Stourbridge the Sherwood Sandstone Group acts as a double, rather than a single, hydrogeological unit. The Permo-Triassic sandstone consists of tilted fault blocks, and direct recharge to the bottom aquifer is thought to occur. The confining layer (Figure 7.3.5) occurs towards the base of the Kidderminster Formation, leaving this together with the Wildmoor Sandstone Formation as the upper aquifer, and the Bridgnorth Sandstone Formation as the bottom aquifer. Interbedded marl bands form the confining layer (Fletcher, 1989). Cementation is not seen in cores and so is unlikely to be the cause of the confinement.

Piezometric head differences exist between the members of a double aquifer, for instance there is a head difference of 15 m between the aquifer couple at Chesterton (Fletcher,

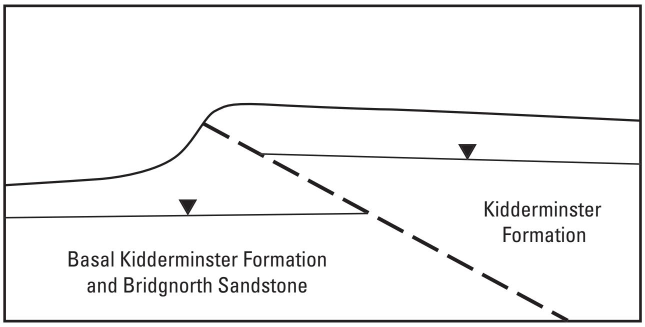


Figure 7.3.5 Schematic cross-section: double aquifer in the Stourbridge area.

1989). A step test conducted on a borehole penetrating such a system gives a curving graph of specific drawdown against yield, rather than a straight line. The relationship becomes increasingly linear as the head difference between the aquifers decreases (Fletcher, 1989).

Water quality differences may also exist between members of a double aquifer. These give rise to short-term quality changes during pumping tests, and divergent data-sets on long term records of analyses from pumped boreholes. At Chesterton, the top aquifer has a nitrate concentration of 19 mg/l, compared to concentrations of less than 5 mg/l in the underlying aquifer.

The ‘double aquifer’ effect is most apparent where there is heavy aquifer exploitation and where there are large topographic differences. This phenomenon is not seen in Shropshire, where the beds dip less steeply, nor in Nottinghamshire where there is probably insufficient lithological contrast (Fletcher, S, personal communication).

Double aquifer case study: Norton [SO 8933 8157]

The properties of the double aquifer system at Norton were investigated by Severn Trent Water Authority (Fletcher, 1984). The borehole was drilled in two stages, initially to just above the confining layer, and subsequently beyond it. Geophysical logging indicated marl bands up to 15 cm thick within the Kidderminster Formation, few of which were recovered in the cores. One of the observation boreholes was packered off to separate the two aquifers. Another had a nest of three piezometers installed, in which an equilibrium head differential of 22 m was measured.

When there was no pumping, the upper aquifer recharged the lower aquifer, via the fully penetrating borehole. At lower pumping rates, the upper aquifer supplied both the lower aquifer and all of the discharging water. At higher pumping rates, both aquifers contributed to the borehole yield. The yield from the borehole is a function of the yield from both aquifers, which in turn is a function of their rest water levels relative to the pumping water level.

Summary

Although the Permo-Triassic sandstones typically act as a single hydrogeological unit, fine-grained horizons can cause hydraulic stratification, giving rise to double or multiple aquifer systems. Marl layers towards the base of the Kidderminster Formation isolate it from the underlying Bridgnorth Sandstone Formation, giving rise to water quality differences and characteristic step test results. Multiple aquifer systems are a feature of the Bromsgrove Sandstone Formation, where the effects of pumping at depth may not be observed at the surface. Low permeability layers can cause artesian conditions; impermeable faults also affect the groundwater flow regime.

Previous hydrogeological investigations

A variety of localised studies have been made of the aquifer properties of the West Midlands. These include accounts of pumping tests by the Severn Trent Region of the National Rivers Authority and the former Water Authority. A PhD thesis by Ramingwong (1974) focused on the Bromsgrove Sandstone Formation. Lovelock (1977) described the various core permeametry data, and described the 'Bridgnorth to Wolverhampton' and 'South Staffordshire, Birmingham and Warwickshire' areas separately.

7.3.2 Hydraulic conductivity and transmissivity

Hydraulic conductivity has been measured on a variety of scales on the Permo-Triassic sandstones. Laboratory permeametry gives the intergranular hydraulic conductivity of core samples. Down-borehole geophysical logging shows where productive fractures occur. Bulk hydraulic conductivity values, combining both fracture and intergranular flow contributions averaged over a kilometre scale, can be obtained from the analysis of pumping tests. Regional scale values are deduced from groundwater flow modelling. Results from these different techniques are considered in turn below.

Core data

Hydraulic conductivity measurements made on core samples give point-specific measurements of intergranular hydraulic conductivity. They give an indication of the matrix-flow component, but do not reflect any contributions of fracture-flow to the total or hydraulic conductivity. Frequency histograms of the British Geological Survey's core database's hydraulic conductivity values are given in Figures 7.3.6 a, c, e and g for each of the Permo-Triassic sandstone formations. They include the data used by Lovelock (1977). Table 7.3.2 gives the associated means and ranges from the database but includes some information from other sources.

The histograms of core hydraulic conductivity for the different formations all show a tendency to a log-normal distribution. The distributions have a negative skew, due to the presence of more low hydraulic conductivity values than extremely high ones. This is probably a result of lithological control; the presence of fine grains and cementation cause dramatic reductions in intergranular hydraulic conductivity. No consistent variation of core hydraulic conductivity with depth is observed in the top 1500 m, from which the samples have been taken, hence depth is clearly not a major control on intergranular hydraulic conductivity.

Bridgnorth Sandstone Formation

The Bridgnorth Sandstone Formation's hydraulic conductivity ranges from 2.5×10^{-4} to 9.4 m/d. Hydraulic conductivity is controlled by grain size distribution rather than cementation; the distribution (Figure 7.3.6a) is approximately log-normal, with a strong negative skew.

Kidderminster Sandstone Formation

The distribution of core hydraulic conductivities of the Kidderminster Sandstone Formation, and its local lateral equivalents (the Cannock Chase Formation, the Nottingham Castle Formation and the Polesworth Formation) has a wide range of values, from 4.6×10^{-6} to 18 m/d, and a pronounced negative skew (Figure 7.3.6c). The lowest hydraulic conductivities occur in the strongly cemented horizons, fluid flow in these is most likely to occur via fractures. Medium-grained strata have intermediate hydraulic conductivities, whilst the higher values are associated with the interbedded coarse sands; the most permeable of the West Midlands Permo-Triassic sandstones.

Wildmoor Sandstone Formation

The Wildmoor Sandstone Formation core hydraulic conductivity ranges from 3.1×10^{-4} to 12 m/d (Figure 7.3.6e). Low values are associated with muddy horizons, cleaner sands have higher hydraulic conductivities.

Bromsgrove Sandstone Formation

The Bromsgrove Sandstone Formation has most core data. They range from 2.6×10^{-4} m/d to 16.4 m/d (Figure 7.3.6g). Hydraulic conductivity increases with grain size. Lovelock (1977) considered the variation of horizontal hydraulic conductivity with grain size for 206 samples from south Staffordshire, Birmingham, Warwickshire:

coarse sands:	6 m/d
medium sands:	1.3 to 6 m/d
silty sands:	0.26–0.39 m/d

Anisotropy

With the exception of the Bromsgrove Sandstone Formation, horizontal hydraulic conductivity values for the different formations are usually greater than vertical values Figures 7.3.6 b, d, f and h show the distributions for the different formations, and their statistics are given in Table 7.3.3. The ratio of the geometric means of horizontal values to vertical values gives the anisotropy ratio. This core-scale anisotropy has the effect of enhancing the aquifer scale anisotropy, which arises from the layering of finer-grained (less permeable) and coarser-grained (more permeable) sediments.

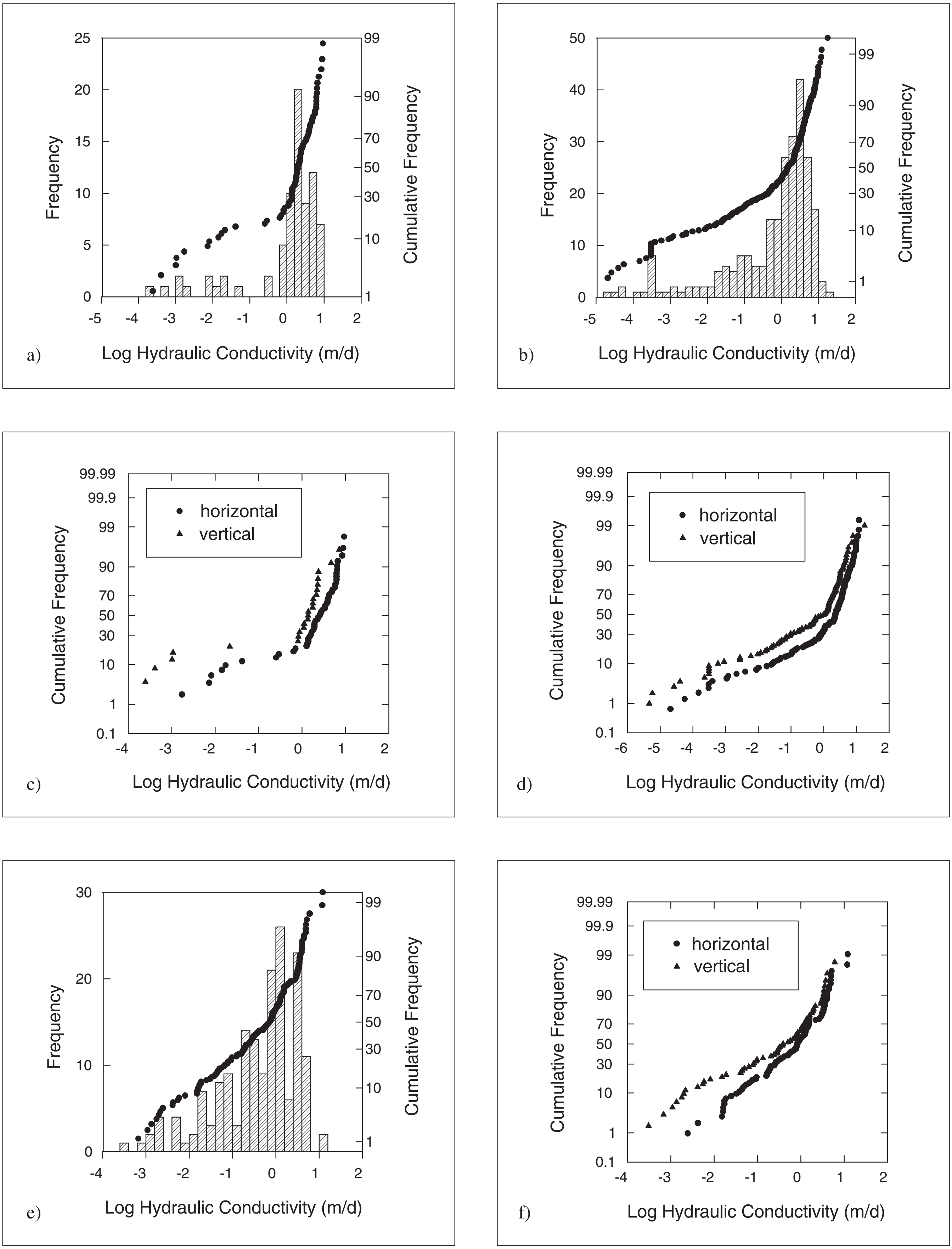
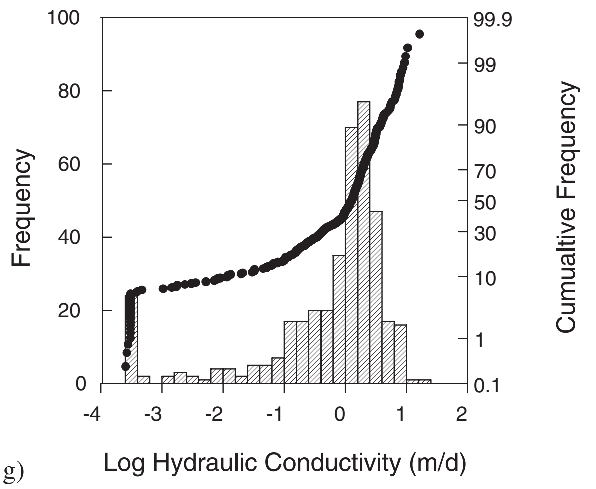


Figure 7.3.6 Distribution of hydraulic conductivity data for Permo-Triassic sandstone samples from the West Midlands, a) Bridgnorth Sandstone Formation — all samples, b) Kidderminster Sandstone Formation (and local equivalents) — all samples, c) Bridgnorth Sandstone Formation — horizontal and vertical samples, d) Kidderminster Sandstone Formation (and local equivalents) — horizontal and vertical samples, e) Wildmoor Sandstone Formation — all samples, f) Wildmoor Sandstone Formation — horizontal and vertical samples, g) Bromsgrove Sandstone Formation — all samples, h) Bromsgrove Sandstone Formation — horizontal and vertical samples.



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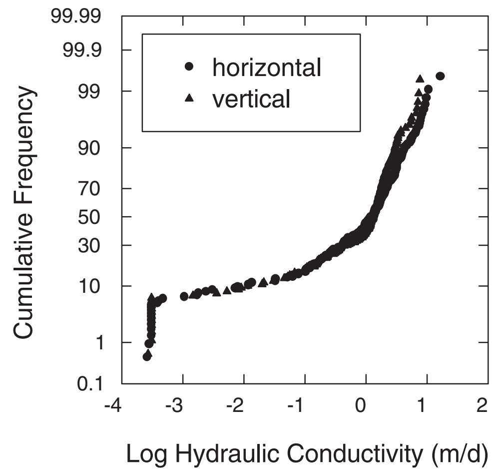

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Table 7.3.2 Core hydraulic conductivity data for the Permo-Triassic sandstones of the West Midlands, by formation.

Formation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Bromsgrove Sandstone	2.6×10^{-4}–16.4	0.28–2.16	1.28	0.50
Wildmoor Sandstone	3.1×10^{-4}–12.0	0.12–1.58	0.73	0.37
Kidderminster Sandstone	4.6×10^{-6}–17.8	0.18–3.5	1.48	0.49
Bridgnorth Sandstone	2.5×10^{-4}–9.4	1.10–4.01	1.95	0.95

Table 7.3.3 Horizontal and vertical core hydraulic conductivity data for the Permo-Triassic sandstones of the West Midlands.

Formation	Orientation	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)	Anisotropy ratio (K_h/K_v)
Bromsgrove Sandstone	Horizontal	0.29–2.59	1.20	0.51	1.1
	Vertical	0.31–1.90	1.31	0.48	
Wildmoor Sandstone	Horizontal	0.19–2.75	0.83	0.56	2.8
	Vertical	0.05–1.46	0.39	0.20	
Kidderminster Sandstone	Horizontal	0.55–4.10	2.29	0.86	3.7
	Vertical	0.06–2.27	1.03	0.23	
Bridgnorth Sandstone	Horizontal	1.4–5.07	2.6	1.43	4.0
	Vertical	0.81–2.22	1.4	0.36	

Ramingwong (1974) conducted four point hydraulic conductivity tests on 104 Bromsgrove Sandstone Formation core samples taken from three boreholes. The anisotropy ratios of individual samples ranged from 5.2 to 0.26. The results are different from those above (which were derived from the Aquifer Properties Database), and are summarised by Rushton and Salmon (1993):

Average hydraulic conductivity	permeable sands	marl
horizontal	7.6 m/d	0.02 m/d
vertical	5.6 m/d	0.01 m/d

Geophysical logging and packer test hydraulic conductivity

Borehole logging in the Bromsgrove area has confirmed the existence of substantial fractures, many developed in the conglomerate bands of the sequence. Salmon (1989) envisages hydraulic conductivity layering similar to that observed in the Merseyside aquifer (Section 7.5.2).

Out-flow double packer testing and geophysical logging of the Bromsgrove Sandstone Formation is described by Ireland (1981). The Cow Lane observation hole, Dunhampton, Worcestershire [SO 848 660] was investigated to a depth of 145 m. Gamma logs showed low hydraulic conductivity clay-grade bands and caliper logs delineated fractured horizons. Packer testing, with the packers spaced 3.25 m apart, gave hydraulic conductivities which ranged between 0.24 and 2.52 m/d. The majority of the high hydraulic conductivity sections are fractured, and the low hydraulic conductivity sections are aquitards.

The transmissivity profile (Figure 7.3.7), based on cumulative average hydraulic conductivity and cumulative aquifer thickness, shows a particularly marked increase at 110 m depth, the level of a significant fracture. A value of 117 m^2/d was obtained for the whole tested section. This compares well with the results of a pumping test at

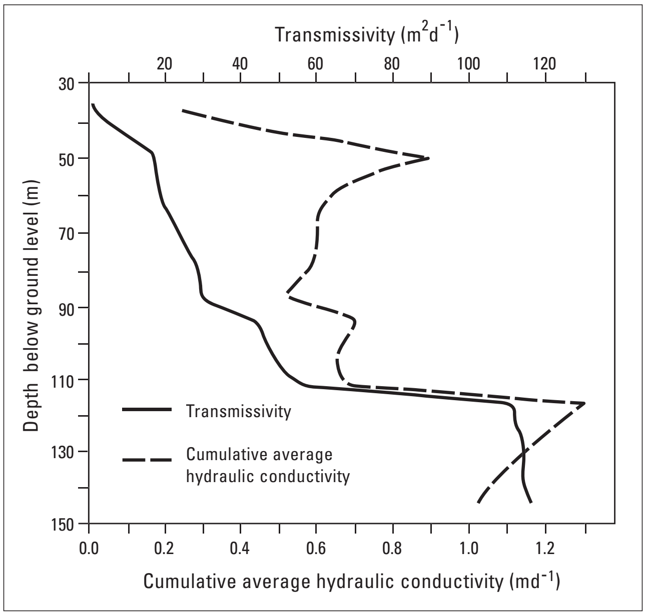


Figure 7.3.7 Packer testing results in the Bromsgrove Sandstone Formation at Cow Lane (after Ireland, 1981).

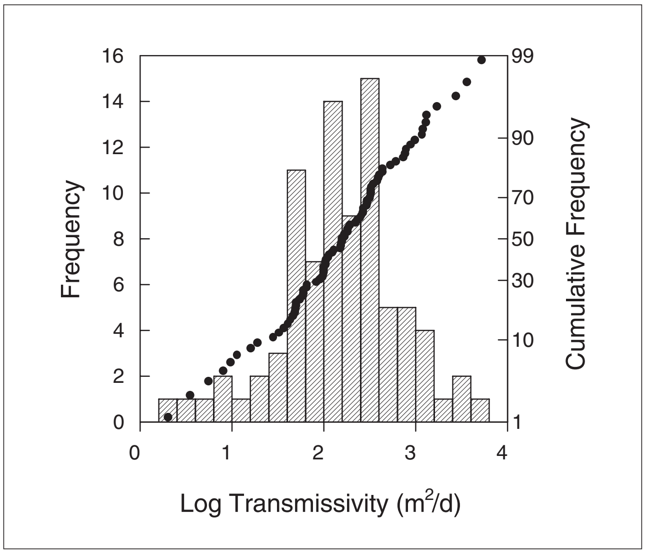


Figure 7.3.8 Distribution of transmissivity data from pumping tests in the Permo-Triassic sandstones in the West Midlands.

Dunhampton pumping station which gave a transmissivity of 125 m^2/d. A bulk hydraulic conductivity of 0.4 m/d is obtained when the transmissivity is divided by the length of packer tested section. This is comparable with the intergranular hydraulic conductivity of sandstones. Thus, although fracture flow is significant at some levels of the borehole, it does not dominate the transmissivity.

Pumping test transmissivity and bulk hydraulic conductivity

Controls on transmissivity are numerous. Productive fractures can give rise to high pumping test transmissivities; these may be enhanced further in regions of extensive faulting. Intergranular hydraulic conductivity (and hence lithology) is a principal control where fracture flow is minor. Borehole depth, the depths of highly permeable zones, and the effective aquifer depth also influence the value of transmissivity. Scale is an important factor too, since pumping tests average the transmissivity on scales of hundreds of metres to kilometres. Confining layers and faults also affect pumping tests and their interpretation.

Transmissivity

The aquifer properties database contains transmissivity records from 85 sites in the West Midlands region. At each site there have been up two different pumping tests; there is a total of 88 tests on record. The log transmissivity histogram (Figure 7.3.8), approximates to a normal distribution, with a range from 2 to 5200 m^2/d; the interquartile range is 60 to 330 m^2/d. The geometric mean is 151 m^2/d, and the median is 158 m^2/d. There is no relationship between the transmissivity values and the lengths of pumping tests.

Tests at Webheath No. 1 [SP 02 66] showed that the Bromsgrove Sandstone Formation's apparent transmissivity values increase as the penetration depth increases. The transmissivity values increase from 45 to 65 and to 95 m^2/d when the depth of penetration of the borehole increased from 189 to 303 and to 392 m respectively. Likewise at Sugarbrook No. 1 [SO 962 681], transmissivity was found to increase from 30 to 65 m^2/d when the depth of penetration increased from 138 m to 286 m (Ramingwong, 1974).

Bulk hydraulic conductivity and the significance of fracture flow

In order to assess the significance of fracture flow, and to directly compare the different formations, the pumping test transmissivity data have been converted to bulk hydraulic conductivities. This removes the thickness variable, by eliminating the effects of different borehole depths, distances to the piezometric surface and thicknesses of confining layers. Thus bulk hydraulic conductivities can be directly compared with intergranular core data. The calculation method is described in Section 7.1.4. Bulk hydraulic conductivity values have been calculated from the database for 66 sites in the West Midlands region. They range from 0.014 to 490 m/d and have an interquartile range of 0.99 to 9.9 m/d. The log bulk hydraulic conductivity histogram (Figure 7.3.9a) shows an approximately normal distribution, and the geometric mean and median are similar: 3.0 m/d and 2.9 m/d respectively.

The lower limit of bulk hydraulic conductivity (0.01 m/d) is four orders of magnitude greater than the lower limit of core hydraulic conductivity data (10^{-6} m/d). This is a function of scale: cores sample centimetre-scale regions, which can consist entirely of low hydraulic conductivity sediments. Such layers do not dominate an entire abstraction borehole, which also intercepts more permeable zones. Hence the lower limit of a borehole bulk hydraulic conductivity tends to be greater than the minimum core values. The upper limit of bulk hydraulic conductivity (490 m/d) is also higher than the upper limit of core data (18 m/d) as a result of fracture flow contributions to the borehole bulk values.

Values of bulk hydraulic conductivity have been subdivided into those associated with the different formations. As only data from those boreholes which penetrate a single formation can be used, the number of bulk hydraulic conductivity values for each formation is small. There are sufficient data to plot frequency histograms for the constituent formations of the Triassic Sherwood Sandstone Group.

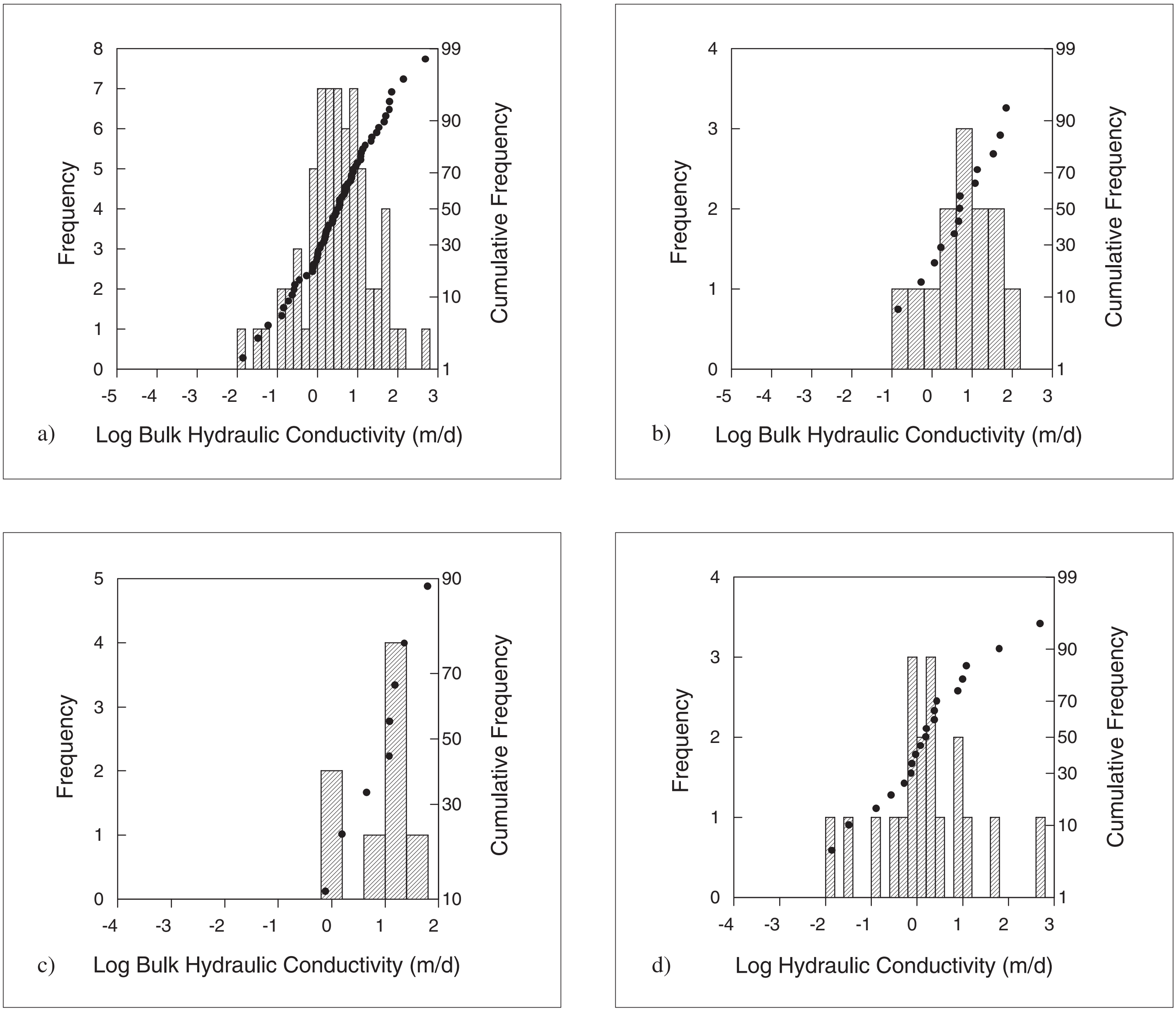


Figure 7.3.9 Distribution of hydraulic conductivity data from pumping tests in the Permo-Triassic sandstones in the West Midlands, a) Permo-Triassic sandstones, b) Kidderminster Sandstone Formation (and local equivalents), c) Wildmoor Sandstone Formation, d) Bromsgrove Sandstone Formation.

(Figures 7.3.9b to d). They plot at and beyond the high end of the associated core hydraulic conductivity spectra (Figures 7.3.6d, f and h), indicating the significance of fracture flow within the formations. Although formation type exerts a control on intergranular hydraulic conductivity, it does not always exert a primary control on bulk hydraulic conductivity. The Bromsgrove Sandstone Formation has the greatest range: up to 490 m/d; statistics are given in Table 7.3.4.

Laboratory and field hydraulic conductivity values for two sites in the Droitwich syncline area, Worcestershire are compared by Ramingwong (1974). At Whitford [SO 935 706], the field hydraulic conductivity of 1.4 m/d was over twice the core value of 0.66 m/d (geometric mean of 27 samples), indicating that fracture flow is significant and accounts for approximately half of the borehole yield. Conversely, at Ombersley [SO 836 629) the field value and lab value (geometric mean of 17 samples) were 0.39 m/d and

Table 7.3.4 Bulk hydraulic conductivity data for the Sherwood Sandstone Group of the West Midlands.

Formation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
All	0.014–486	1.02–9.90	2.93	3.00
Bromsgrove Sandstone	0.014–486	0.53–2.71	1.58	1.58
Wildmoor Sandstone	0.77–62.6	3.06–19.1	12.1	8.06
Kidderminster Sandstone	0.14–69.2	1.14–33.3	4.79	4.93

0.36 m/d respectively, implying that intergranular flow is locally dominant.

Lovelock (1977) estimated from core samples an intergranular transmissivity of 268 m^2/d for the Kidderminster Formation at Littleton Colliery in Staffordshire. The pumping test derived total transmissivity was calculated as 2770 m^2/d, indicating that there, 90% of the flow is from fractures.

Six out of seven pumping tests on the Bromsgrove Sandstone Formation, analysed by Ramingwong (1974) in the Droitwich–Kidderminster–Bromsgrove area of the Worcester basin, had a consistent mean bulk hydraulic conductivity of 0.3 m/d, with associated transmissivity values ranging between 30 and 400 m^2/d. The seventh, a test at Whitford [SO 935 706] had a value five times greater. This could be due to it being sited on the Hagley Fault which has a high transmissivity (Black and Barker, 1981).

Specific capacity and borehole yields

Specific capacity

The database has specific capacity records at 71 sites in the West Midlands region. It exhibits a very broad range of values, from 0.34 to 81 000 m^3/d/m, and has an interquartile range of 28 to 230 m^3/d/m. The log specific capacity histogram (Figure 7.3.10) shows an approximately normal distribution. The geometric mean is 82 m^3/d/m and the median is similar at 74 m^3/d/m. Specific capacity data show a general increase with transmissivity, although they can vary by at least an order of magnitude (Figure 7.3.11). Specific capacity is affected by the same factors as transmissivity and in addition, borehole radius and the duration of pumping.

Ramingwong (1974) adjusted specific capacities, for well losses, different well radii, and different pumping periods, hence deriving values which were independent of pumping rate. These were then used to compute yield per metre drawdown per metre of aquifer, which was used to compare well performances with aquifer properties. The adjusted specific capacity per metre of drawdown was found to vary between 0.27 m^3/d/m and 0.68 m^3/d/m. It showed a general increase as drawdown increased and therefore as the thickness of aquifer in use was reduced. This suggests that the lower part of the Bromsgrove Sandstone Formation has a higher yield per metre of drawdown per metre of aquifer than that of the upper part of the Formation. This can be attributed to larger grain size and, in some areas, fracture flow.

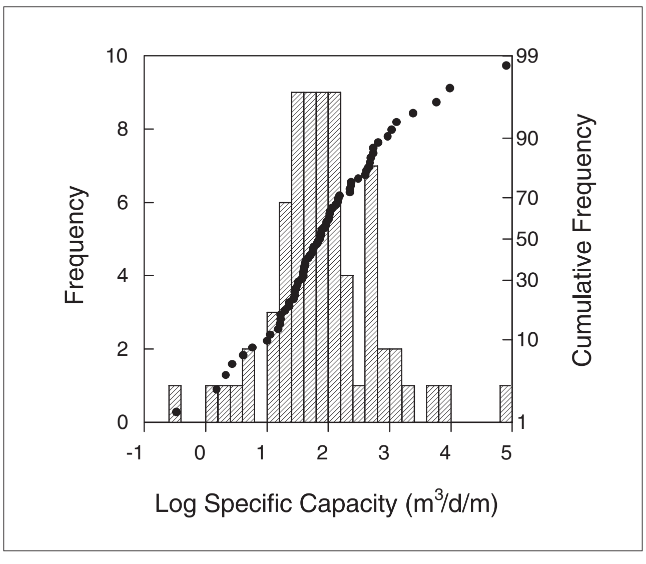


Figure 7.3.10 Distribution of specific capacity data from the Permo-Triassic sandstones in the West Midlands.

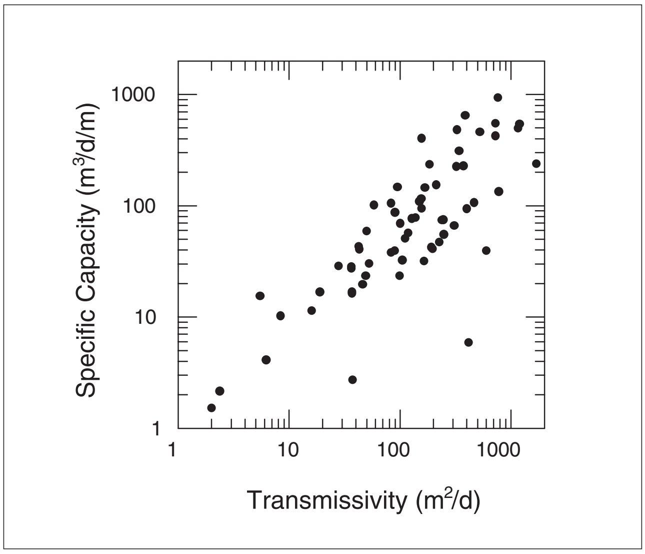


Figure 7.3.11 Plot of specific capacity (uncorrected) against transmissivity for the Permo-Triassic sandstones of the West Midlands.

Yields

Boreholes in the Permo-Triassic Sandstones of the River Trent Valley with 0.7 to 1 m diameters commonly yield between 5000 and 10 000 m^3/d. Lower yields are found in the area between Ashbourne and Derby and the faulted strip of Cannock Chase Formation separating the Stafford and Needwood basins, north of Cannock Chase. At Burton-upon-Trent, where the Sherwood Sandstone Group is over 500 m below the surface, yields are also poor: 900 m^3/d to 1700 m^3/d with corresponding specific capacities of: $<$20 m^3/d/m. This is probably due to a lower intergranular hydraulic conductivity (Downing et al., 1970). In the Burton-upon-Trent area, the finer grained Bromsgrove Sandstone Formation does not give as good yields as the underlying Cannock Chase Formation. Supplies are usually only suitable for local purposes, although occasional deep bores give quite large yields (Stevenson and Mitchell, 1955). Around Coalville, the yields of public water supply boreholes vary from 1700 to 2700 m^3/d (Worssam and Old, 1981). In the Coventry area, along the western margin of the Hinckley Basin, the Sherwood Sandstone Group is represented solely by the Bromsgrove Sandstone Formation, which possesses little primary or secondary permeability in this region. Aquifer recharge is limited by extensive argillaceous drift cover and yields are generally very low, ranging from 260 to 520 m^3/d.

Model hydraulic conductivity

Knipe et al. (1993) modelled the Birmingham area as a single layer. The Bromsgrove, Wildmoor and Kidderminster Sandstone formations were treated as one unit, with a hydraulic conductivity of 1 to 1.5 m/d. This was multiplied by aquifer thickness to obtain transmissivity, the values of which ranged between 20 and 330 m^2/d. These are comparable to the seven pumping test derived transmissivities of the area, which varied between 65 and 370 m^2/d. Sensitivity analysis revealed that the model was far more reactive to river bed hydraulic conductivity and overall recharge than to transmissivity.

Layering

Layers of low hydraulic conductivity are likely to have a significant effect on regional flow patterns (e.g. Rushton and Salmon, 1993). Vertical head gradients may need to be large for water to pass through low conductivity zones. The combination of the slow but extensive vertical flow through marl bands and the significant horizontal flow through the more permeable zones allows a small number of boreholes to abstract water from a wide area. The low hydraulic conductivity bands spread the effect of pumping more evenly across the aquifer.

In the vicinity of boreholes, the presence of low hydraulic conductivity bands may increase drawdowns because large groundwater head gradients are required to draw water vertically through low hydraulic conductivity zones. Small increases in abstraction rate may result in significant increases of drawdown.

Rushton and Salmon (1993) used a layered radial-flow model to represent the groundwater conditions of the Kidderminster, Wildmoor Sandstone, and Bromsgrove Sandstone formations at Bromsgrove. The modelled sandstone vertical and horizontal hydraulic conductivities were 0.3-0.5 and 1 m/d respectively, and the interbedded marl vertical hydraulic conductivity was 0.001 m/d. The field measurements since, 00 were reproduced adequately by the model.

In contrast, a single layer model required a horizontal hydraulic conductivity of less than 0.3 m/d in order to reproduce piezometric heads. However this resulted in the spring flows becoming too low, and the modelled drawdowns in the abstraction wells became excessive. The success of the multi-layered model relative to the single-layer one demonstrated that bands of low hydraulic conductivity critically affect the groundwater flow. Rushton and Salmon (1993) concluded that three-dimensional models should be used whenever possible for such aquifers, thus incorporating the effect of vertical flows through low conductivity zones.

Summary

Core permeametry measurements show that grain size has a control on intergranular hydraulic conductivity with finer grained horizons being less permeable. The significance of fracture flow to boreholes is demonstrated by comparing core data with pumping test data, and by a packer test at Cow Lane. The packer test hydraulic conductivity varied non-uniformly with depth, reflecting the layered and fractured nature of the Bromsgrove Sandstone Formation. Computer groundwater flow models which incorporate vertical layering most successfully reproduce piezometry. The ranges obtained by the different methods of measuring hydraulic conductivity are compared in Table 7.3.5. The model values lie to the high end of the core data range and to the low end of the pumping test data range.

7.3.3 Porosity and storage

Core porosity

Porosity data measured on West Midlands Permo-Triassic sandstone core samples show considerable variation, ranging from 2% to 36%. The range and variability can be attributed to the differing sizes, degrees of sorting and roundness of the sand grains, and to the extent of weathering and diagenesis. Statistical information from the Aquifer Properties database is given in Table 7.3.6, and is considered on a formation basis. The maximum porosity values of the formations are similar, at around 35%. Minimum porosities are far more variable, and are dependent principally on the degree of cementation — however despite this the data suggest that the average porosities of the formations are not dissimilar, with arithmetic means in the range 24% to 28% and median values of 26% to 30%.

Variation with formation

Although the Bridgnorth Sandstone Formation has a porosity range of 17 to 34%, most of the values are high, lying in the 26 to 24% range (Figure 7.3.12a). Such high

Table 7.3.5 Comparison of hydraulic conductivity values from different methods.

Measurement method	Scale	Hydraulic conductivity (m/d)	
		Range (m/d)	Geometric mean(s)
Core permeametry	Intergranular	10^{-6}–20	0.4–1.0
Packer–matrix	Intergranular	0.1–1.0	—
Packer–fracture	Fracture	1.4–2.5	—
Pumping test	Borehole	0.014–490	1.6–8.1
Model	Regional	10^{-3}–1	—

Table 7.3.6 Core porosity data for the Permo-Triassic sandstones of the West Midlands.

Formation	Range (%)	Interquartile range (%)	Median (%)	Arithmetic mean (%)
Bromsgrove Sandstone	8.0–36.2	25.7–29.7	27.4	26.8
Kidderminster Sandstone	3.6–33.8	19.6–28.4	25.7	23.8
Wildmoor Sandstone	17.6–35.3	24.2–28.2	26.9	26.4
Bridgnorth Sandstone	16.6–33.6	27.5–31.8	29.5	28.4

porosities can be attributed to the lack of cementation. In contrast, the Kidderminster Formation/Cannock Chase Formation etc. (Figure 7.3.12b) is widely cemented and has porosities as low as 4%. It has a highly negatively skewed normal distribution, with a maximum value of 34%: the high values are correspond to the coarse-grained and more-friable sands (Lovelock, 1977).

The Wildmoor Sandstone has a porosity range of 18 to 35% (Figure 7.3.12c); the values are approximately normally distributed. Porosity is reduced by silt and clay constituents and by cementation. Higher values are found in the less-cemented friable zones, and in the clean medium-grained sands. The porosity range of the Bromsgrove Sandstone Formation (Figure 7.3.12d) is 8% to 36%; the distribution having a slight negative skew. Well cemented fine-grained sands have the lowest porosities, higher values correspond to clean well sorted medium-grained sands. Many of the coarse sands have patchy cementation, which reduces their potential porosity (Lovelock, 1977).

Porosity and hydraulic conductivity

Figures 7.3.13a to d shows the relationships between core porosity and log hydraulic conductivity from the aquifer properties database for the different formations. There is a variable degree of correlation. Rocks with the same porosity but with different grain size, shapes and lithological contents can behave differently in relation to fluid flow. Pore throat sizes, and surface retention and capillary forces around and between grains, particularly clay and micaceous grains, help to cause these variations (Ramingwong, 1974).

Pumping test storage coefficients

The database has values of storage coefficient from 11 sites in the West Midlands region, ranging from 2×10^{-4} to 0.15. The geometric mean and median are 2.5×10^{-3} and 1.6×10^{-3} respectively. The interquartile range of the storage coefficient histogram (Figure 7.3.14) is 1.0×10^{-3} to 0.01. These values are typical of Permo-Triassic sandstones, with unconfined (specific yield) values being rare, even in unconfined strata.

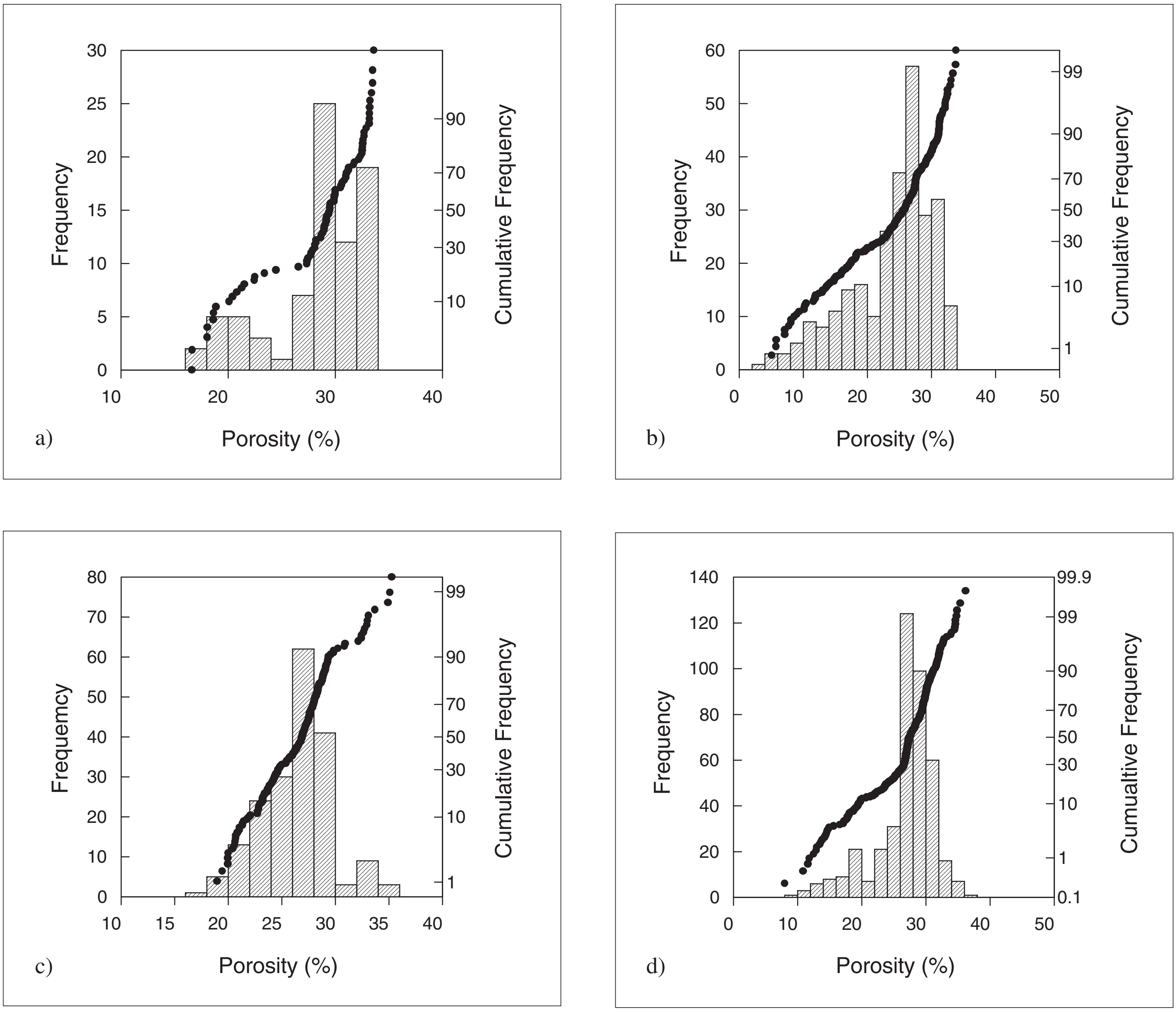


Figure 7.3.12 Distribution of porosity data for Permo-Triassic sandstone samples from the West Midlands, a) Bridgnorth Sandstone Formation, b) Kidderminster Sandstone Formation (and local equivalent), c) Wildmoor Sandstone Formation, d) Bromsgrove Sandstone Formation.

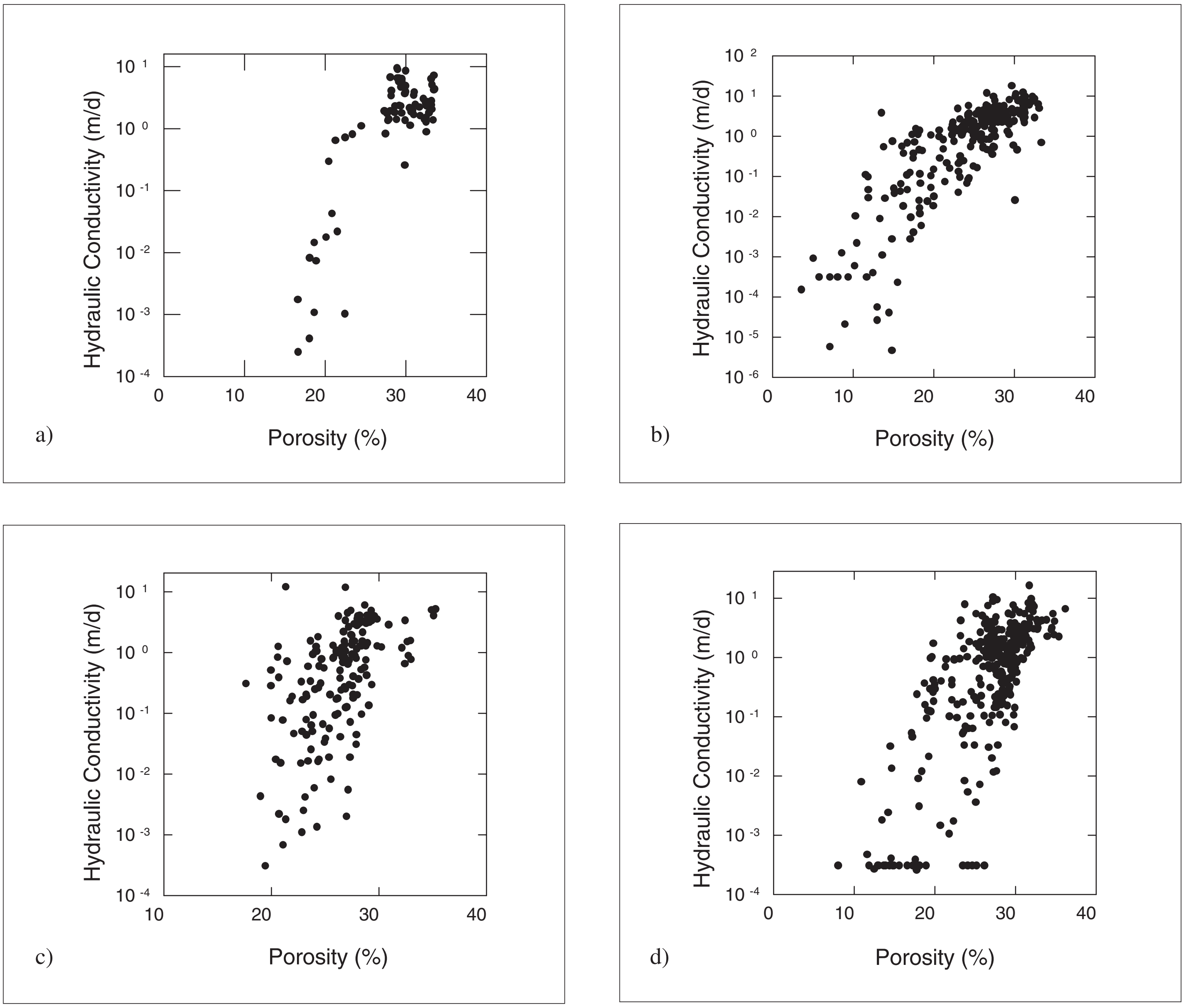


Figure 7.3.13 Plots of hydraulic conductivity against porosity for Permo-Triassic sandstone samples from the West Midlands, a) Bridgnorth Sandstone Formation, b) Kidderminster Sandstone Formation (and local equivalents), c) Wildmoor Sandstone Formation, d) Bromsgrove Sandstone Formation.

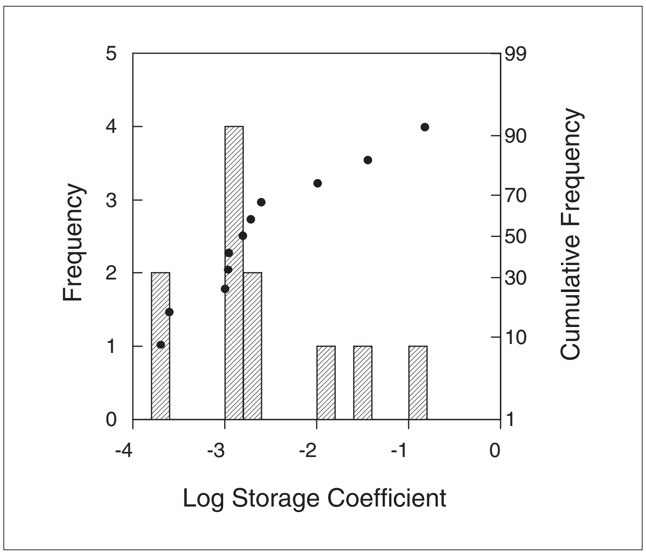


Figure 7.3.14 Distribution of storage coefficient data from pumping tests in the Permo-Triassic sandstones of the West Midlands.

Specific yield

The specific yield (Sy) of the Sherwood Sandstone Group within the Nurton faulted block (Section 7.3.1) can be calculated as 0.12, assuming that it equals the discharge rate (Q) per drawdown rate (s/t) per faulted block area (A),

i.e. $Sy = Q/(s/t \times A)$

where $Q = 8340\ m^3/d$ (8 Ml/d)...........recorded
$s/t = 0.1$ m /day ....recorded
$A = 0.7\ km^2$...........................modelled

Model storage

A confined storage coefficient of 5×10^{-4} and a specific yield of 0.15 were used for the Birmingham model of Knipe et al. (1993). The latter equates with results from a one month pumping test at IMI in Witton [SP 078 920]. Similar values were used by Rushton and Salmon (1993). Their Bromsgrove aquifer model had a specific yield of 0.1. The underlying confined layers were assigned a storage coefficient of 1×10^{-4}.

Summary

There are no marked trends of porosity with depth in the Permo-Triassic sandstone aquifer in this region, but porosity and hydraulic conductivity are positively correlated. The specific yield value used in the Birmingham model is comparable to that calculated from the draining of the faulted block at Nurton, and reputedly to that obtained from pumping test analysis. It is lower than the mean measured values of interconnected porosity. Storage coefficient values used for computer modelling of groundwater flow are of the same order as those present on the Aquifer Properties Database.

7.4 SHROPSHIRE

7.4.1 Introduction

Geological and geographical setting

General description

The area described lies within the catchment of the River Severn and encompasses Shrewsbury, Baschurch, Rednal, Wem, Hodnet, Shawbury and Longdon (Figure 7.4.1). The Permo-Triassic sandstone crops out on the southern rim of the Cheshire Basin, and is the region's major aquifer. It is under the jurisdiction of the Midlands Region of the Environment Agency.

This region is considered separately because of the distinctiveness of its geology and Permo-Triassic stratigraphy with respect to adjacent areas. The region is bounded to the west and south by older Palaeozoic or Precambrian rocks. To the east, the Permo-Triassic sequence of the West Midlands requires separate treatment due to its greater stratigraphical complexity. Paucity of information in the area between Ellesmere and Wrexham demarcates an appropriate northern boundary.

Previous investigations in Shropshire have focused on individual areas such as North and South Perry, North Shrewsbury, and Roden (Figure 7.4.2). There are no abrupt changes or clear-cut distinctions between the aquifer properties in these sub-areas, hence this text considers the region as a whole. Locations of places mentioned in the text are shown in Figure 7.4.1.

Regional structure

The area lies on the southern margin of the Cheshire Basin, a fault-bounded sedimentary basin which experienced at least two major phases of subsidence during the Permian and Triassic periods. The Basin contains a thick infill of Permo-Triassic sedimentary rocks, overlying folded and peneplaned Carboniferous strata. Local thickness changes within the Permo-Triassic sequence reflect fault movements during deposition (Downing and Gray, 1985).

Stratigraphy

The current and previous stratigraphical nomenclature are detailed in Table 7.4.1. The Permo-Triassic Sherwood Sandstone Group in the Shropshire region is subdivided into four formations, each of which is laterally persistent and characterised by different hydraulic properties. The formations are, in upward succession: the Kinnerton Sandstone, the Chester Pebble Beds, the Wilmslow Sandstone and the Helsby Sandstone (Warrington et al., 1980).

The Kinnerton Sandstone Formation (formerly Lower Mottled Sandstone) probably spans the boundary between the Permian and Triassic systems. It consists mostly of

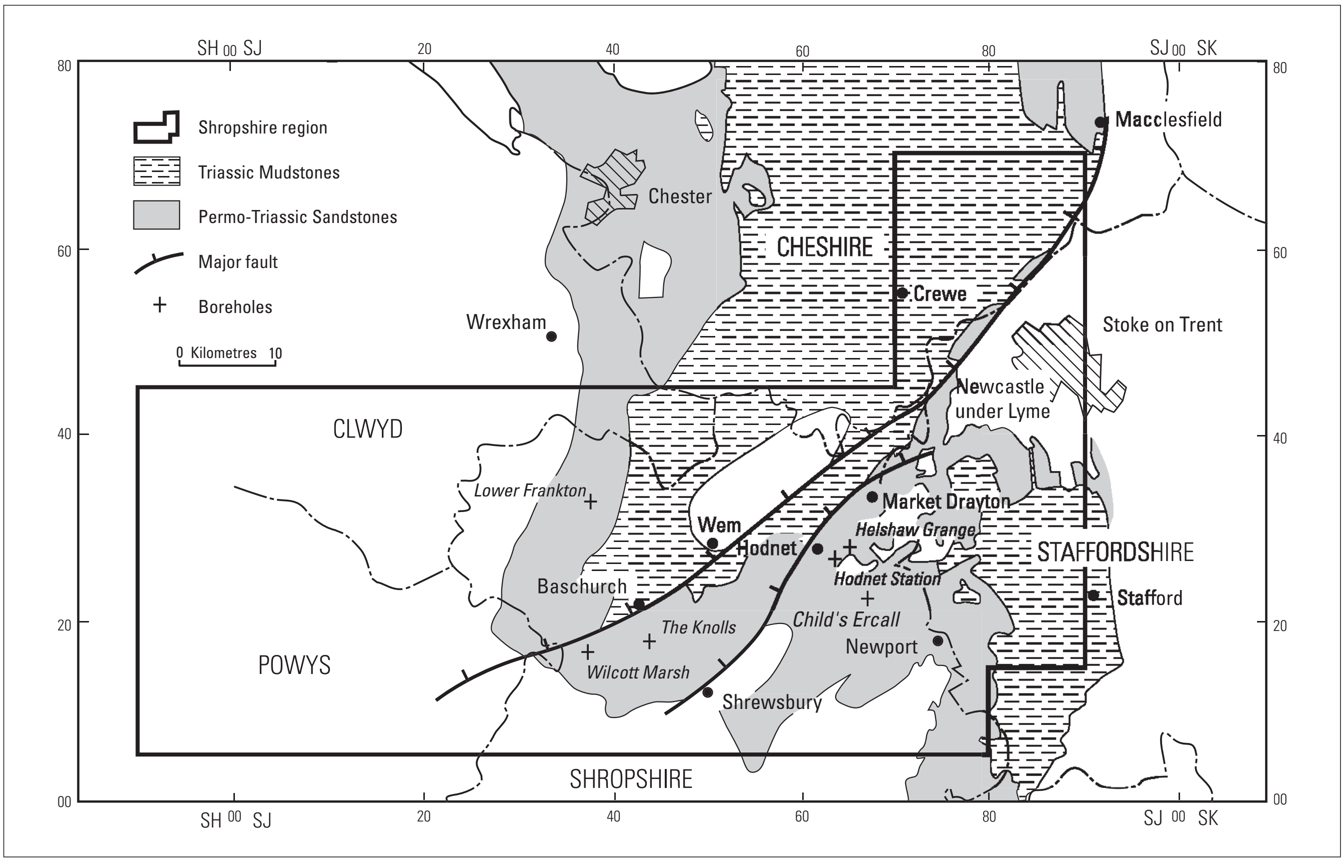


Figure 7.4.1 Shropshire — region covered and locations of places referred to in the text.

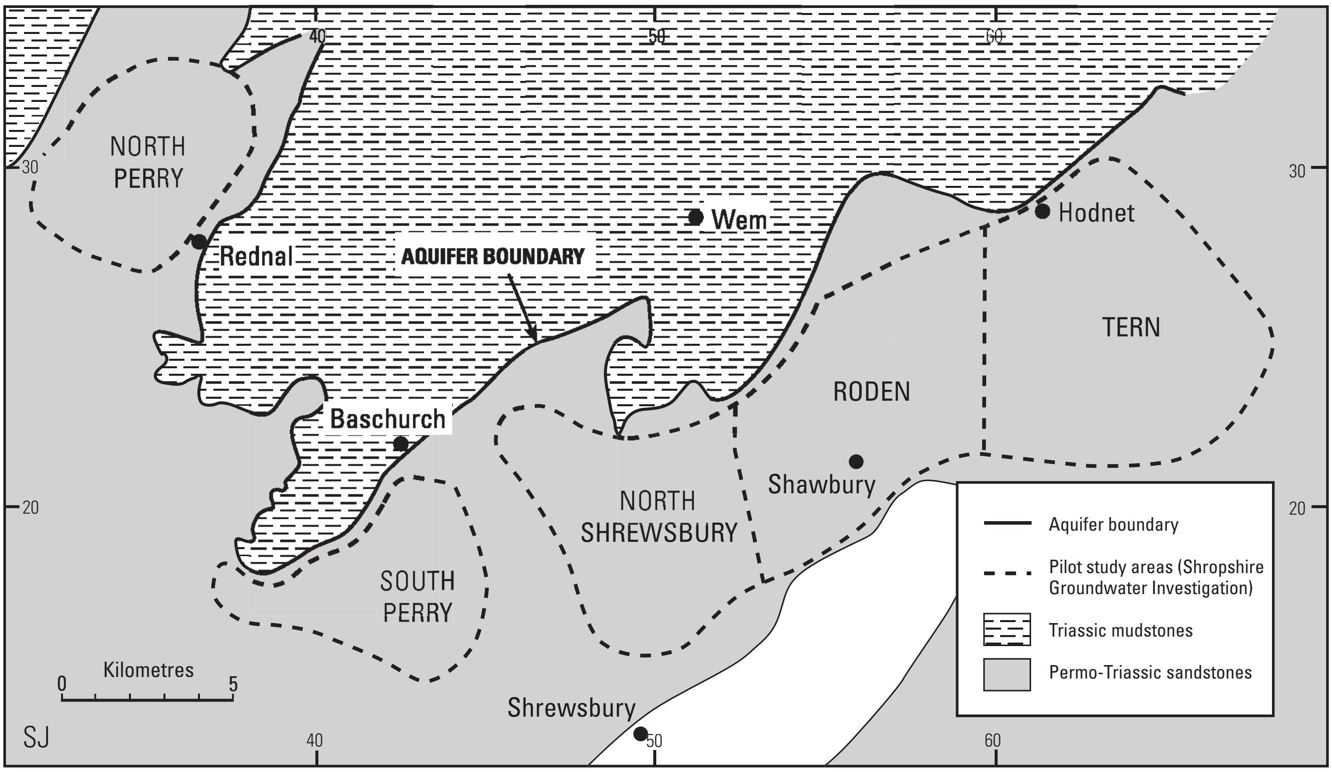


Figure 7.4.2 Areas of previous investigations in the Shropshire region.

Table 7.4.1 Permo-Triassic stratigraphy of Shropshire (after Warrington et al., 1980).

System and lithostratigraphical division			Previous name	Aquifer unit	Thickness (m)
TRIASSIC	Mercia Mudstone Group	Mudstone Unit	Keuper Marl	Aquitard	c.270
	Sherwood Sandstone Group	Helsby Sandstone Formation	Lower Keuper Sandstone	Aquifer	c. 20–200
		Wilmslow Sandstone Formation	Upper Mottled Sandstone		c. 200–425
		Chester Pebble Beds Formation	Bunter Pebble Beds		c. 90–300
PERMIAN		Kinnerton Sandstone Formation	Lower Mottled Sandstone		0–300

low-angle cross-stratified sandstone with subordinate siltstone, the latter becoming more common towards the top. Medium- to coarse-grained, well-sorted sandstones with well-rounded, 'millet-seed' grains are present in the bottom half of the formation (Lovelock, 1977).

The Chester Pebble Beds Formation (formerly Bunter Pebble Beds) consists mainly of reddish brown, cross-stratified coarse-grained sandstones with variable quantities of pebbles interspersed throughout. Mudstone beds occur sporadically within the formation (Lovelock, 1977). Gamma ray logs through the formation, conducted in ten boreholes in the Tern area, show only minor fluctuations in response, with no definite indication of mudstone beds (Severn River Authority, 1972).

The Wilmslow Sandstone Formation (formerly Upper Mottled Sandstone) is generally the thickest unit within the Sherwood Sandstone Group in the Shropshire region, and resembles the Kinnerton Sandstone Formation in lithology.

The overlying Helsby Sandstone Formation (formerly Lower Keuper Sandstone) is comparatively thin and more complex lithologically. It consists of a series of upward-fining units, each typically consisting of reddish brown conglomerate or breccia at the base, passing upwards into coarse- to fine-grained sandstone and finally into green or red mudstone. The Helsby Sandstone Formation is overlain by the mudstone-dominated lithologies of the Mercia Mudstone Group, which forms the upper part of the Permo-Triassic sequence in the region.

Superficial (drift) deposits of Quaternary age locally cover the Permo-Triassic strata. Drift cover in the Tern area is generally thin and patchy. The River Perry areas are extensively covered by drift, up to 100 m thick in the north. Much of the drift lies within glacially carved channels, which have cut down into the Permo-Triassic deposits. The Roden and North Shrewsbury areas also have drift cover (Severn Trent River Authority, 1978).

Faults

The major faults displacing the Permo-Triassic strata in the region are the Wem and Hodnet faults, both of which have a south-west to north-east trend with downthrows to the north-west. Minor north-south trending faults also occur. The Wem Fault throws the Mercia Mudstone Group against the Sherwood Sandstone Group at Baschurch. The Hodnet Fault juxtaposes the Sherwood Sandstone Group against Longmyndian and late Carboniferous strata near Shrewsbury, and against the Mercia Mudstone north of Hodnet (Fletcher, 1977).

Hydrogeology

The Permo-Triassic sandstone of Shropshire acts as a single aquifer. Unlike the north of the Cheshire Basin, there is no Permian marl present, and hence the Triassic and Permian strata, as well as their constituent formations, are in hydraulic continuity.

The Kinnerton Sandstone Formation's uniformity and thickness, together with its high porosity make it ideal for water supply. It is soft enough to make drilling straightforward but will generally stand open without screening. The Chester Pebble Beds Formation has a generally lower porosity and is more cemented, with much lower hydraulic conductivity than the underlying Kinnerton Sandstone Formation. Despite being difficult to drill, it is nevertheless widely exploited (Fletcher, 1977).

The thick, dominantly fine-grained Wilmslow Sandstone Formation has similar properties to the Kinnerton Sandstone Formation. Marl bands exaggerate vertical anisotropy. The Helsby Sandstone Formation comprises a complex sequence of conglomerates to fine-grained sandstones and mudstones (Lovelock, 1977).

Hydraulic significance of faults

Where large displacements cause juxtaposition of permeable and impermeable strata, the hydraulic continuity across a fault can be broken or significantly reduced. For instance groundwater flow is affected at Hodnet, where the Hodnet Fault causes the Sherwood Sandstone Group to be set against the Mercia Mudstone Group (Fletcher, 1977). Faults which do not interrupt sandstone continuity have not been observed to significantly affect groundwater flow (Fletcher, S, personal communication).

Previous hydrogeological investigations

North Shropshire was studied intensively between 1971 and 1978 during the 'Shropshire Groundwater Investigation'. Three pilot areas were investigated, from west to east: the 'North and South Perry pilot areas', the 'Roden and North Shrewsbury pilot area', and the 'Tern pilot area' (Figure 7.4.2). The Tern area was studied first, the River Perry areas second, and the Roden and North Shrewsbury areas were investigated last (Severn Trent River Authority 1978). Fletcher (1977) produced an MSc thesis on the hydrogeological characteristics of the Sherwood Sandstone Group of North Shrewsbury, and Al-Sam (1973) analyzed Tern Catchment pumping test data.

7.4.2 Hydraulic conductivity and transmissivity

Core data

Frequency histograms of the British Geological Survey database core hydraulic conductivity values are given in Figure 7.4.3. These illustrate the hydraulic conductivity distribution of the Permian Kinnerton Sandstone Formation, and the three constituent formations of the Triassic Sherwood Sandstone Group. Table 7.4.2 gives the associated means and ranges from the database as well as information from other sources.

No consistent variation of core hydraulic conductivity with depth is observed in the top 140 m, from which the samples have been taken, hence depth is clearly not a major control on intergranular hydraulic conductivity. Histograms of core hydraulic conductivity for the different formations all show a significant negative skew, due to the presence of more low hydraulic conductivity values than extremely high ones. This is a result of lithological control; the presence of fine grains and cementation cause dramatic reductions in intergranular hydraulic conductivity.

Variation with formation

KINNERTON SANDSTONE FORMATION

The Kinnerton Sandstone Formation's hydraulic conductivity has the biggest range of all the Permo-Triassic sandstone formations: from 2×10^{-5} to 15 m/d (Table 7.4.2), with a median value of 0.44 m/d. The distribution (Figure 7.4.3a) has a strong negative skew. This large variation in properties reflects the lithological diversity. The low intergranular hydraulic conductivities correspond to the siltstones and very fine-grained sandstones of the upper part of the formation. Coarser 'millet-seed' sandstones occur at lower levels; these can have extremely high hydraulic conductivity values. Muddier sandstones have intermediate hydraulic conductivity values. The laminated nature of the sediments gives rise to strong permeability anisotropy.

Table 7.4.2 Core hydraulic conductivity data for the Permo-Triassic sandstones of Shropshire.

Group or Formation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Helsby Sandstone	1.5×10^{-3}–2.9	0.56–4.1	0.86	0.33
Wilmslow Sandstone	9.3×10^{-3}–6.0	0.056–1.13	1.28	0.70
Chester Pebble Beds	3.1×10^{-4}–15	0.1–3.4	1.5	0.57
Kinnerton Sandstone	2×10^{-5}–15	0.02–2.6	0.44	0.16

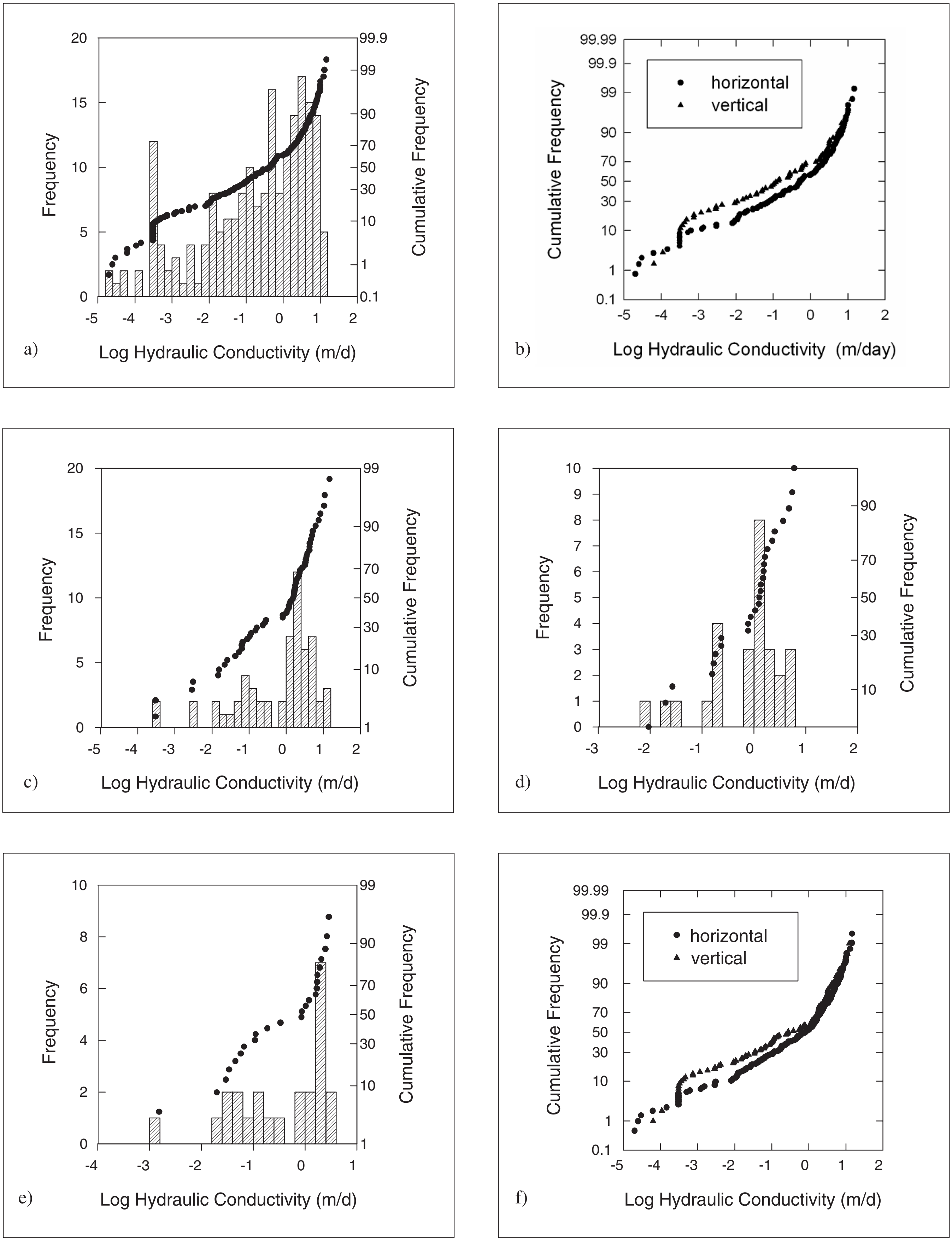


Figure 7.4.3 Distribution of hydraulic conductivity data for Permo-Triassic sandstone samples from the Shropshire region, a) Kinnerton Sandstone Formation — all samples, b) Kinnerton Sandstone Formation — horizontal and vertical samples, c) Chester Pebble Beds Formation — all samples, d) Wilmslow Sandstone Formation — all samples, e) Helsby Sandstone Formation — all samples, f) Sherwood Sandstone Group — horizontal and vertical samples.

Chester Pebble Beds Formation

The core hydraulic conductivities of the Chester Pebble Beds Formation show a log-normal distribution (Figure 7.4.3c), with a wide range of values, from 3.1×10^{-4} to 15 m/d. These reflect the degree of cementation more than grain size. Hydraulic conductivity is low where the cementation is well developed, and is much higher where there is less cementation. The arithmetic mean is 2.3 m/d, and the standard deviation is 3.0 m/d.

Wilmslow Sandstone Formation

The Wilmslow Sandstone Formation core hydraulic conductivity ranges from 9.3×10^{-3} to 6.0 m/d (Figure 7.4.3d), however data are limited. The dominantly fine-grained sandstones occur in both cemented and uncemented states. Cemented samples have lower hydraulic conductivities than the cemented ones (Lovelock 1977). The average hydraulic conductivity is 1.6 m/d, with a standard deviation of 1.6 m/d.

Helsby Sandstone Formation

The Helsby Sandstone Formation has least core data. The arithmetic mean hydraulic conductivity of the 24 samples is 0.99 m/d, with a standard deviation of 0.97 m/d. They range from 1.5×10^{-3} m/d to 2.9 m/d (Figure 7.4.3e). Low values are a result of cementation of the coarse sandstones at the base of the formation, and of very fine grain sizes towards the top of the formation, where it passes upwards into the Mercia Mudstone Group. Cross-stratified sands in the middle of the formation have the highest hydraulic conductivities.

Anisotropy

Horizontal and vertical core hydraulic conductivity distributions are plotted for the Kinnerton Sandstone Formation and the Sherwood Sandstone Group in Figure 7.4.3b and Figure 7.4.3e respectively, and statistics of the different distributions are given in Table 7.4.3. Horizontal values are usually greater than vertical ones. The ratio of the geometric means of horizontal and vertical hydraulic conductivity values gives the anisotropy ratio. This is 3 for the Kinnerton Sandstone Formation, and 2 for the Sherwood Sandstone Group. Although there may be relatively small differences between horizontal and vertical hydraulic conductivities within a horizon, the layered natures of the sandstones means that the aquifer as a whole may have a considerably greater anisotropy.

Geophysical borehole logs

The logging of ten boreholes in the Tern area is described by Severn River Authority (1972). Temperature logs showed a steady increase with depth with no sharp changes in the profile, other than at certain horizons in the Childs Ercall [SJ 665 233] and Helshaw Grange [SJ 634 291] boreholes. At Hodnet station [SJ 621 281] the caliper and television logs confirmed the existence of a large, near vertical fracture at a depth of 50 m and small fractures at 60 m and 64 m. The logs show that intergranular flow predominates, and that fracture flow is significant in some localities.

Pumping test transmissivity and bulk hydraulic conductivity

Transmissivity

The aquifer properties database contains transmissivity records from 112 sites in the Shropshire region. At each site there have been up to four different pumping tests; there is a total of 147 tests on record. There is no relationship between transmissivity value and length of pumping test.

The site transmissivity values range from 9 to 4770 m^2/d, and have an interquartile range of 97 to 440 m^2/d. The transmissivity histogram (Figure 7.4.4) shows a log-normal distribution and has a geometric mean of 200 m^2/d, and a median of 240 m^2/d.

Bulk hydraulic conductivity and the significance of fracture flow

In order to assess the significance of fracture flow, and to compare directly the different formations, the pumping test transmissivity data have been converted to bulk hydraulic conductivities using the methodology described in Section 7.1.4. This removes the thickness variable, by eliminating the effects of different borehole depths, distances

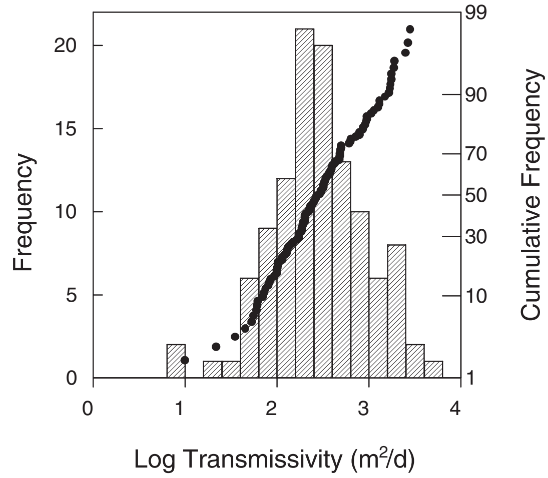


Figure 4.4.4 Distribution of transmissivity data from pumping tests in the Permo-Triassic sandstones of the Shropshire region.

Table 7.4.3 Horizontal and vertical core hydraulic conductivity data for the Permo-Triassic sandstones of Shropshire.

Group or formation	Orientation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Sherwood Sandstone Group	Horizontal	2×10^{-5}–15	0.06–2.62	0.82	0.31
	Vertical	6.2×10^{-5}–12	0.02–1.89	0.28	0.14
Kinnerton Sandstone Formation	Horizontal	2×10^{-5}–15	0.039–2.8	0.51	0.22
	Vertical	6.2×10^{-5}–12	2.9×10^{-3}–1.9	0.12	0.074

to the piezometric surface and thicknesses of confining layers. Thus bulk hydraulic conductivities can be directly compared with intergranular core data. Bulk hydraulic conductivities were determined for 98 sites, they range from 0.093 to 46 m/d, and have an interquartile range of 1.8 to 8.4 m/d (Table 7.4.4). The bulk hydraulic conductivity distribution is approximately log-normal (Figure 7.4.5a). The geometric mean is 3.9 m/d, and the median is 3.8 m/d.

The lower limit of bulk hydraulic conductivity is several orders of magnitude greater than the lower limit of core hydraulic conductivity data. This is a scale effect since core samples are at the centimetre-scale, which can consist entirely of low hydraulic conductivity sediments. Such layers do not however necessarily dominate the entire stratigraphy penetrated by an abstraction borehole. Thus on a borehole scale, the presence of higher hydraulic conductivity sediments, sometimes coupled with productive fractures, ensure that the minimum bulk hydraulic conductivities have a greater magnitude than minimum core hydraulic conductivities. The upper limit of bulk hydraulic conductivity is 31 m/d, which is higher than the upper limit for core data. These higher total borehole hydraulic conductivities are caused by fracture flow contributions.

Values of bulk hydraulic conductivity have been subdivided into those associated with the different formations (Table 7.4.4). As only data from those boreholes which penetrate a single formation can be used, the number of bulk hydraulic conductivity values for each formation is small. There are sufficient data to plot frequency histograms for the Kinnerton Sandstone Formation and the Pebble Beds Formation (Figures 7.4.5b, c). Both plot at and beyond the high end of the associated core hydraulic conductivity spectra (Figures 7.4.3a, c), indicating the significance of fracture flow within the formations. They have similar ranges: 0.093 to 24 m/d and 0.33 to 16 m/d respectively. This indicates that although formation type exerts a control on intergranular hydraulic conductivity, it does not exert a primary control on bulk hydraulic conductivity.

The above values of bulk hydraulic conductivity assume no flow from the aquifer beneath the borehole and may therefore be overestimates. Fletcher (1977) added 7 m to the actual borehole depths when calculating bulk hydraulic conductivities for six boreholes in the Roden and North Shrewsbury area. Bulk hydraulic conductivities of 1.0, 2.1, 7.6, 2.0, 1.4 and 1.8 m/d were obtained for the different sites, which were in better agreement with core hydraulic conductivity data from the Tern area. Nevertheless, a fracture flow component was attributed to Harcourt Mill, which had the anomalously high value of 7.6 m/d.

Pumping test analyses of cored boreholes in the Tern area showed that transmissivity variations reflect the variations in estimated thickness of saturated aquifer. This suggests that the hydraulic conductivity of the Sherwood Sandstone Group is fairly constant with depth throughout the area (Severn River Authority, 1972). Bulk hydraulic conductivities were calculated as 0.9 to 2.2 m/d. High hydraulic conductivity values were assumed to be due to deep and extensive weathering, which had presumably been developed during glaciation of the area, but which could also result from fracture flow.

Severn River Authority (1972) concluded, after comparing observations of cores, pumping tests and geophysical logging, that the Sherwood Sandstone Group in the Tern area is unlikely to be fractured on a large scale. The total flow is probably derived from a combination of intergranular and fracture flow. Worthington (1976) suggests field conductivity values of 0.3 to 2.5 m/d, which when compared to his geometric mean intergranular value of 0.3 m/d, also indicates a variable fracture contribution to transmissivity.

Pumping test case studies

Analysis of a four day constant rate test at The Knolls [SJ 423 173], South Perry area showed that leakage occurred from the overlying drift, where perched groundwater systems occur between 16 and 42 m below ground level. The transmissivity value was 200 m^2/d, the same as that at Wilcott Marsh [SJ 376 176], and typical of the South Perry aquifer. A transmisssivity of 25 m^2/d was obtained from nearby Aeksea [SJ 355 193], which was considered to be anomalous, possibly due to poor well development (Severn Trent River Authority, 1974).

A nine day pumping test at Helshaw Grange [SJ 634 292] in the Tern catchment, was conducted in order to investigate whether the River Tern acted as a recharge boundary. Nine observation holes were monitored. All showed a typical Theis type curve response with no indication of delayed yield or boundary effects. Water levels in two of the boreholes remained above the river level, indicating that the natural groundwater gradient had not been reversed. Although the river may act as a partial recharge boundary, leakage would only occur if pumping was carried out for longer, for example at least 100 days (Severn Trent Water Authority, 1978).

The drawdown-time responses of four observation wells for a constant rate test at Lower Frankton [SJ 366 312], in the south Perry Pilot area, all show a confined response. The effects spread rapidly in the confined aquifer and it was inferred that drawdowns were soon influenced by the two barrier boundaries of the Whittington and Hordley Faults. The observation wells gave different transmissivity values, varying from 380 to 5320 m^2/d. The highest values may represent the transmissivity of the basal gravel unit of the drift which allows preferential flow (Severn Trent River Authority, 1978).

In summary, pumping tests are influenced by a variety of factors, such as leakage from overlying superficial deposits and impermeable faults. The way in which these are interpreted can affect the deduced values of the aquifer properties.

Specific capacity

The database has specific capacity records at 84 sites in the Shropshire region. It ranges from 1.9 to 3300 m^3/d/m, and has an interquartile range of 97 to 440 m^3/d/m. The log specific

Table 7.4.4 Bulk hydraulic conductivity data for the Permo-Triassic sandstones of Shropshire.

Formation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
All	0.093–46	1.8–8.4	3.84	3.94
Chester Pebble Beds	0.33–16	1.3–8.4	3.86	3.28
Kinnerton Sandstone	0.094–25	5.9–15	10.6	6.94

capacity histogram (Figure 7.4.6) exhibits an approximately normal distribution and has a geometric mean of 200 m^3/d/m. This is similar to the median, 240 m^3/d/m. Specific capacity shows a general increase with transmissivity, although they can vary by at least an order of magnitude (Figure 7.4.7). Specific capacity is affected by the same factors as was transmissivity, in addition to effects attributable to borehole radius and pumping duration.

Summary

Both lithology and cementation have a control on intergranular hydraulic conductivity. Temperature and flow logs show that fracture flow is significant in some, but not all, boreholes. Discrepancies between bulk and intergranular hydraulic conductivity values (Table 7.4.5) illustrate the local importance of fracture flow.

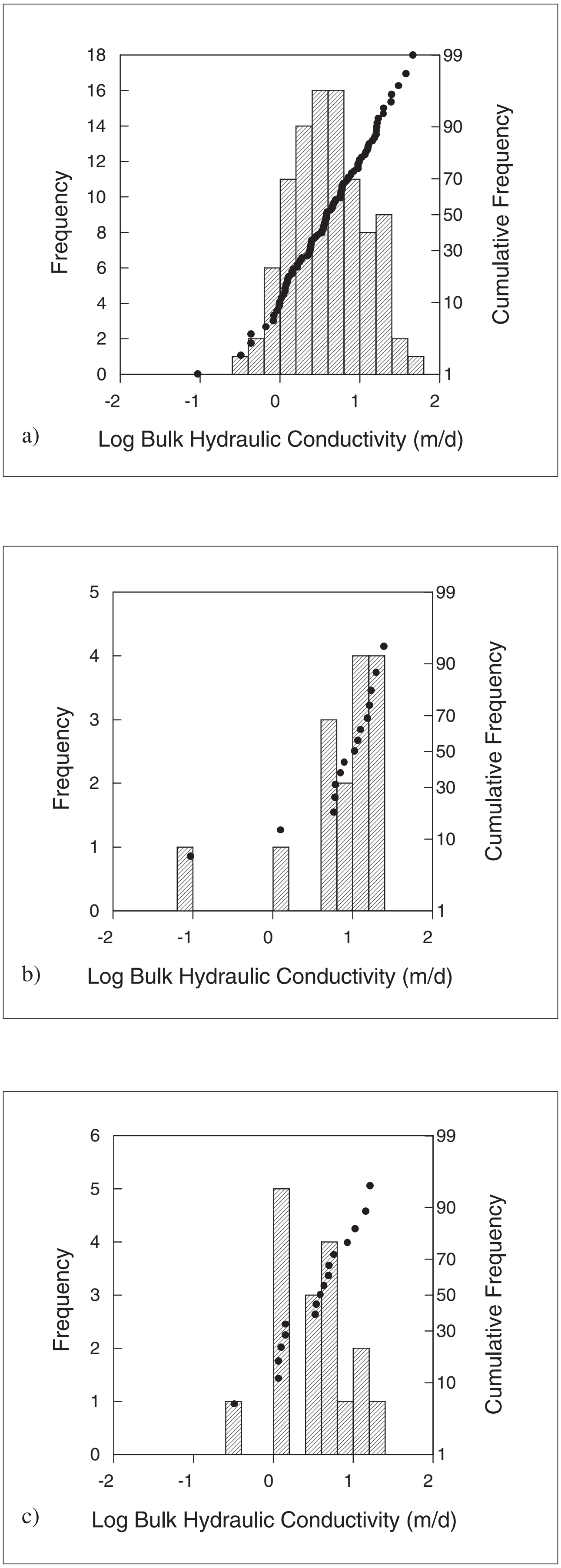


Figure 7.4.5 Distribution of bulk hydraulic conductivity data from pumping tests in the Permo-Triassic sandstones of the Shropshire region, a) Permo-Triassic sandstones, b) Kinnerton Sandstone Formation, c) Chester Pebble Beds Formation.

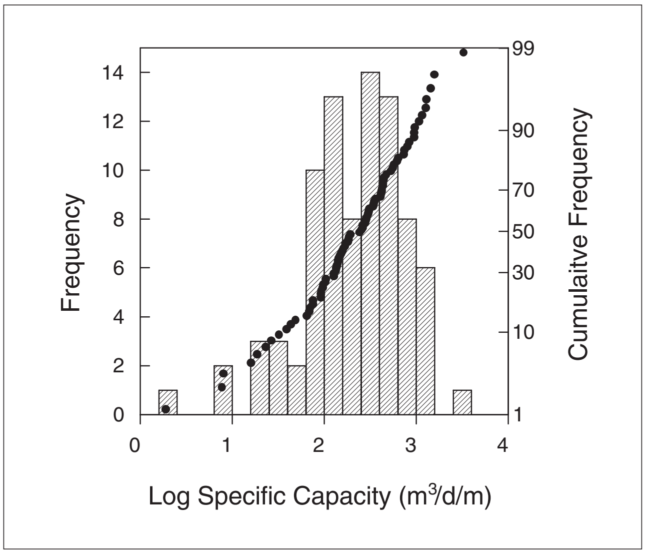


Figure 7.4.6 Distribution of specific capacity data from pumping tests in the Permo-Triassic sandstones of the Shropshire region.

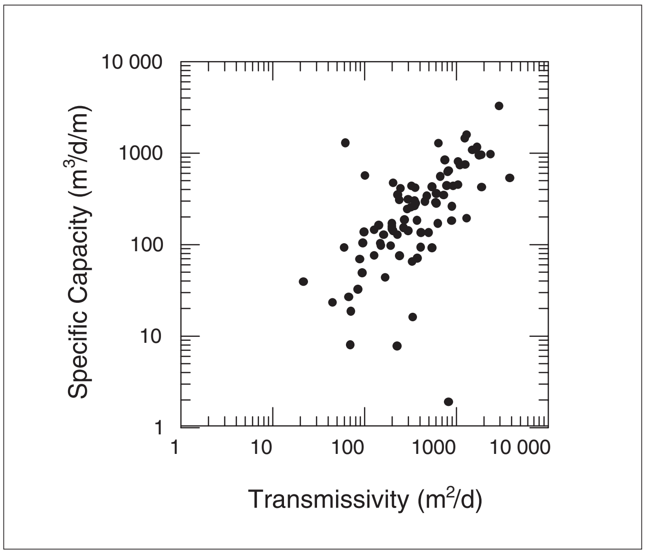


Figure 7.4.7 Plot of specific capacity against transmissivity for the Permo-Triassic sandstones of the Shropshire region.

Table 7.4.5 Comparison of hydraulic conductivities measured at different scales in the Permo-Triassic sandstones of Shropshire.

Measurement method	Hydraulic conductivity type	Hydraulic conductivity (m/d)	
		Range	Geometric mean(s)
Core permeametry	Intergranular	10^{-5} to 15	0.2–0.7
Pumping test	Bulk	0.09–50	4

7.4.3 Porosity and storage

Core porosity

Variation with formation

Porosity measurements are available from core samples. There is a considerable variation of core porosity values in the various Permo-Triassic sandstone formations, with a range from 5.5 to 34%. This variability can be attributed to variable cementation, the differing grain size, degree of sorting of the sediments, the degree of grain roundness, and to the extent of weathering. Figure 7.4.8 shows the frequency distributions of core porosities held on the British Geological Survey database and Table 7.4.6 presents relevant statistical information.

The Permian Kinnerton Sandstone Formation has an approximately normal porosity distribution which is slightly negatively skewed (Figure 7.4.8a). It has the biggest range of porosities of all the formations, varying from 6 to 34%. As with the hydraulic conductivity variations, the porosity variations can be attributed to a combination of grain-size and cementation, with the lowest values coming from cemented siltstones towards the top of the formation, and higher values coming from cement-free regions of the millet-seed sands.

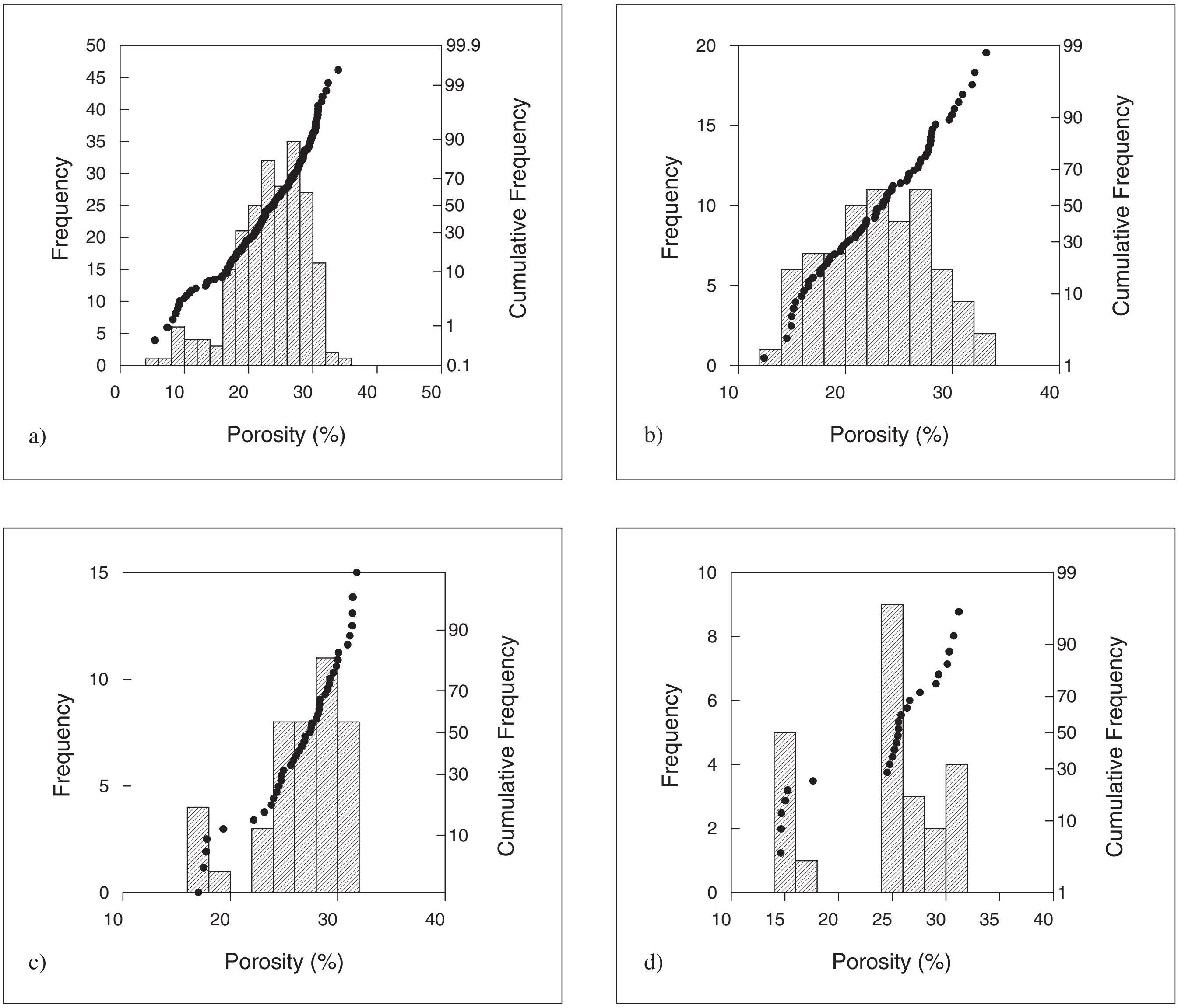


Figure 7.4.8 Distribution of porosity data for Permo-Triassic sandtone samples from the Shropshire region, a) Kinnerton Sandstone Formation, b) Chester Pebble Beds Formation, c) Wilmslow Sandstone Formation, d) Helsby Sandstone Formation.

Table 7.4.6 Core porosity data for the Permo-Triassic sandstones of Shropshire.

Formation	Range (%)	Interquartile range (%)	Median (%)	Arithmetic mean (%)
Helsby Sandstone	14.7–31.2	19.4–28.7	25.6	24.2
Wilmslow Sandstone	17.0–31.8	24.5–29.3	27.4	26.5
Chester Pebble Beds	12.4–33.2	19.4–27.1	23.5	23.2
Kinnerton Sandstone	5.5–34.0	20.0–27.6	23.9	23.2

The porosities sampled in the Chester Pebble Beds Formation range from 12 to 33%. Their distribution (Figure 7.4.8b) is approximately Gaussian, and is not skewed. Where cementation is developed, porosities are low. High porosities are associated with the coarser cleaner sands in areas where cementation is reduced.

The Wilmslow and Helsby Sandstone formations have similar porosity values, with ranges of 17 to 32% and 15 to 31% respectively. Their distributions (Figures 7.4.8 c and 7.4.8d) are not Gaussian; this may be due to the small sample sizes. Cementation and lithological variability cause the porosity variations.

Variation with depth and hydraulic conductivity

There is no evidence from the core porosity values in the database of a fall in porosity with depth in the upper 140 m of the aquifer. Plots of porosity against hydraulic conductivity are shown for the different formations in Figure 7.4.9. The correlation is strongest for the Wilmslow Sandstone Formation (Figure 7.4.9c). Although porosity

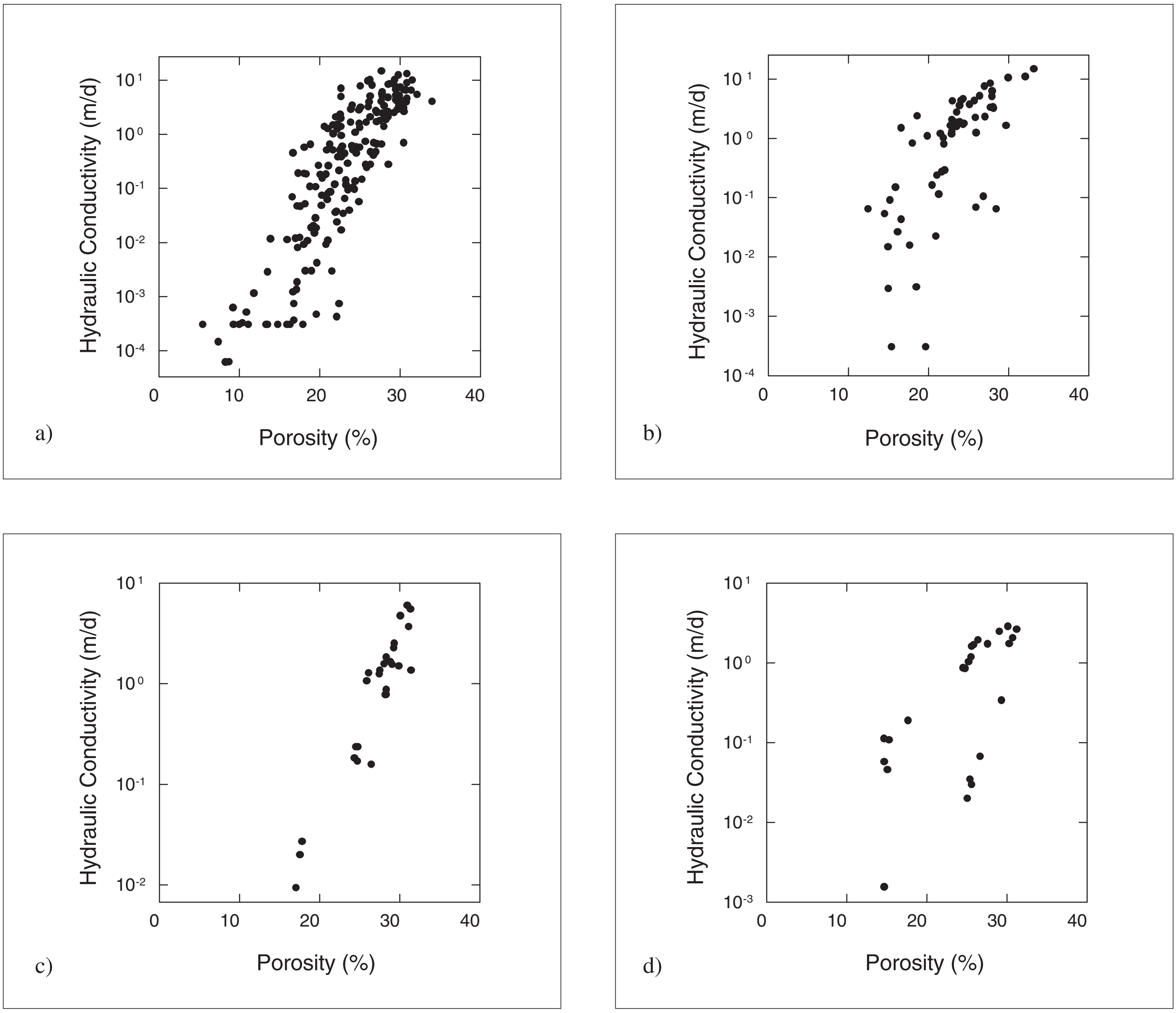


Figure 7.4.9 Plots of intergranular hydraulic conductivity against porosity for Permo-Triassic sandstones samples from the Shropshire region, a) Kinnerton Sandstone Formation, b) Chester Pebble Beds Formation, c) Wilmslow Sandstone Formation, d) Helsby Sandstone Formation.

generally increases with hydraulic conductivity, the hydraulic conductivity value associated with a particular porosity can vary by four or five orders of magnitude. This is because pore throat sizes affect hydraulic conductivity, whereas it is pore size that controls porosity. These in turn, are influenced to different extents by degree and type of cementation, and varying grain size, shape and sorting.

Pumping test storage coefficients

The database has storage coefficient values for 42 sites in the Shropshire region. The representative site values range from a confined storage values of 2.3×10^{-8} to a specific yield value of 0.19. The storage coefficient histogram (Figure 7.4.10) shows an approximately log-normal distribution (with the exception of three very low values); it has a geometric mean of 7.9×10^{-4} and a median value of 9.4×10^{-4}. The interquartile range is 3.5×10^{-4} to 3.8×10^{-3}. There is some correlation between storage value and pumping test length. In Figure 7.4.11, all pumping test analysis results are plotted against test length. Low storage values, of 10^{-4} and less, are not found in tests over 400 hours in length, probably due to delayed yield responses as discussed in Section 7.1.4.

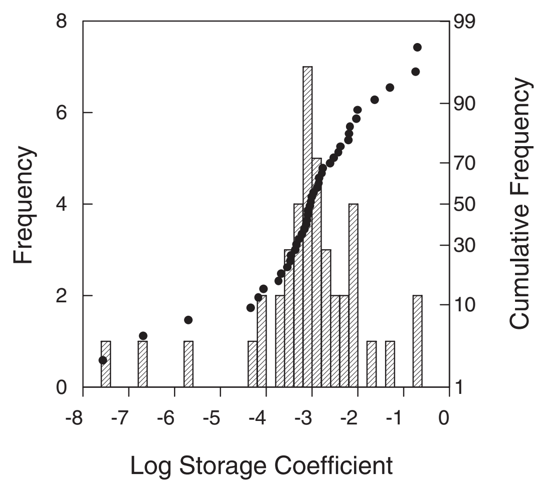


Figure 7.4.10 Distribution of storage coefficient data from pumping tests in the Permo-Triassic sandstones of the Shropshire region.

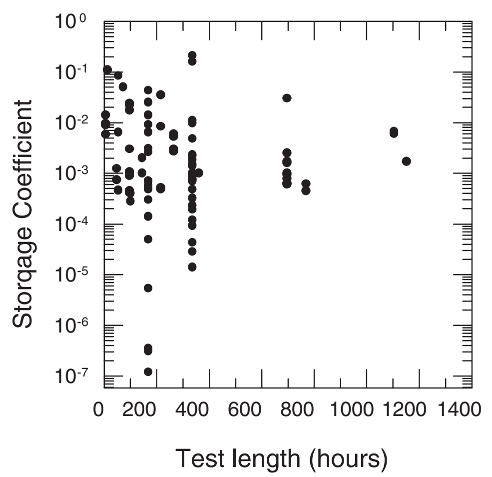


Figure 7.4.11 Plot of storage coefficient against pumping tests length for the Permo-Triassic sandstones of the Shropshire region.

Summary

The Permo-Triassic sandstones are variably confined with superficial deposits, through which leakage can occur. Porosities vary between formations; the Permian Kinnerton Sandstone Formation has the greatest range of values. Specific yield values lie within the porosity range.

7.5 CHESHIRE AND SOUTH LANCASHIRE

7.5.1 Introduction

Geological and geographical setting

General description

The region described encompasses Wrexham, Chester, Wirral, Liverpool, Warrington, Manchester, Ormskirk, Formby and Southport (Figure 7.5.1). It is under the jurisdiction of North West and Welsh Regions of the Environment Agency, and the Permo-Triassic sandstones comprise its major aquifer.

This region is considered separately because of the distinctiveness of its geology and Permo-Triassic stratigraphy with respect to adjacent areas. The Triassic Sherwood Sandstone Group in this region is subdivided into four formations (Warrington et al., 1980) each with different hydraulic properties. In contrast, no constituent formations are recognised within the group in the Fylde region to the north. Paucity of data for the region between Wrexham and Ellesmere demarcates an appropriate southern boundary with the Shropshire region.

Cheshire and south Lancashire can be subdivided into areas such as the Lower Mersey Basin, north Merseyside, Wirral, west Cheshire and Manchester (Figure 7.5.2), upon which previous investigations have focused. There are no abrupt changes or clear-cut distinctions between aquifer properties within the sub-areas, hence this text considers the region as a whole. The positions of locations mentioned in the text are indicated in Figure 7.5.1.

Regional structure

The area includes the majority of the Cheshire Basin, and the southern end of the West Lancashire Basin (Figure 7.5.3). Earth movements at the culmination of the Variscan Orogeny in late Carboniferous times resulted in local faulting and uplift associated with reactivated, basement faults. Rifting associated with the same faults took place in the Permo-Triassic, resulting in the rapid subsidence of both these basins and the accumulation of thick Permo-Triassic sequences. These infill a pre-Permian topography of folded and faulted Carboniferous rocks. The basins are bounded to the east by the Pennines and to the west by the Irish Sea and Welsh Borderlands. The West Lancashire Basin is the onshore extension of the northern Irish Sea Basin, and is connected *en echelon* to the Cheshire Basin.

The maximum depth to the base of the Permo-Triassic sediments exceeds 3 km in the West Lancashire Basin beneath the Ormskirk–Southport plain. The base of the Permo-Triassic sequence in the Cheshire Basin is at a depth of over 4 km to the north-east of Crewe, in excess of 1.2 km in the north of the north Merseyside area and about 0.7 km in the Lower Mersey Basin (University of Birmingham, 1981 and 1984).The preserved thickness of the Permo-

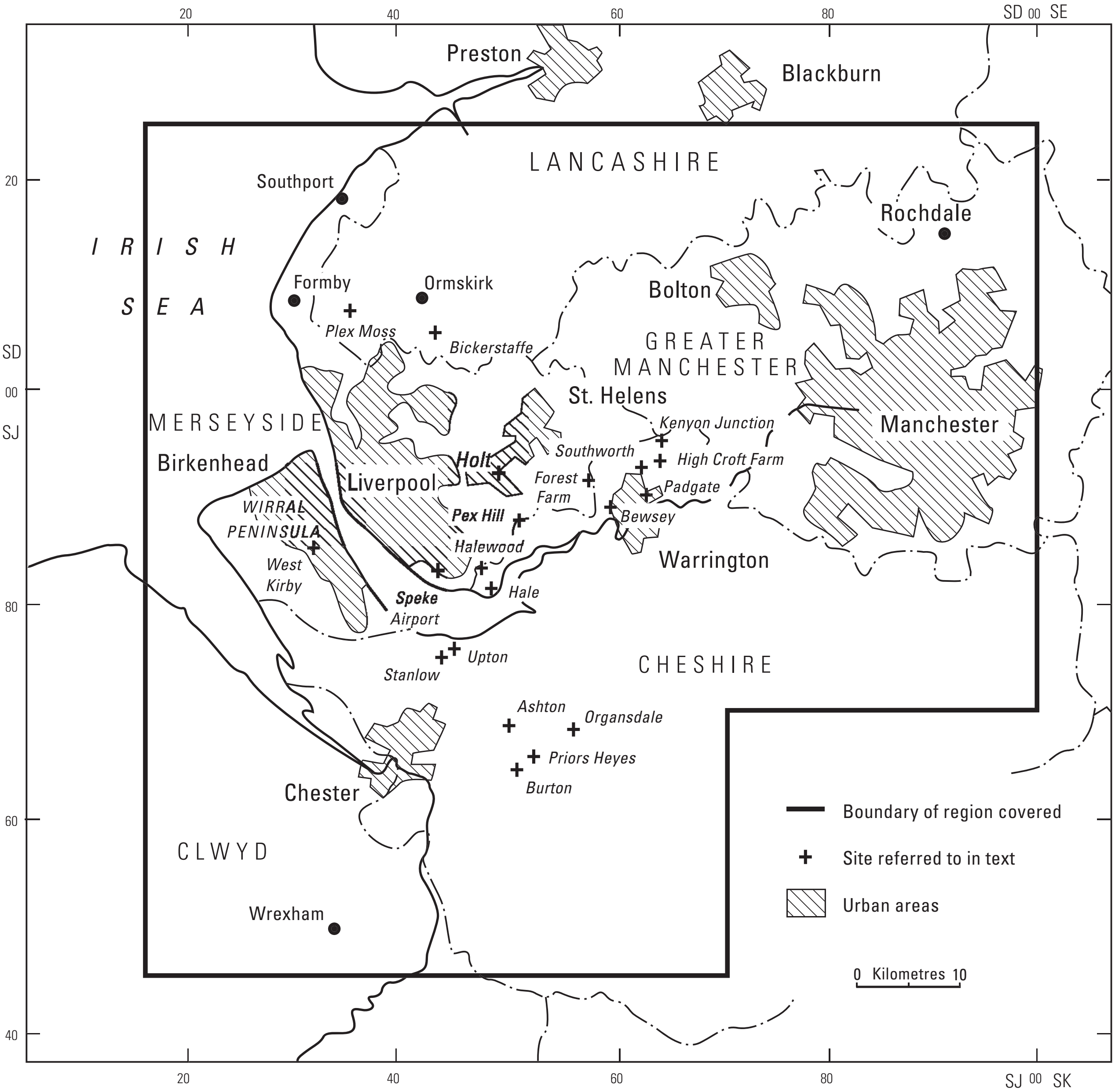


Figure 7.5.1 Cheshire and south Lancashire — region covered and locations of places referred to in the text.

Triassic in the Cheshire Basin declines westwards as the feather edge of the outcrop is approached.

Stratigraphy

The current and previous stratigraphic nomenclature is detailed in Table 7.5.1. The Permian Collyhurst Sandstone Formation consists of dune-bedded aeolian sandstone and corresponds to the lower part of the former Lower Mottled Sandstone unit. The overlying Manchester Marl Formation represents a marine incursion from the north in the late-Permian. The argillaceous and calcareous sediments of this formation become more sandy to the west, as it passes laterally into the interbedded sandstones and siltstones of the Bold Formation.

The Sherwood Sandstone Group in the region is subdivided into four formations, each of which is laterally persistent and characterised by different hydraulic properties. The formations are, in upward succession: the Kinnerton Sandstone, the Chester Pebble Beds, the Wilmslow Sandstone and the Ormskirk/Helsby Sandstone.

The Kinnerton Sandstone Formation (formerly Lower Mottled Sandstone) probably spans the boundary between the Permian and Triassic systems. It consists mostly of cross-stratified sandstone with subordinate siltstone, the latter becoming more common towards the top. The depositional environment was predominantly aeolian. In west Cheshire, where the Manchester Marl/Bold Formation is not recognised, the Kinnerton Sandstone Formation is not differentiated from the Collyhurst Sandstone Formation.

Both the base and top of the Chester Pebble Beds Formation (formerly Bunter Pebble Beds) are gradational and difficult to define. The formation consists mainly of reddish brown, cross-stratified, coarse-grained pebbly sandstone or conglomerate of fluvial origin. Sporadic beds and lenses of mudstone also occur.

The Wilmslow Sandstone Formation (formerly Upper Mottled Sandstone) is generally the thickest unit within the Sherwood Sandstone Group in the region. It consists of cross-stratified, pebble-free sandstone, strongly resembling

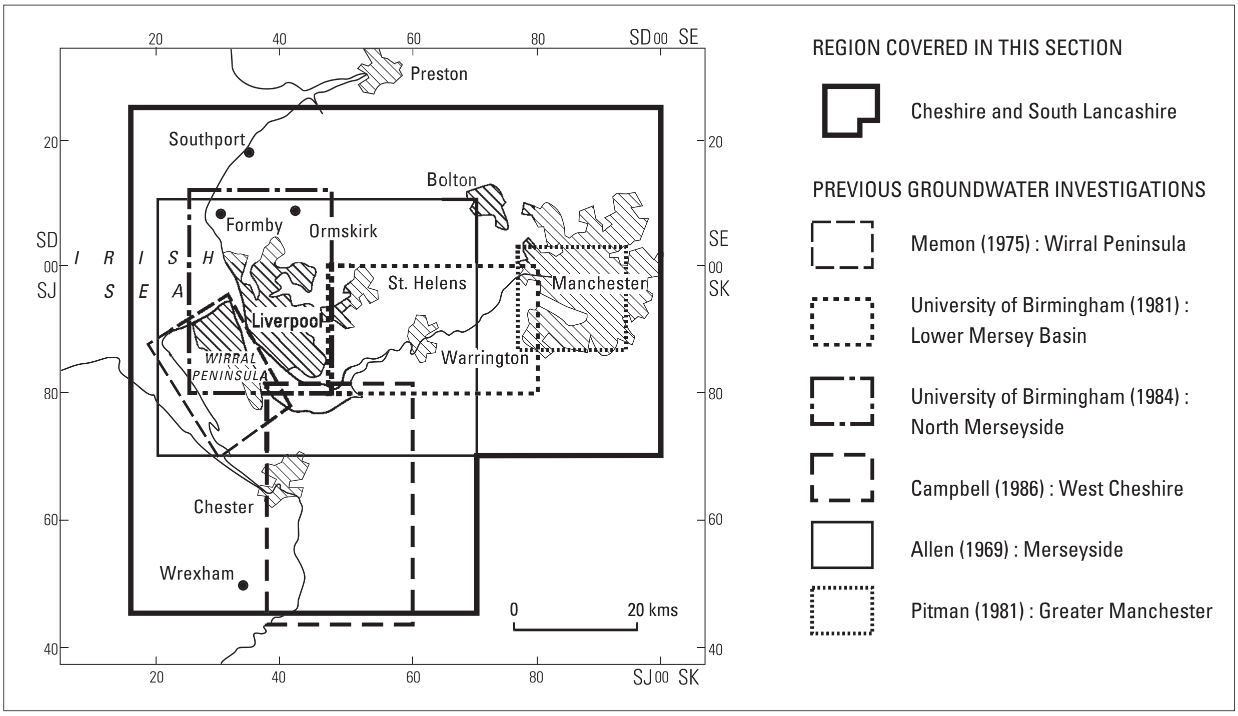


Figure 7.5.2 Areas of previous investigations in Cheshire and south Lancashire.

the Kinnerton Formation. The lower part of the formation is probably fluvial in origin, the upper part probably aeolian.

The base of the overlying Ormskirk/Helsby Sandstone Formation (formerly Lower Keuper Sandstone) is slightly disconformable. The formation consists mainly of sandstone, commonly pebbly, with subordinate mudstone; both fluvial and aeolian depositional environments are represented.

The Sherwood Sandstone Group is overlain by the mudstone-dominated lithologies of the Mercia Mudstone Group, which forms the upper part of the Permo-Triassic sequence in the region.

Formation thicknesses in Merseyside are detailed in Table 7.5.1. In west Cheshire, the Kinnerton/Collyhurst Sandstone (undivided) is up to 600 m thick in the Upton area, thinning towards the Aldersey inlier. The Chester Pebble Bed Formation ranges from 150 to 300 m in thickness; the Wilmslow and the Helsby Sandstone Formations have maximum thicknesses of 400 and 150 m respectively (Warrington et al., 1980).

Faults

The major faults of the Lower Mersey Basin and north Merseyside (Figure 7.5.4) are of normal style and trend north–south or north-west–south-east. Many faults have vertical displacements (throws) of 50 to 100 m; larger throws up to 300 m occur on the Croxteth, Kirkdale, Boundary, Eccleston, Winwick, and Warburton faults (University of Birmingham, 1981). Thickness changes of Permo-Triassic formations across some of these faults indicates syndepositional movement. The Wirral peninsular is intensely faulted, with major normal faults trending north–south with downthrows to the west. Minor faults trend east–west (Memon, 1975).

Major north–south-trending faults with large throws cross West Cheshire. The Eccleston Fault brings Carboniferous rocks to the surface around Aldersey [SJ 45 58]. The outcrop of the Sherwood Sandstone Group is fault bound to the east, where the Mercia Mudstone Group is downthrown against it.

Fractures

Joint surveys were carried out by University of Birmingham (1981) at Southworth Hall [SJ 61 93], Holt Lane [SJ 48 92] and Pex Hill [SJ 50 88] quarries, in the Chester Pebble Beds Formation. Bedding plane joints were predominant with relatively few vertical joints.

In the upper section of the aquifer, Quaternary weathering has reduced cementation to the extent that the sandstone has locally become friable and fractures are considered to be of secondary importance.

Hydrogeology

The major aquifer within the Permo-Triassic sequence is the Triassic Sherwood Sandstone Group (Table 7.5.1). Its four constituent formations are all in hydraulic continuity. Siltstones within the basal part of the overlying Mercia Mudstone Group and sandstones in the underlying Permian succession are also significant water bearing units.

The Permo-Triassic sandstones are generally well sorted and fine to medium grained. They are predominantly poorly cemented with high porosities. However, the pebbly horizons within the Chester Pebble Beds Formation and the Helsby/Ormskirk Sandstone Formation are generally more cemented, have lower porosities and are slightly less permeable than the rest of the Sherwood Sandstone Group (University of Birmingham, 1981). Their high strength relative to the other Permo-Triassic Formations causes more widespread and less random jointing (Lovelock, 1977).

Mudstones occur throughout most of the Sherwood Sandstone Group but are most common in the Chester Pebble Beds and the Ormskirk Sandstone formations. Individual mudstone beds are usually less than 0.5 m thick and probably laterally discontinuous. Thick mudstones may form local hydraulic barriers, but are unlikely to constitute regional barriers due to their limited extent.

Stratification within the Chester Pebble Beds Formation and parts of the Helsby Sandstone, due to the interlayering of siltstones and mudstones, can isolate layers of sandstone. This is particularly apparent in west Cheshire. The

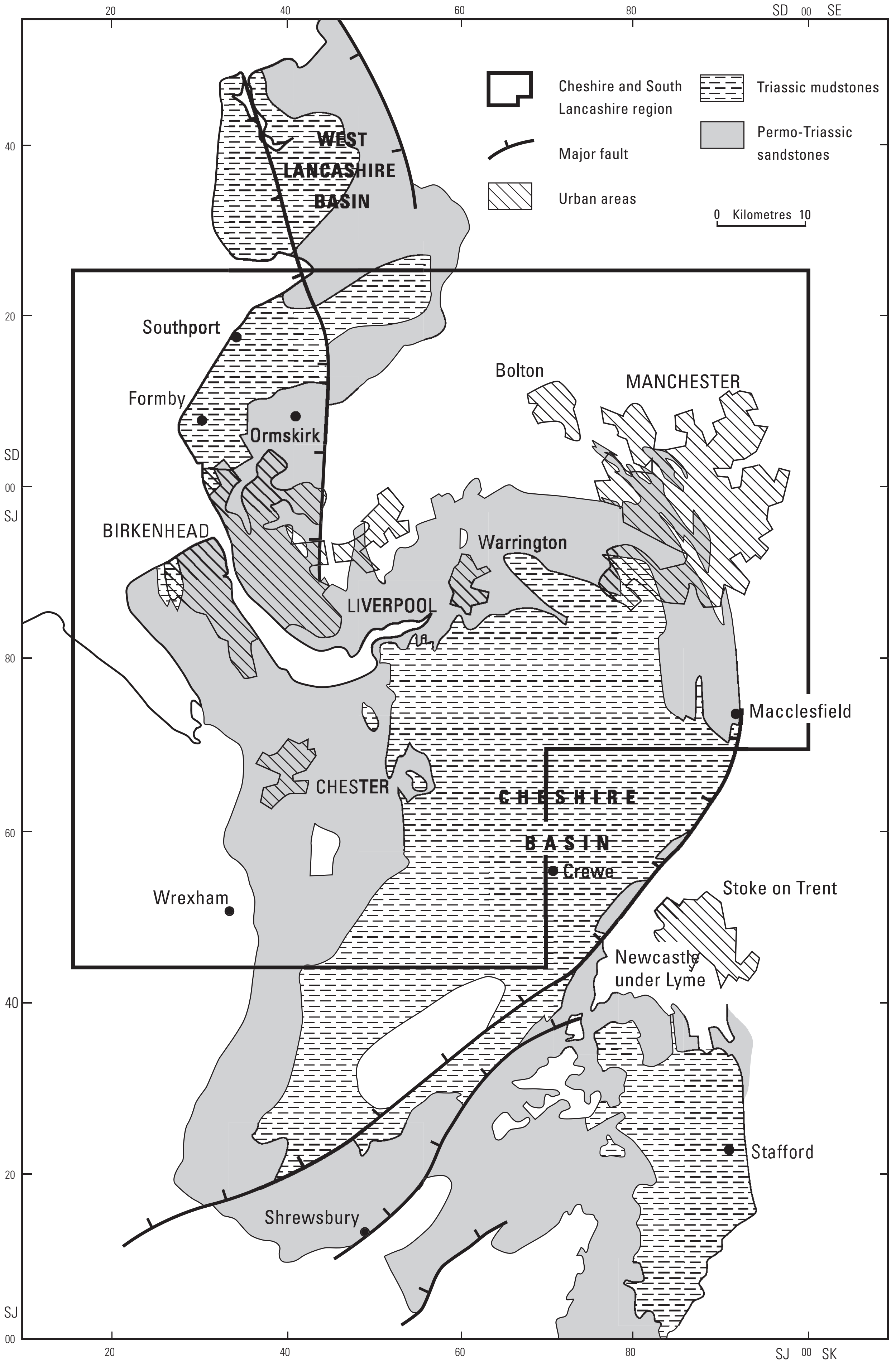


Figure 7.5.3 Geology and Permo-Triassic basins in Cheshire and south Lancashire.

Table 7.5.1 Permo-Triassic stratigraphy of Cheshire and south Lancashire (after University of Birmingham, 1981 and 1984).

System and lithostratigraphical division		Previous division	Aquifer unit	Thickness Lower Mersey Basin (m)	Thickness north Mersey-side (m)
TRIASSIC Mercia Mudstone Group	Mudstone Unit	Lower Keuper Marl	Aquitard	405	200
	Tarporley Siltstone Formation	Keuper Waterstones	Mainly aquitard	30–60	45–75
TRIASSIC Sherwood Sandstone Group	Ormskirk/Helsby Sandstone Formation	Lower Keuper sandstones	Aquifer	>181–295	100–120
	Wilmslow Sandstone Formation	Upper Mottled Sandstone		>205–480	280
	Chester Pebble Beds Formation	Bunter Pebble Beds		>316–375	145–420
	Kinnerton Sandstone Formation	Lower Mottled Sandstone (upper unit)	Aquifer	0–>80	10–80
PERMIAN	Manchester Marl Formation/ *Bold Formation*	Manchester Marls	Mainly aquitard/ *aquifer*	10–225	0–40/ *10–50*
	Collyhurst Sandstone Formation	Lower Mottled Sandstone (lower unit)	Aquifer	283–720	0–300

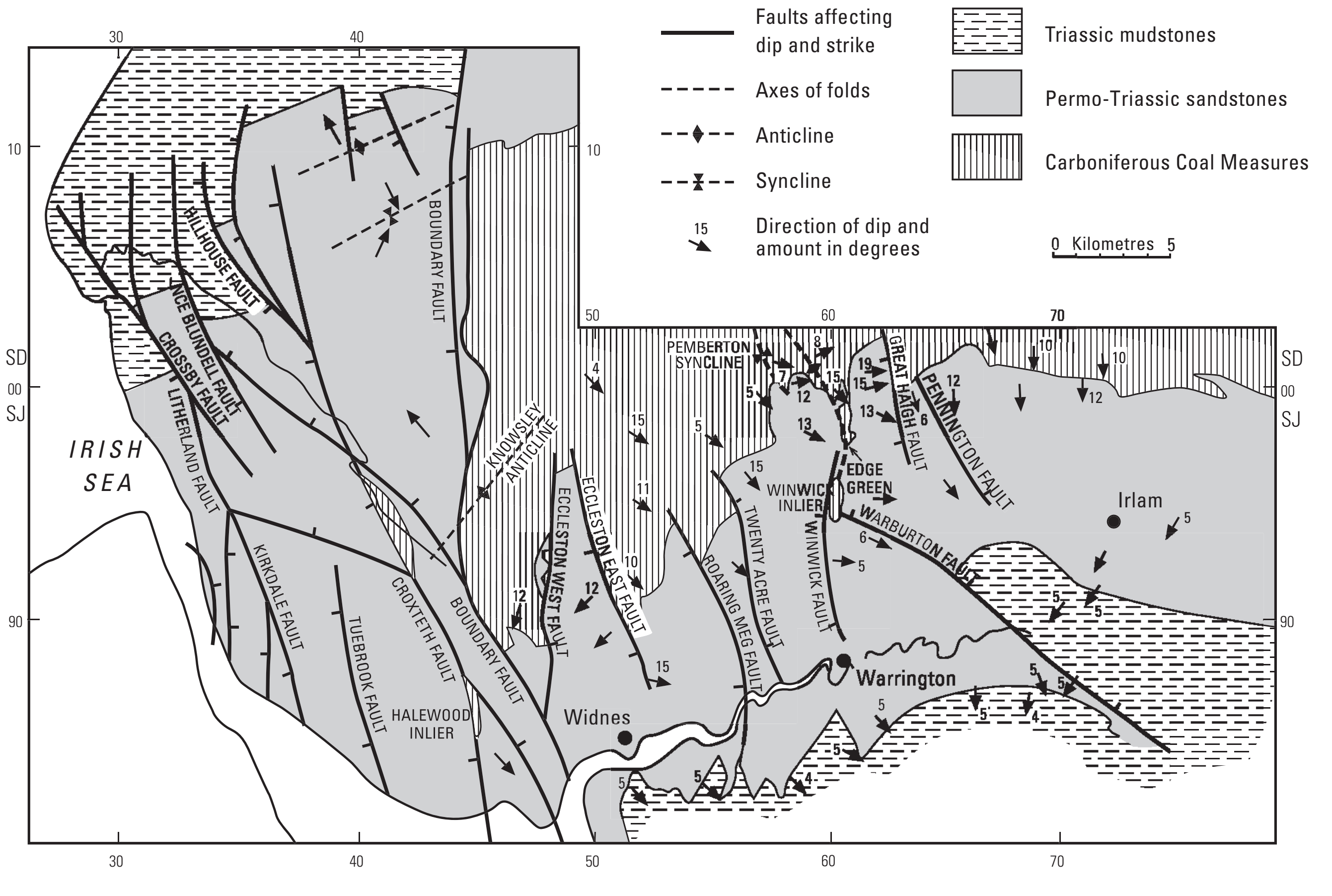


Figure 7.5.4 Structural features: north Merseyside and Lower Mersey Basin (after University of Birmingham, 1981).

confining effect can give rise to perched water tables, as documented from the Delamere and Peckforton Hills (Campbell, unpublished).

Collyhurst Sandstone Formation

The Collyhurst Sandstone Formation is present in Merseyside and south Lancashire. It is a fine- to medium-grained, well-sorted, poorly cemented sandstone with a high hydraulic conductivity. Its occurrence at great depth in most parts of the region limits its significance as an aquifer. Exploitation is limited to the outcrop area in south Manchester and Stockport. The formation becomes more important in this area because of its increased thickness relative to that further east and due to intense faulting which permits a free interflow at many points with the Sherwood Sandstone Group higher in the sequence (Campbell, J E, and Walthall, S, personal communication).

Bold/Manchester Marl Formation

The Bold/Manchester Marl Formation occurs in Merseyside and south Lancashire. It separates the Collyhurst Sandstone Formation from the overlying Sherwood Sandstone Group. It varies in thickness from 10 m in the south to 90 m in the Formby area, where it is at a depth of about 1000 m.

The Manchester Marl Formation consists mainly of mudstones of low hydraulic conductivity which inhibit vertical hydraulic continuity over much of the central and eastern parts of the Lower Mersey basin and Manchester area. Westwards, it passes laterally into the Bold Formation which becomes progressively sandier and more permeable. In the extreme west of the Cheshire Basin, (roughly west of the Eccleston East Fault), the Bold Formation cannot be differentiated from the sandstone formations above and below, bringing the Sherwood Sandstone and Collyhurst Sandstone aquifer units into hydraulic continuity.

Kinnerton Sandstone Formation

The Kinnerton Sandstone Formation is poorly cemented and fine to medium grained, with few mudstone lenses. In west Cheshire, the Manchester Marl/Bold Formation is not recognised, and the Kinnerton and Collyhurst Sandstones are therefore not differentiated.

Chester Pebble Beds Formation

The Chester Pebble Beds Formation consists of relatively well cemented and indurated, cross-laminated, medium- to coarse-grained pebbly sandstone with interbedded mudstone (University of Birmingham, 1981). It is the most significant aquifer unit and yields 1000–2000 m^3/d almost everywhere. Its competence results in most fractures staying open (Campbell, J E, and Walthall, S, personal communication). Drilling is straightforward and a stable-sided borehole can be constructed without casing.

Wilmslow Sandstone Formation

The Wilmslow Sandstone Formation is predominantly a cross-bedded, weakly cemented fine-grained sandstone with some interbedded medium- and coarse-grained layers. It crops out beneath the Mersey channel. In places, for example west Cheshire, it can be highly fractured within 150 m of the ground surface (Campbell, 1986). However, due to its poorly cemented and soft nature, it may not always be competent enough for fractures to stay open. Water supply boreholes penetrating it frequently pump sand (Campbell, J E, and Walthall, S, personal communication). Although borehole sides can collapse, casing is generally unnecessary.

Ormskirk/Helsby Sandstone Formation

The formation consists mainly of fine- to medium-grained, poorly cemented sandstone with subordinate beds of mudstone and conglomerate. It has been divided into three members: Thurstaston, Delamere and Frodsham. The middle unit, the Delamere Member, is absent in west Cheshire. It is softer and less pebbly than the members above and below and has similar hydraulic properties to the Chester Pebble Beds Formation (Campbell, J E, and Walthall, S, personal communication). Mudstone layers increase in abundance towards the top of the formation, so that anisotropy increases as the overlying Mercia Mudstone is approached. The formation as a whole is a poor aquifer relative to the Wilmslow Sandstone Formation and Chester Pebble Beds Formation (Peacock, A J, personal communication).

Tarporley Siltstone Formation

The Tarporley Siltstone Formation consists of interbedded sandstone, siltstone and mudstone organised into a series of fining-upward sequences. It represents a transitional facies between the Sherwood Sandstone and Mercia Mudstone groups, though is defined as part of the latter. Sandstone beds within the Tarporley Siltstone may form minor aquifers.

Effective aquifer thickness

There are several strands of evidence which indicate that the effective thickness of the Permo-Triassic Sandstone aquifer is less than its total thickness. The presence of deep old saline water, for instance at 800 m below sea level at Chester, suggests that groundwater flow may be insignificant at depth. Low vertical to horizontal permeability ratios, recorded in deep boreholes in west Cheshire, imply that the effective depth of the aquifer is not much deeper than the deepest production boreholes (Campbell, 1986).

The frequency of open fractures in Merseyside reduces markedly below depths of 100 to 200 m, again indicating that only a proportion of the total thickness may contribute significantly to the aquifer. Therefore, it has been suggested by University of Birmingham (1981) that for practical purposes the aquifer can be considered to consist of two zones: an upper, relatively permeable fractured zone extending to a depth of about 200 m below Ordnance Datum, and a deeper, low hydraulic conductivity zone with only minor fracturing that extends to the base of the Sherwood Sandstone Group.

Hydraulic significance of faults

EFFECT OF DISPLACEMENT

Where fault movement is small relative to the aquifer thickness, and the fault zone is permeable, hydraulic continuity across a fault may be maintained. However, where large displacements cause juxtaposition of permeable and impermeable strata, the hydraulic continuity across the fault can be broken or significantly reduced. Examples are the Croxteth Fault, North Merseyside and the Winwick Fault, Lower Mersey Basin (Figure 7.5.4), which cause Carboniferous strata to be up-thrown against Permo-Triassic deposits and inliers of Carboniferous deposits to outcrop. They can only be modelled if their assigned transmissivities are significantly lower than the regional values (University of Birmingham, 1981 and 1984).

When aquifer units are thin, (for example the Collyhurst Sandstone Formation in the north of the area), even small displacements can break hydraulic continuity. Conversely sandstones within the base of the Mercia Mudstone Group can be brought into hydraulic continuity with the Sherwood Sandstone Group through fault displacement. Faulting can offset marly layers, allowing increased fluid flow within the sandstones.

Extensive faulting results in complex geology in the east Manchester area. Faults may facilitate the circulation of water by the displacement of the minor marl bands (Taylor, 1957). Faults east of the Pendleton Fault have elevated the Manchester Marl aquitard into a series of north-west–south-east-trending barriers to groundwater flow, tilted to the south-west. Where the Manchester Marl outcrops, for example along the West Manchester Fault, it divides the Permo-Triassic sediments into isolated aquifer blocks. Most blocks taper and thin northwards. Thinning of the Permo-Triassic Sandstones on the upthrown faces of the faulted blocks produces regional hydraulic anisotropy (Pitman, 1981).

Effect of infill

The nature of the fault zones is difficult to predict and both permeable and impermeable faults occur. Some faults are filled with loose, porous debris. Others have impermeable clay infill. The Roaring Meg Fault in the Lower Mersey Basin (Figure 7.5.4), does not interrupt sandstone continuity but can only be successfully modelled if the transmissivity across it is reduced to 5% of the regional value. The fault delineates a transition between water chemistry types which also suggests that it is of low hydraulic conductivity (University of Birmingham, 1981). Resistivity data in the region of Hale [SJ 47 81] indicate that the saline interface there has been disturbed by a low-permeability fault zone (University of Birmingham, 1981).

Hard, altered, reduced porosity zones surrounding some faults have been recorded. Moore (1902) measured hydraulic conductivity variations across a fault at West Kirby [SJ 21 86] where Triassic sediments were discoloured within 1 m of a metre wide fault zone. A 40% fall in porosity occurred near the fault; it was suggested that this was due to rock compression and the presence of rock flour (University of Birmingham, 1981). Where boreholes have encountered faults, the cores are frequently broken and records show fault zones extending up to some 40 m. At Bewsey [SJ 592 894] and Halewood [SJ 464 838] calcite cementation occurs in the faulted zone. At Bewsey minor clay gouge is also present. Mining subsidence has caused recent local movement. At Holcroft Lane Observation Borehole [SJ 6857 9370] some of the fractured material has been recemented (University of Birmingham, 1981).

Barrier example: Sandon Dock

Campbell (1987) describes how faulting affects the tidal response of observation borehole hydrographs, and how it can influence pumping test results. The presence of a low hydraulic conductivity fault (Figure 7.5.5) at Sandon Dock, Liverpool [SJ 335 925] is deduced from borehole hydrographs and is consistent with borehole lithological data. The tidal efficiency (change in borehole water level per change of tidal level) of three boreholes (numbers 321, 325 and 327) to the inland side of the fault is 5%, whereas that of the nearby three boreholes (numbers 326, 328 and 331), on the fault's seaward side is 30%. Thus the fault appears to restrict flow across it.

Analysis of a pumping test carried out on inland borehole 325, using observation boreholes 321 and 327 adjacent to the fault indicated aquifer properties which overestimated the drawdown at borehole 325. The modelled storage was increased from 3×10^{-3} to 8×10^{-3} to account for this.

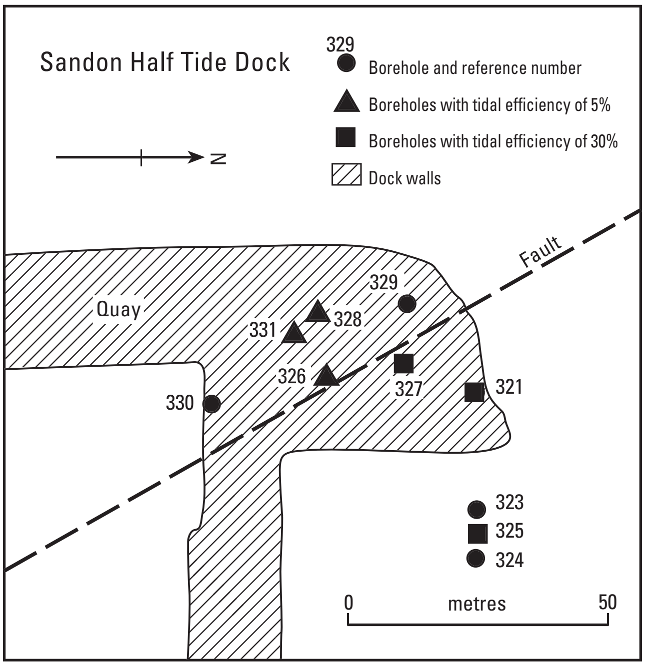


Figure 7.5.5 Hydraulic influence of faulting at Sandon Dock (after Campbell, 1987).

A step test on borehole 326, produced little drawdown in observation boreholes 321, 325, and 327 on the opposite side of the fault. The water level in borehole 325 actually rose because the tidal rise exceeded the drawdown. A 7 day pumping test on seaward holes 326, 328, and 331 produced only 0.9 m drawdown at borehole 327, inland of the fault. A drawdown of 5 m would have been expected if the fault barrier had been absent.

Aquifer boundary example: Ormskirk

An asymmetrical cone of depression (Figure 7.5.6) resulting from six years of abstraction from a supply borehole at Bickerstaffe Pumping Station, 3 km south of Ormskirk [SD 420 035] is described by Allen (1969). It is 2 km east of the Boundary Fault, which separates Coal Measures

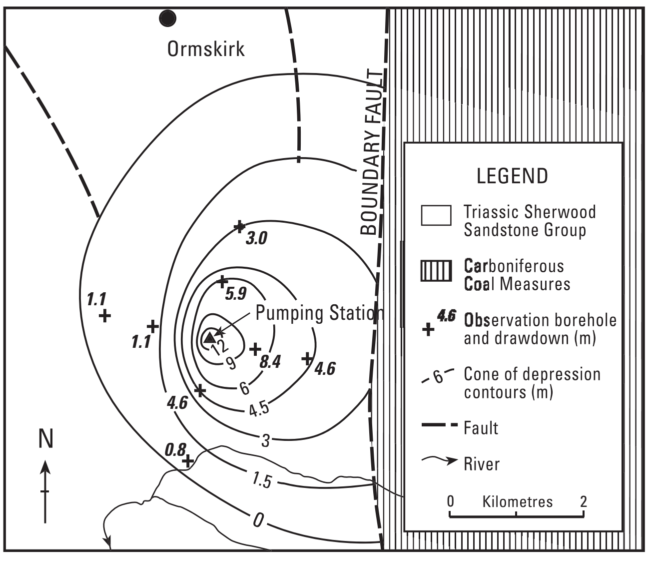


Figure 7.5.6 Aquifer boundary influencing a cone of depression at Ormskirk (after Allen, 1969).

upthrust to the east from the Sherwood Sandstone Group to the west. Observation boreholes at right-angles to the abstraction well indicate a cone of depression elongated parallel to the fault, with a greater drawdown adjacent to it. Interpretation of drawdowns, at the various observation wells, would yield misleading aquifer parameters if the effect of the barrier boundary nature of the fault was not taken into account.

Previous hydrogeological investigations

The most detailed aquifer properties studies undertaken in Cheshire and south Lancashire are the two Saline Groundwater Investigations, Phase 1 — Lower Mersey Basin and Phase 2 — North Merseyside. These studies were conducted in the 1980s jointly by University of Birmingham and The North West Water Authority.

A series of papers and a variety of internal North West Water Authority hydrogeological reports are associated with the Saline Groundwater Investigations. Most subsequent work, for instance the NRA Source Protection Zone proformas, have drawn heavily on the results of these studies. Earlier studies include PhD theses by Allen (1969), Memon (1975), and Pitman (1981) and MSc theses by Ali (1973), Campbell (1982) and Thompson (1969). The major study areas are delineated in Figure 7.5.2, and references are listed in Section 7.5.5. The whole of the region is covered by a hydrogeological map (Lewis et al., 1989).

7.5.2 Hydraulic conductivity and transmissivity

Core data

Hydraulic conductivity measurements made on core samples give point-specific measurements of intergranular hydraulic conductivity. They give an indication of the matrix-flow component, but do not reflect any contributions of fracture-flow to the total transmissivity. The Aquifer Properties Database includes data used by Lovelock (1977). Frequency histograms of its core hydraulic conductivity values are given in Figures 7.5.7a to 7.5.7e. These illustrate the hydraulic conductivity distribution of the Permian Kinnerton Sandstone Formation, and the Triassic Sherwood Sandstone Group and its three constituent formations. Table 7.5.2 gives the associated means and ranges from the database.

Variation with formation

The histograms of core hydraulic conductivity for the different formations all show a tendency towards a log-normal distribution, with a pronounced negative skew. The skew is a result of lithological control; the presence of fine grains and cementation cause dramatic reductions in intergranular hydraulic conductivity.

PERMIAN KINNERTON/COLLYHURST SANDSTONE FORMATION

The Kinnerton/Collyhurst Sandstone Formation's hydraulic conductivity ranges from 3.7×10^{-5} to 10 m/d, with an interquartile range of 0.13 to 1.8 m/d (Figure 7.5.7a). The lower hydraulic conductivity values result from the sampling of fine-grained layers and the influence of mudstone lenses, rather than cementation, which is poor in the Kinnerton/Collyhurst Sandstone Formation. The fine-grained members are the lateral equivalents of the Bold/Manchester Marl Formation. The Kinnerton/Collyhurst Sandstone Formation has a higher proportion of values exceeding 1 m/d than the overlying Triassic Chester Pebble Beds Formation and Wilmslow Sandstone Formation. These can be attributed to the medium- to coarse-grained aeolian sandstone components and the lack of cementation. The geometric mean of the data is 0.40 m/d, and the median is 0.80 m/d.

TRIASSIC SHERWOOD SANDSTONE GROUP

The three constituent formations of the Sherwood Sandstone Group, all of which are in hydraulic continuity, have similar upper and lower limits of hydraulic conductivity. A combination of the effects of cementation and fine-grained sediments dominate the low hydraulic conductivity end, which has a minimum of 3.7×10^{-5} m/d (Figure 7.5.7b). High hydraulic conductivity values, of up to 15 m/d can be attributed to the presence of medium- to coarse-grained sands. The range is also similar to that of the Permian Kinnerton Sandstone Formation.

The core hydraulic conductivities of the Chester Pebble Beds Formation, shown in Figure 7.5.7c, have an interquartile range of 0.05 to 0.98 m/d. These moderate hydraulic conductivities reflect the generally indurated nature of the formation. The median value is 0.33 m/d, and the geometric mean is 0.17 m/d. The range of values is wide, from 2.5×10^{-4} m/d to 15 m/d, resulting from a combination of variable cementation and lithology. Subaerial weathering reduces cementation in outcrop samples (Lovelock, 1977). Sand grain sizes vary from fine to coarse, and interbedded mudstones are present. A low hydraulic conductivity peak occurs at 3×10^{-4} m/d. This is also present in data from the Wilmslow Sandstone Formation, and can be attributed to it being the lower end of the measuring range.

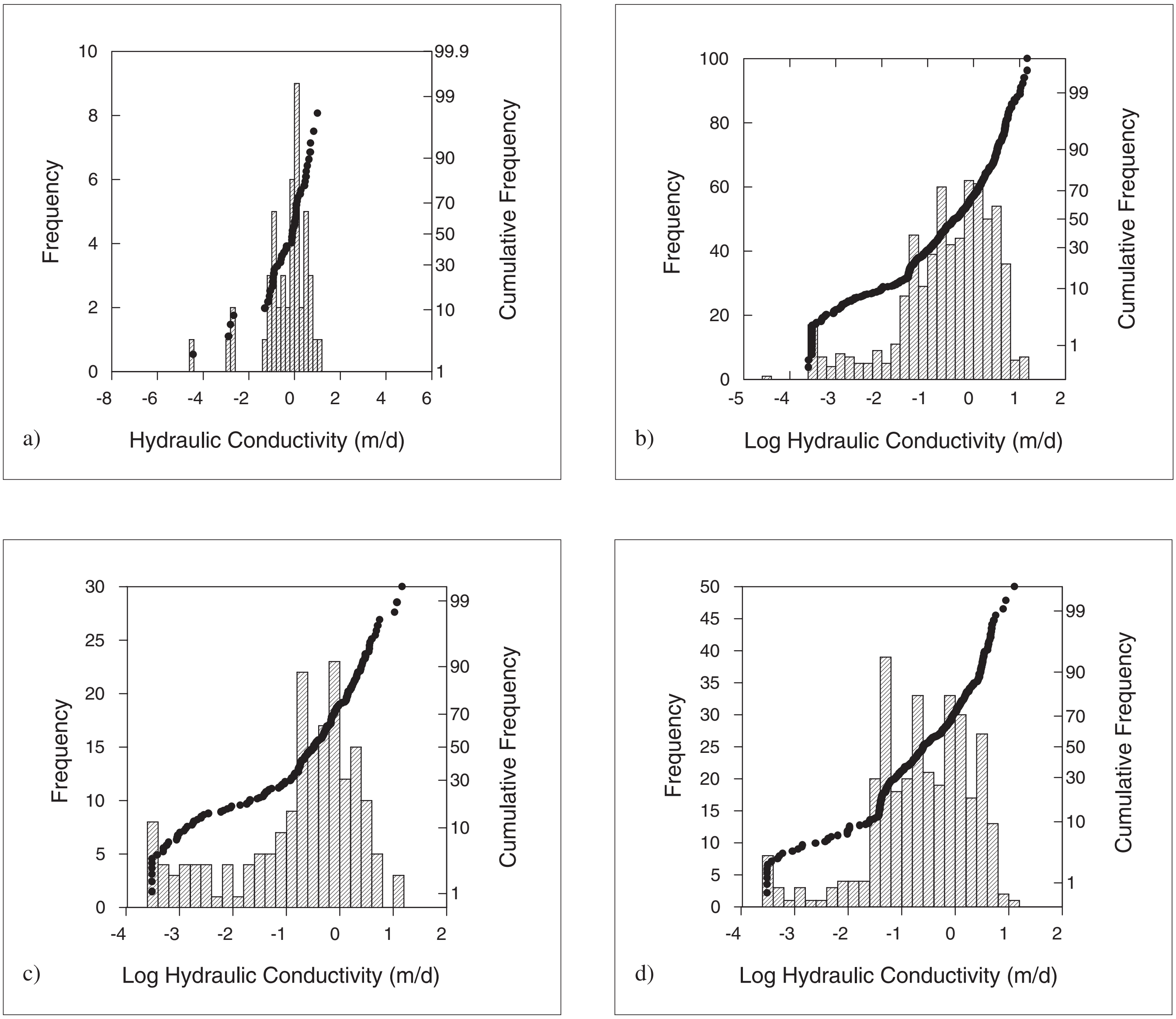
The Wilmslow Sandstone Formation core hydraulic conductivity histogram (Figure 7.5.7d) ranges from 2.6×10^{-4} to 13 m/d. The geometric mean is 0.22 m/d, and the median is 0.25 m/d. The interquartile range of 0.56 m/d to 4.1 m/d is wide and reflects the great lithological variation. Fine-grained sandstones have interbedded medium- and coarse-grained sands. Clean sands of fine to medium grain-size can give high hydraulic conductivity values, whereas beds with a high mud content have low hydraulic conductivities. The presence of silicified veins and weak cementation also give rise to low values of hydraulic conductivity (Lovelock, 1977).

The Helsby/Ormskirk Sandstone Formation's hydraulic conductivity (Figure 7.5.7e) ranges from 3.1×10^{-4} to 15 m/d and has a high interquartile range: 0.56 to 4.1 m/d, despite the cementation. The sandstone is coarse grained and clean; cementation has largely occurred only at the contact points of the individual sand grains. The well-sorted nature of the sand grains has led to the presence of wide, well-defined pore channels, with correspondingly high hydraulic conductivities. Fine- and medium-grained sandstone layers with subordinate mudstones and marl layers have associated lower hydraulic conductivities. The geometric mean is 1.2 m/d, and the median is 1.8 m/d.

Variation with grain size and core scale anisotropy

At Kenyon Junction [SJ 648 965] it was found that intrinsic permeability increases with grain size in the Chester Pebble Beds Formation, and that the average horizontal permeability for a given grain size exceeds the vertical value by up to seven times (Table 7.5.3). Horizontal to vertical permeability ratios of individual cores varied from less than 1:1 to over 50:1. Only 8% of the samples had a vertical permeability that was higher than the horizontal one (University of Birmingham, 1981).

Figure 7.5.8a shows the horizontal and vertical hydraulic conductivity distributions of the Collyhurst Sandstone For-



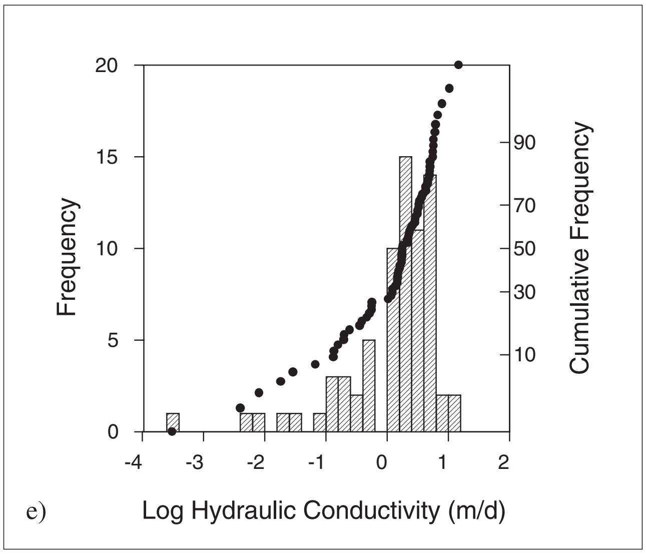


Figure 7.5.7 Distribution of hydraulic conductivity data for Permo-Triassic sandstone samples from Cheshire and south Lancashire, a) Collyhurst–Kinnerton Sandstone Formation, b) Sherwood Sandstone Group, c) Chester Pebble Beds Formation, d) Wilmslow Sandstone Formation, e) Helsby–Ormskirk Sandstone Formation.

mation. Horizontal values are usually greater than vertical ones. The geometric mean of horizontal values is 0.39, and that of vertical values is 0.17. Their ratio, the mean core-scale anisotropy ratio, is 2.4. Similarly, the anisotropy ratio for the Sherwood Sandstone Group (Figure 7.5.8b) is 2.3. Statistics of the different distributions are given in Table 7.5.4. Although there may be relatively small differences between horizontal and vertical hydraulic conductivities within a horizon, the layered natures of the sandstones means that the aquifer as a whole may have considerable anisotropy. However, where finer-grained interlayers are less common, abstraction wells may risk drawing saline water up from depth.

Variation with depth

No consistent variation of core hydraulic conductivity with depth is observed in the top 150 m of the aquifer, from which the samples have been taken. There is no apparent depth trend in either the samples from single boreholes, in samples from each formation, or from the Permo-Triassic Sandstones taken collectively because lithological variation, rather than depth, acts as the major control on intergranular hydraulic conductivity. Higher permeability, friable material near the surface may not have been sampled.

Table 7.5.2 Core hydraulic conductivity data for the Permo-Triassic sandstones of Cheshire and south Lancashire.

Group or Formation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Sherwood Sandstone	3.7 ¥ 10^{-5}–15	0.08–1.5	0.39	0.26
Helsby Sandstone	3.1 ¥ 10^{-4}–15	0.56–4.1	1.8	1.2
Wilmslow Sandstone	2.6 ¥ 10^{-4}–13	0.056–1.13	0.25	0.22
Chester Pebble Beds	2.5 ¥ 10^{-4}–15	0.05–0.98	0.33	0.17
Collyhurst/Kinnerton Sandstone	3.7 ¥ 10^{-5}–10	0.13–1.8	0.80	0.40

Table 7.5.3 Relationship between permeability and lithology, from gas permeametry on Chester Pebble Beds Formation samples from Kenyon Junction (after University of Birmingham, 1981).

Grain size	Average intrinsic permeability (millidarcies)*		Ratio of horizontal to vertical permeability
	Horizontal	Vertical	
Medium to coarse	2049	13480	1.52
Medium	629	281	2.24
Medium to fine	56	14	4.0
Fine	14	2	7.0
Very fine	<0.01	<0.01	
Weighted mean	928	494	1.9

* 1 darcy is approximately equal to 0.64 m/d for water at 10°C.

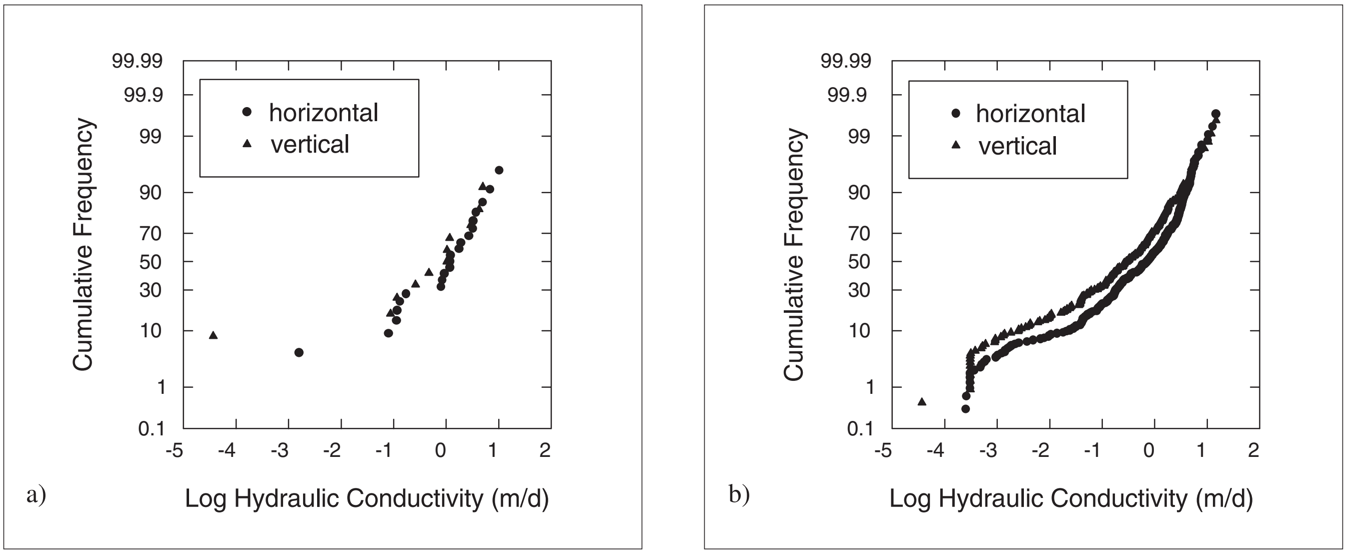


Figure 7.5.8 Distribution of hydraulic conductivity data for horizontal and vertical Permo-Triassic sandstone samples from Cheshire and south Lancashire, a) Collyhurst–Kinnerton Sandstone Formation, b) Sherwood Sandstone Group.

Table 7.5.4 Vertical and horizontal core hydraulic conductivity statistics for the Permo-Triassic sandstones of Cheshire and south Lancashire.

Group or formation	Orientation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Sherwood Sandstone	Horizontal	2.5 ¥ 10^{-4}–15	0.14–2.37	0.72	0.40
Group	Vertical	2.6 ¥ 10^{-4}–13	0.04–1.21	0.29	0.17
Collyhurst/ Kinnerton	Horizontal	1.6 ¥ 10^{-3}–10	0.15–3.2	1.2	0.78
Sandstone	Vertical	3.8 ¥ 10^{-5}–4.9	0.10–2.9	1.0	0.32

Packer test hydraulic conductivity and geophysical logging

Packer tests were carried out in the Lower Mersey Basin and in west Cheshire for the Saline Groundwater Investigations. Transmissivities were calculated for each test zone using empirical formulae. These were divided by the length of the test zone in order to obtain average bulk hydraulic conductivities, which could then be compared with core data. The cumulative transmissivities compare well with pumping-test transmissivities when turbulent flow is minimised (Ingram et al., 1981a and 1981b).

Four sites were investigated in west Cheshire: Organsdale [SJ 5507 6830], Priors Heyes [SJ 5130 6645], Burton [SJ 5056 6464] and Stanlow [SJ 4309 7620] (Figure 7.5.1). Figure 7.5.9 shows hydraulic conductivity variations with depth. Significant hydraulic conductivity increases can be attributed to fracture flow. Campbell (1986) summarised the results thus:

1. Hydraulic conductivity values obtained in fractured sections are generally much higher than in the unfractured sections.
2. A zone of high hydraulic conductivity exists in the top part of the aquifer where fractures are common.
3. Underlying this is a low hydraulic conductivity zone (generally less than 1 m/d) where intergranular flow predominates and fractures are rare.

In the Lower Mersey Basin, packer testing was conducted at Padgate [SJ 629 900], Kenyon Junction [SJ 648 965], and Halewood [SJ 464 838] (Figure 7.5.1). Average bulk packer test hydraulic conductivities are compared with average core hydraulic conductivities, by formation, in Table 7.5.5. Profiles of average hydraulic conductivity suggest that there are a number of zones of unusually high hydraulic conductivity. Figure 7.5.10 shows the profile of cumulative transmissivity at Kenyon Junction. At Halewood, approximately 80% of flow was attributed to fractures and the Bold Formation was found to have a low hydraulic conductivity where it is not fractured (Walthall and Ingram, 1981). Similarly, at Padgate 85% of the transmissivity of the 170 m of the Chester Pebble Beds Formation penetrated was attributed to subhorizontal fracture flow (Walthall and Ingram, 1982). Different results were obtained over the same 80 to 90 m depth interval at two observation boreholes only 30 m apart, indicating that zones of higher hydraulic conductivity can be very localised (University of Birmingham, 1981)

Borehole Closed Circuit Television (CCTV) logging indicates that fractures are preferentially developed in the softer, less well-cemented sandstones, such as the Wilmslow Sandstone Formation. For example, in the Padgate [SJ 629 900] and Bewsey [SJ 592 894] boreholes they occur at an average of ten per 10 m. In the more-cemented Chester Pebble Beds Formation there is an average of two to three bedding plane fractures per 10 m of section down to a depth of 150 m at Croft [SJ 644 945]. Below this, the average is one fracture per 50 m. In the underlying Collyhurst Sandstone Formation, vertical joints are common but are frequently recemented with silica.

It is, however, difficult to tell the difference between original 'real' fractures and 'apparent' secondary ones, which have been created by the borehole drilling, development and abstraction. These man-made fractures develop fastest in easily eroded formations and can impart the appearance of a high fracture density, but these apparent fractures are not of regional significance because they are borehole scale phenomena.

Geophysical borehole logs and CCTV at Padgate [SJ 629 900] confirm that the zones with higher packer test hydraulic conductivity coincide with fractures. The lateral extent of both horizontal and vertical fractures is poorly known however. At the Kenyon Junction borehole site [SJ 643 965] fractures extend between boreholes 30 m apart, while at Padgate fracture patterns can be correlated in boreholes 90 m apart. The presence of fractures does not necessarily indicate higher hydraulic conductivity. In certain regions hydraulic conductivities are low despite fracturing, for example at a depth of 120 m in the Padgate borehole. Permeable zones are more frequent in its upper 90 m, indicating that a greater proportion of the water flows in this region (University of Birmingham, 1981).

Non-fractured zones were found to have very uniform properties; they have low flows and linear injection flow rate versus head plots. Typical hydraulic conductivity values for these zones are comparable with laboratory values.

Summary

Packer test and core data are only comparable for zones in which fracturing is not significant and the borehole walls are not clogged (Ingram et al., 1981). Where there is fracturing, the ratio of packer to core test data gives an indication of its significance. For instance, when intrinsic permeability values were compared with packer test results

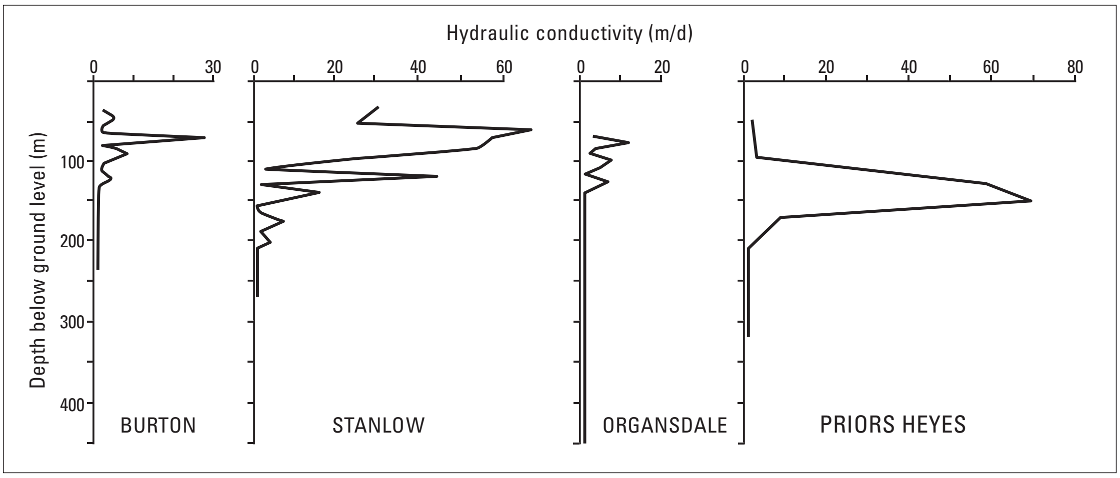


Figure 7.5.9 Depth variations of hydraulic conductivity from packer tests at four sites in the Permo-Triassic sandstones of west Cheshire (after Campbell, 1986).

Table 7.5.5 Comparison of packer test and core hydraulic conductivity data from sites in the Lower Mersey Basin (after Walthall and Ingram, 1982).

Formation	Borehole	Comments on packer test results	Average packer test hydraulic conductivity (m/d)	Average core hydraulic conductivity (m/d)
Wilmslow Sandstone	Padgate No. 2	1.96	0.65	
Chester Pebble Beds	Padgate No. 1	Too low. Borehole not cleaned before testing	0.52	0.50
	Padgate No. 2	No large fractures	2.14	0.50
		Zone contains several large fractures	6.09	0.50
	Kenyon Junction		2.40	0.59
Bold	Halewood	Section dominated by large fracture	2.17	0.06
Collyhurst Sandstone		Contains very permeable zone	6.81	0.85

at the Padgate borehole, it was inferred that 80% of the aquifer transmissivity is due to fracture flow.

Pumping test transmissivity and bulk hydraulic conductivity

Controls on transmissivity are numerous. Productive fractures can give rise to high pumping test transmissivities, which may be enhanced further in regions of extensive faulting. Intergranular hydraulic conductivity (and hence lithology) is the principal control where fracture flow is minor. Borehole depth, the depths of highly permeable zones, and the effective aquifer depth also influence the value of transmissivity. Scale is also an important factor, since transmissivities from pumping tests are averages at the scale of the test (hundreds of metres to kilometres).

Although geology is the prime control on pumping test transmissivity, the constructions and depth of boreholes and piezometers, the type of test, and method of analysis also influence the apparent transmissivity. These added variables are a lesser concern in laboratory core analysis, where measurement techniques are far more readily standardised. Case studies are described below.

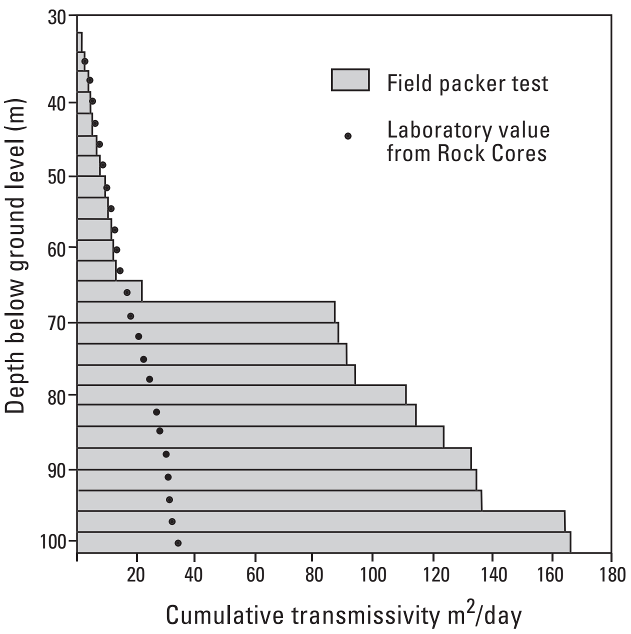


Figure 7.5.10 Cumulative transmissivity distribution from core and packer test data at Kenyon Junction (after University of Birmingham, 1981).

Transmissivity

The aquifer properties database contains transmissivity records from 138 sites in the Cheshire region. At each site there have been up to four different pumping tests, making a total of 147 tests on record. There is no relationship between transmissivity value and length of pumping test.

The site transmissivity values range from 0.90 to 4900 m^2/d, with an interquartile range of 120 to 530 m^2/d. Fracture flow is particularly significant at high values. The log transmissivity histogram (Figure 7.5.11) shows an approximately normal distribution, the geometric mean is 220 m^2/d and the median is 250 m^2/d.

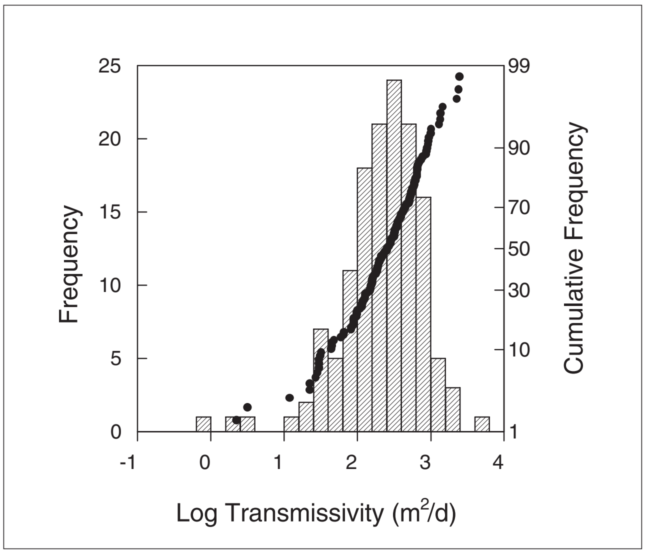


Figure 7.5.11 Distribution of transmissivity data from pumping tests in the Permo-Triassic sandstones of the Cheshire and south Lancashire region.

The variation appears to be random and does not appear to correlate with likely contributory factors such as sandstone thickness, glacial geomorphology or land subsidence. It is thought to reflect the number, distribution and efficiency of fractures encountered by a particular borehole at a specific locality, more than the major differences in lithologies and intergranular hydraulic conductivities (University of Birmingham, 1981; Campbell, 1986). The significance of fracturing and lithology are considered in more detail below. Large transmissivity variations in Manchester and the Irwell valley are thought, by Pitman (1981), to be induced by extensive faulting.

Bulk hydraulic conductivity

In order to assess the significance of fracture flow, and to directly compare the different formations, the pumping test transmissivity data have been converted to bulk hydraulic conductivities. This removes the thickness variable, by eliminating the effects of different borehole depths, distances to the piezometric surface and thicknesses of confining layers. Thus they can be directly compared with core data. The method of calculation is described in Section 7.1.4. Bulk hydraulic conductivities were determined for 57 sites, and range from 0.16 to 46 m/d (Figure 7.5.12a), the interquartile range is 1.16 to 5.29 m/d. The geometric mean and median are both 2.5 m/d. There are no sub-regional variations. High and low bulk hydraulic conductivity variations, like transmissivity variations, are distributed randomly.

The lower limit of bulk hydraulic conductivity is four orders of magnitude greater than the lower limit of core hydraulic conductivity data. This is a function of scale: whilst cores sample centimetre-scale regions, which can consist entirely of low hydraulic conductivity sediments it is highly unlikely that such layers would dominate the entire thickness of strata penetrated by an abstraction borehole. The upper limit and means of bulk hydraulic conductivity are also higher than the respective values for core data. Fracture flow contributions cause these higher total borehole hydraulic conductivities.

When values of bulk hydraulic conductivity were considered on a formation basis no significant difference between the formations was indicated (Figures 7.5.12b–d). This suggests that although formation type exerts a control on intergranular hydraulic conductivity, it does not exert a primary control on bulk hydraulic conductivity. This statement must however be considered tentative in view of the limited data available.

Core data and pumping test data are rarely both available at the same site. One example is the Ashton Main Borehole, West Cheshire [SJ 505 689], where the mean intergranular hydraulic conductivity of 16 samples was found to be 2.4 m/d (Mersey and Weaver River Authority, 1970), which is 40% of the bulk hydraulic conductivity. However, this figure is biased towards low values, as the hydraulic conductivity tests were conducted on the better-cemented chippings collected from the drilling flush water, whilst the softer, possibly more permeable, lithologies would not have been sampled. Both core and pumping test data are available from the Pocket Nook borehole [SJ 639 974] in the Chester Pebble Beds Formation. The bulk hydraulic conductivity at this site is 5.2 m/d, 64 times greater than the geometric mean of the core data hydraulic conductivity, indicating the important contribution of fracture flow to the borehole.

Intergranular and bulk hydraulic conductivities within the Greater Manchester area are very similar Pitman (1981). Exceptions, where there are large variations in transmissivity, (e.g. the Rank Hovis test), are found along the Irwell valley and westwards towards the Worsley fault. Pitman infers that fracture flow may be more important in the Pebble Beds Unit than the Wilmslow Sandstone Formation.

Pumping test case studies

Extensive pumping tests have been carried out at certain sites within the region. The following case studies illustrate the complexities of pumping tests and their analysis. Both the way in which the test is carried out and how it is analysed, affect the calculated values of transmissivity and bulk hydraulic conductivity. Critical factors include the depths of piezometers and observation wells compared to the level of productive zones within the aquifer, choice of pump level, production well depth, the effect of anisotropy and faults on observation wells and whether early or late data are used for calculations.

KENYON JUNCTION [SJ 648 965], LOWER MERSEY BASIN

A test at Kenyon Junction, for the Saline Groundwater Investigation, made use of a series of vertically spaced piezometers in an observation hole 34.5 m from the abstraction borehole. There was a significant variation between water levels at the free surface and those in deeper piezometers, indicating that permeability anisotropy is significant. The degree of response depends on the hydraulic conductivity of the zones which the piezometer samples. The results were interpreted with an analytical model which could take account of the variations of head with depth. The best fitting model gave a horizontal hydraulic conductivity of 1 to 1.4 m/d, and a vertical hydraulic conductivity of 0.3 to 0.7 m/d. It was concluded that this technique of providing piezometers at differing depths gives the most reliable pumping test interpretations (University of Birmingham, 1981).

PLEX MOSS [SD 357 089], NORTH MERSEYSIDE

At Plex Moss, an observation borehole with four piezometers was constructed 32 m from the abstraction borehole. Piezometer 1, positioned below a marl band, exhibited the largest drawdown (Figure 7.5.13) from which a transmissivity of 480 m^2/d was calculated. Transmissivities calculated from piezometers 2–4 situated above the marl band are much higher and they are less representative, as they do not take into account the full response of the aquifer or the fact that a considerable proportion of the inflow comes from beneath the marl band (University of Birmingham, 1984).

PADGATE [SJ 629 900], LOWER MERSEY BASIN

The effect on pumping tests of varying the intake level was investigated at Padgate. This borehole penetrates hypersaline water at depth so that flow zones are sharply highlighted by salinity contrasts. The contribution from fractures was found to increase when the pump intake was situated opposite them. The test also indicated that pumped water quality can be influenced by the choice of pump level (Peacock, 1981).

ASHTON [SJ 505 689], WEST CHESHIRE

Extensive pump testing was carried out at Ashton in May 1970. The boreholes penetrate the drift and Chester Pebble Beds Formation. Drawdowns were recorded at observation holes 1, 2, 3 and 4, situated 180 m south, 140 m east, 170 m north-west and 640 m north-west of the main production borehole respectively (Mersey and Weaver River Authority, 1970).

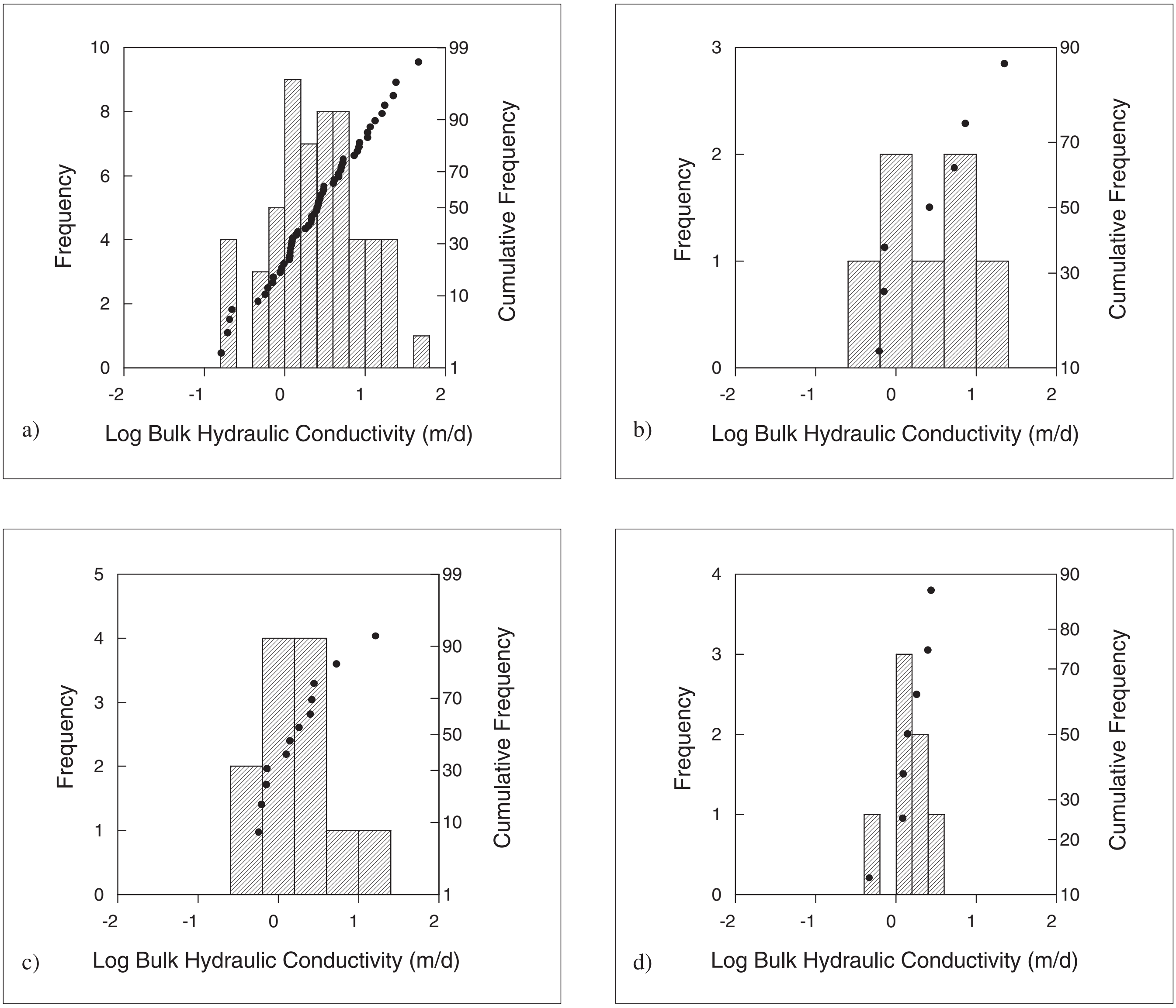


Figure 7.5.12 Distirbution of bulk hydraulic conductivity data from pumping tests in the Permo-Triassic sandstones of the Cheshire and south Lancashire region, a) Permo-Triassic sandstones, b) Collyhurst–Kinnerton Sandstone Formation, c) Chester Pebble Beds Formation, d) Wilmslow Sandstone Formation.

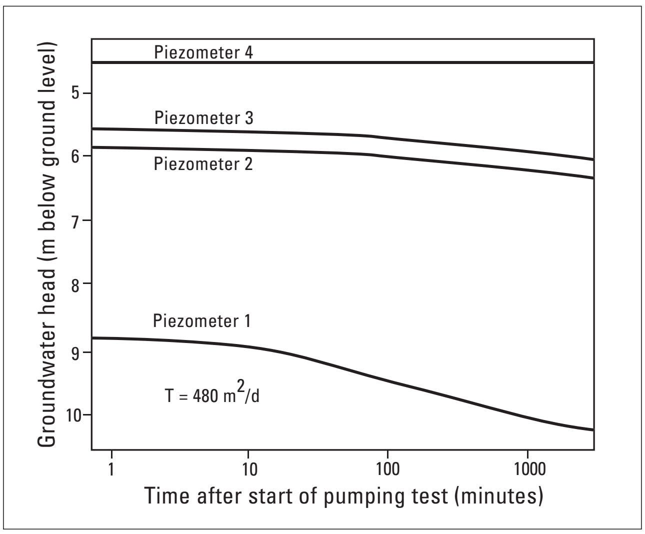


Figure 7.5.13 Response of piezometers at Plex Moss (after University of Birmingham, 1984).

Tests were initially conducted when the main borehole was 240 m deep. Then it was backfilled to a depth of 179 m and retested. The new transmissivity values calculated were not significantly different, suggesting that the most productive zones were above the basal 70 m.

Tests on the backfilled borehole were conducted at pumping rates of 2300 and 4400 m^3/d. The transmissivity values were up to 33% lower at the higher pumping rate, possibly due to increasing turbulence (Table 7.5.6). Early and late Theis analysis derived values of transmissivity and storage were compared by using them to predict the time at which there would be a 30 cm drawdown in observation borehole 4. The early values were found to give results most similar to those observed in the field. Therefore they were assumed to be most applicable in the short term. An average bulk hydraulic conductivity of 5.9 m/d was derived by dividing the mean early transmissivity value by the thickness of aquifer exposed in the borehole.

The array of observation boreholes at the Ashton pump test allowed consideration of lateral variations of transmissivity. Values calculated for observation boreholes 1 to 3

Table 7.5.6 Transmissivity values calculated for the Ashton pump-test (after Mersey and Weaver Authority, 1970).

Borehole (and distance from main borehole)	Discharge rate (m^3/d)	Reversed Theis Transmissivity (m^2/d)	
		Early recovery data	Late recovery data (* is drawdown data)
Main (0 m)	2300	620	360
	4400	470	280
Observation 1 (180 m south)	2300	780	350
	4400	710	340
Observation 2 (140 m east)	2300	810	600
	4400	540	390
Observation 3 (170 m north-west)	2300	600	*410
	4400	470	*360
Observation 4 (610 m north-west)	2300	260	260
	4400	260	630

were reasonably consistent. However, minimal effects of pumping at Mouldsworth [SJ 503 704] were observed at observation borehole 4 compared with the other Ashton boreholes. This could be due to the presence of an impermeable fault between Mouldsworth and observation borehole 4, which would be consistent with the inferred geology. Correlation of geological core logs with gamma logging across the site indicated 30 m of displacement between observation boreholes 3 and 4.

At the main borehole, and at the three closest observation boreholes, transmissivity values calculated from late data were lower than early data ones (Table 7.5.6). An early average of 640 m^2/d decreased with time to 440 m^2/d. This corresponds to an increasing rate of drawdown, which could result from delayed yield from storage, barrier boundary conditions, leaky artesian conditions or a reduction of transmissivity with distance from the pumped well. Conversely, the fourth observation borehole experienced a drawdown rate which decreased with time, possibly due to leakage from a river to the north or the nearby fault acting as a semi-permeable barrier.

Organsdale [SJ 550 683], west Cheshire

The production borehole at Organsdale penetrated 67 m of Helsby Sandstone Formation, followed by 230 m of Wilmslow Sandstone Formation. 260 m to the west, observation borehole 1 penetrated a similar depth of Helsby Sandstone Formation, and then 200 m of Wilmslow Sandstone Formation, before terminating in the Chester Pebble Beds Formation at a depth of 460 m. Faulting at the test site is likely, field evidence of which can be seen at the nearby Eddisbury Hill and could explain the difference in thickness of the Wilmslow Sandstone Formation between the production well and observation borehole 1. The second observation borehole had a depth of 60 m and was located 165 m to the north of the abstraction borehole (Mersey and Weaver River Authority, 1972).

A 7 day pumping test at a constant rate of 4400 m^3/d was followed by a 3 day recovery, and then two days of pumping at a constant rate of 8800 m^3/d. Water levels were monitored at the two observation holes. The production borehole transmissivity values were substantially lower than the observation borehole values, which was taken to indicate that well losses are significant and production borehole values are unreliable. A mean transmissivity of 5700 m^2/d was calculated for the observation boreholes. A significant fracture flow contribution would help to explain the high yields and would be consistent with the packer test findings (Figure 7.5.9). Data which showed a marked departure from the type curve, such that the rate of drawdown was doubled, were analysed for discharging image well conditions. Calculated distances to image wells were found to correspond to the distance to the nearby Delamere and Eddisbury Pumping Stations [SJ 561 677 and SJ 558 694], which were both operational during testing (Mersey and Weaver River Authority, 1972).

Summary

Fracture flow exerts the major control on transmissivity. Its inherent random nature means that transmissivity values and their associated bulk hydraulic conductivity values, are locally variable and difficult to predict. Intergranular hydraulic conductivity, and hence lithology, is important where fracture flow is less dominant. The importance of fracture flow can be determined with greater accuracy by packer testing than by comparing core and bulk hydraulic conductivities.

Specific capacity

The database has specific capacity records at 29 sites in the Cheshire and south Lancashire region. They range from 6.8 to 1500 m^3/d/m and have an interquartile range of 37 to 220 m^3/d/m (Figure 7.5.14). The geometric mean is 98 m^3/d/m and the median is 68 m^3/d/m. There is insuf-

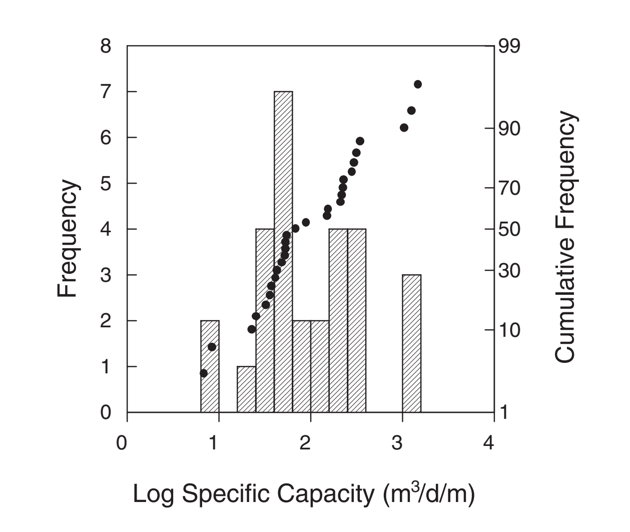


Figure 7.5.14 Distribution of specific capacity data from pumping tests in the Permo-Triassic sandstones of the Cheshire and south Lancashire region.

ficient data to meaningfully subdivide on the basis of formation.

Specific capacity data show a general increase with transmissivity, although there is substantial scatter (Figure 7.5.15). Both Memon (1975) and Allen (1969) calculate transmissivities from specific capacities in order to supplement sparse transmissivity data. University of Birmingham (1981) consider that such data are likely to be biased towards low values, as most of them come from industrial wells which are commonly shallow. Further inaccuracies result from the assumption of 100% well efficiency. To account for wells actually having significant well losses, University of Birmingham (1981) suggested that the transmissivities derived from specific capacity data should be doubled; providing a closer fit to the pumping test derived transmissivity frequency distribution.

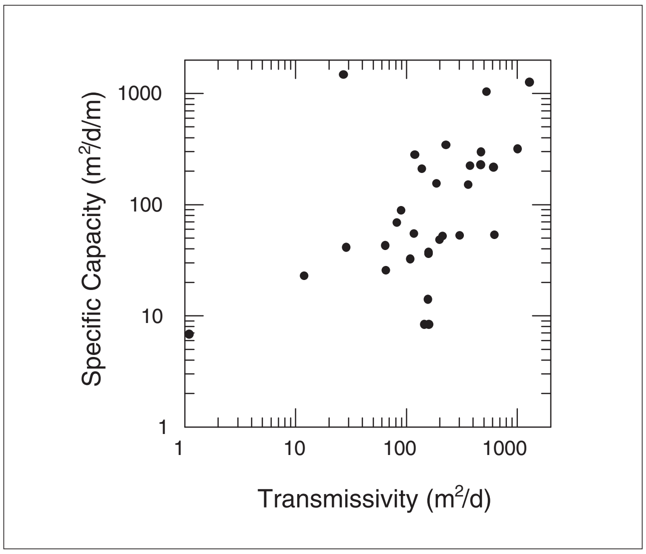


Figure 7.5.15 Plot of specific capacity against transmissivity for the Permo-Triassic sandstones of the Cheshire and south Lancashire region.

Model hydraulic conductivity

When the north Merseyside and Lower Mersey Basin areas were modelled, it was assumed that the general fracture system is regular on a regional scale, despite the fracture distribution, size, frequency and extent appearing to be fairly random, at least on a local basis (University of Birmingham, 1981 and 1984). A regional transmissivity of 300 ± 150 m^2/d was used for the Lower Mersey Basin (Figure 7.5.16). The aquifer was modelled with two layers, in order to reflect the upper part of the aquifer contributing a greater proportion of the transmissivity. The upper layer was given a hydraulic conductivity of 1.7 m/d, and the lower one a hydraulic conductivity of 0.17 m/d. The boundary between the two layers was put at 200 m below Ordnance Datum, in the absence of conclusive information that it should be a function of glacial topography or present topography. Minor adjustments were made in the vicinity of faults. It was predicted that this universal approach may cause errors of up to 2 m in modelled groundwater head values.

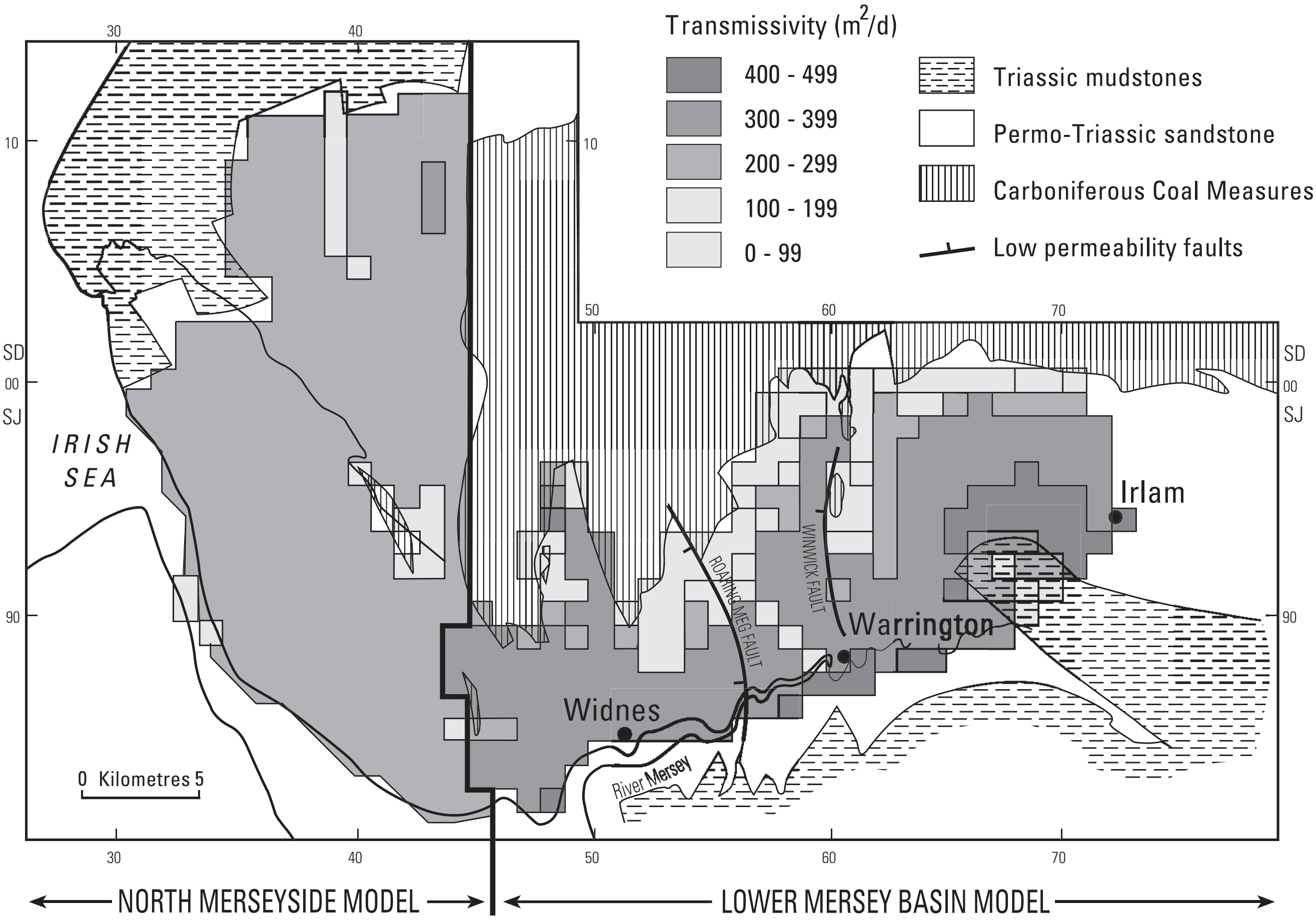


Figure 7.5.16 Model transmissivity distribution used within the Cheshire and south Lancashire region (data from University of Birmingham, 1981, 1984).

Exceptions to the uniform hydraulic conductivity distribution were made adjacent to the Roaring Meg and Winwick faults. The 1979 groundwater heads could only be modelled accurately if the transmissivity across them was reduced to 5% of the regional value. Other faults may also be impermeable but, due to their position and trend, they have little influence on the 1979 flow regime and therefore do not need to be modelled with low transmissivities.

University of Birmingham (1981) state that, because the modelling with these universally applied aquifer parameter values was successful, the flow within the aquifer on a regional basis is dominated almost entirely by the distribution and magnitude of the inflows and outflows. This also supports the evidence from pumping tests that the aquifer transmissivity is largely independent of total sandstone thickness over much of the area. (The validity of this argument does however depend on the extent to which recharge to and outflows from, the aquifer are known).

Summary

The Saline Groundwater Investigation models (University of Birmingham, 1981 and 1984) assume that the Permo-Triassic Sandstone's intergranular hydraulic conductivities are 0.1 to 10 m/d, with an average of 0.5 m/d. This value is lower than the 1.7 m/d used in the upper layer of the model, indicating that fracture flow is of regional importance. The interquartile range of database pumping-test-derived bulk hydraulic conductivities is similar, (1.2 to 5.3 m/d). However their geometric mean of 2.5 m/d is higher than the modelled value (Table 7.5.7). This indicates that fracture flow is less important on a regional scale than it is on a borehole scale.

Similarly, an intergranular hydraulic conductivity for the Chester Pebble Beds Formation of 0.5 m/d is considered to be representative for the Liverpool area by Campbell (1987), Walthall and Campbell (1985), and Peacock (1993). If pumping-test-derived bulk hydraulic conductivity is greater than this, then significant fracture flow is likely (Campbell, 1987).

Scale effects must therefore be borne in mind when considering hydraulic conductivity. Fracture flow is insignificant on a core scale but can dominate the flow to a borehole. On a regional scale, the degree of fracture interconnection affects how significant fracture flow is to the total transmissivity. Conversely, lithology exerts a strong control on a core scale, but is only of significance at the borehole scale when fracture flow is negligible.

7.5.3 Porosity and storage

Porosity

Porosity measurements are available from core samples and, to a limited extent, from radiometric downhole porosity logging. There is a considerable variation of core porosity values in the various Permo-Triassic sandstone formations, with a range from 6 to 35%. This variability can be attributed to the differing grain size, degree of sorting of the sediments, grain shape variation and the extent of cementation. Figure 7.5.17 shows the frequency distributions of core porosities held on the British Geological Survey's database and Table 7.5.8 gives statistical information.

The Permian Kinnerton Sandstone Formation has an approximately Gaussian porosity distribution (Figure 7.5.17a), ranging from 13 to 32%, with an arithmetic mean of 26%. Variations are due to the degree of sorting, and the range of grain-sizes, rather than cementation. The Sherwood Sandstone Group's porosity histogram (Figure 7.5.17b) has a similar distribution. The mode is the same, but the range is slightly larger, from 6 to 35%. The three constituent formations have distinctively different porosity distributions.

The porosities sampled in the Chester Pebble Beds Formation range from 11 to 29%. Their distribution (Figure 7.5.17c) is approximately Gaussian, with a negative skew. Although most values are in the 20 to 28% range, there is a larger proportion of values under 20% than in either of the overlying two formations. The low porosities result from cementation, which is widespread at only a few metres beneath the surface. Outcrop samples have higher porosities,

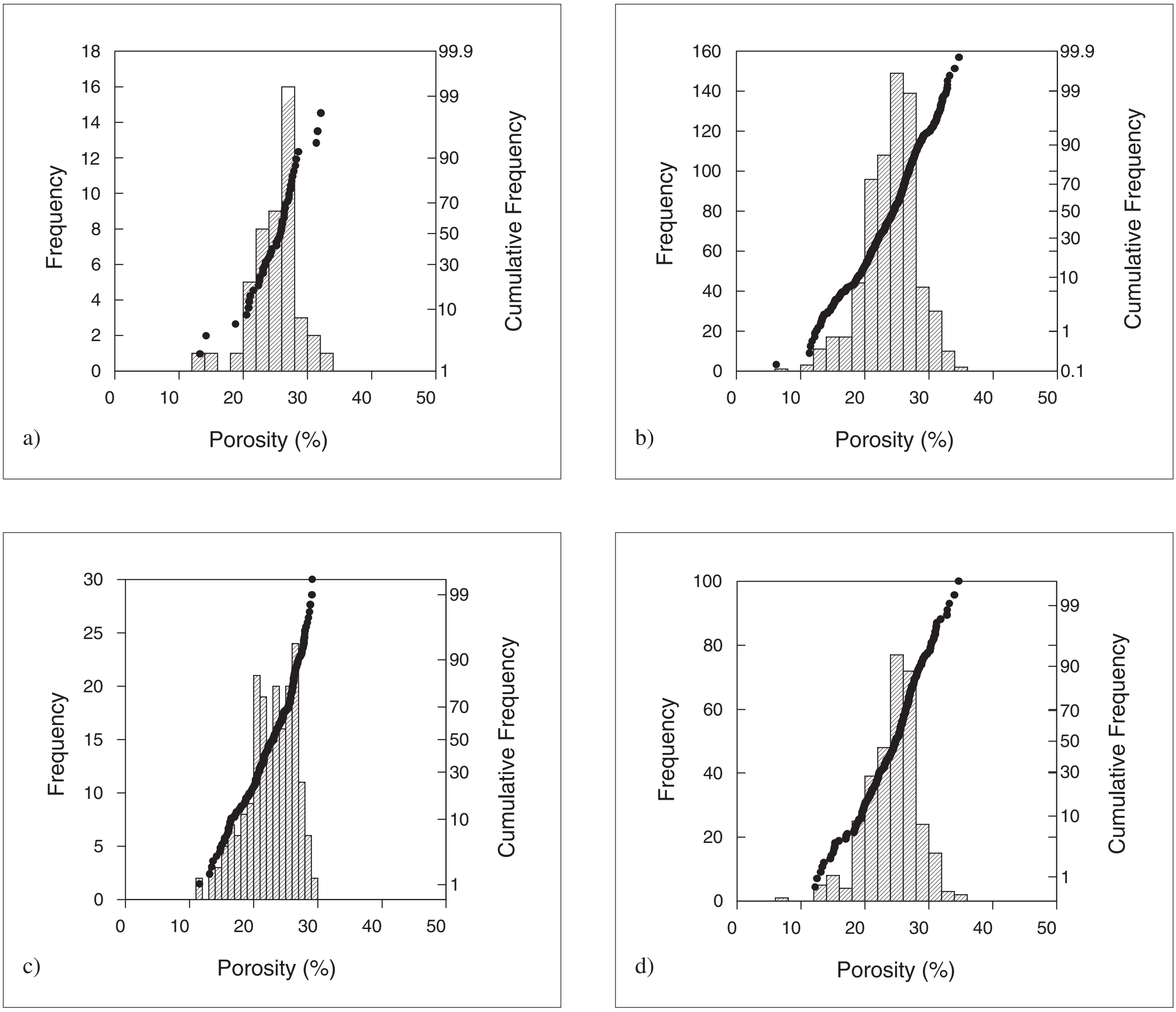
Table 7.5.7 Comparison of hydraulic conductivities for the Permo-Triassic sandstones of Cheshire and south Lancashire measured at different scales.

Measurement method	Hydraulic conductivity type	Hydraulic conductivity (m/d)	
		Range	Geometric mean(s)*
Core permeametry	Intergranular	10^{-5} to 15	0.2–1.2
Packer — predominantly fracture	Fracture	—	2.1–6.8
Pumping test	Bulk	0.2 to 50	2.5
Model	Regional		1.7

* Geometric means are representative of the different formations.

Table 7.5.8 Core porosity data for the Permo-Triassic sandstones of Cheshire and south Lancashire.

Group or Formation	Range (%)	Interquartile (%)	Median (%)	Arithmetic mean (%)
Sherwood Sandstone	6.2–34.7	21.6–26.5	24.6	24.0
Helsby Sandstone	20.2–32.9	23.2–28.6	25.1	25.8
Wilmslow Sandstone	6.2–34.7	22.0–26.9	24.9	24.3
Chester Pebble Beds	11.6–29.2	20.4–25.8	23.1	22.6
Collyhurst–Kinnerton Sandstone	13.3–32.1	23.1–27.2	25.8	25.0



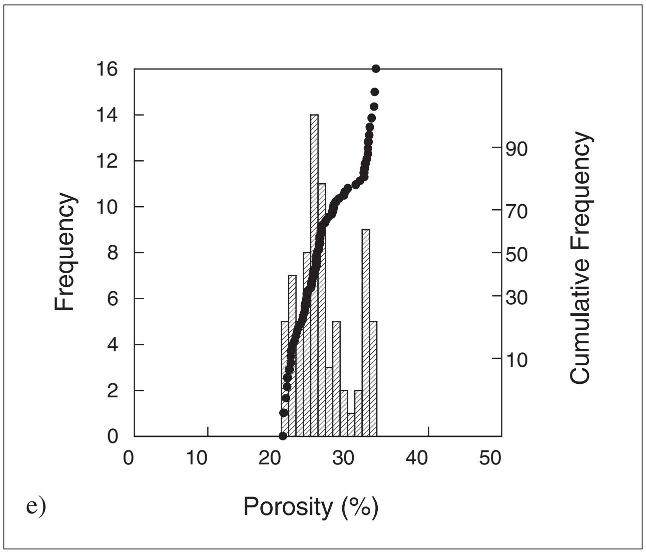


Figure 7.5.17 Distribution of porosity data for Permo-Triassic sandstones samples from the Cheshire and South Lancashire region, a) Collyhurst–Kinnerton Sandstone Formation, b) Sherwood Sandstone Group, c) Chester pebble Beds Formation, d) Wilmslow Sandstone Formation, e) Helsby–Ormskirk Sandstone Formation.

due to the subaerial weathering of the intergranular cement. (Lovelock, 1977). Gamma logs of the Ashton [SJ 505 689] observation boreholes in west Cheshire showed increased porosity and reduced clay content in the Pebble Beds Formation relative to the overlying Wilmslow Sandstone Formation, presumably due to the lower content of fine-grained sediments (Mersey and Weaver River Authority, 1970).

The Wilmslow Sandstone Formation has the greatest porosity extremes of all the Permo-Triassic Sandstones, the minimum and maximum values are 6 and 35% respectively. The porosity histogram (Figure 7.5.17d) shows a normal distribution, with an arithmetic mean of 24.3%, and an interquartile range of 22.0 to 26.9%. Clean, well-sorted samples have higher porosities than the muddier poorly sorted samples. Varying degrees of cementation also exert a control on porosity (Lovelock, 1977).

The Ormskirk–Helsby Sandstone Formation has the narrowest porosity range (Figure 7.5.17e), of 20 to 33%, with the largest proportion of high values. Although there is widespread cementation, it is principally at grain contacts and does not severely reduce the porosity. The well-sorted nature of the grains gives rise to the high porosities.

Variation of porosity with depth

There is no evidence from either the core porosity values in the database or from the radiometric logging conducted at

11 boreholes in north Merseyside (University of Birmingham, 1984), of a fall in porosity with depth in the upper 100 m of the aquifer. However, it is likely that porosity is reduced in deeper parts of the aquifer. Variations in cementation with depth have been noted by Greenwood and Travis (1915) and Double (1933) in boreholes from the Wirral, where increases in calcite cement were observed between 120 m and 167 m respectively. In the 200 m deep Speke Airport observation borehole [SJ 4234 8329] radiometric logging revealed a small fall in porosity below 140 m.

Porosity and hydraulic conductivity

Although hydraulic conductivity generally increases with porosity in the sandstones (Figure 7.5.18a–d), the hydraulic conductivity value associated with a particular porosity may vary by four or five orders of magnitude. The variations in grain size and sorting, and the extent and type of cementation, make it difficult to relate porosity and hydraulic conductivity qantitatively.

Pumping test storage coefficients

The database has storage coefficient records at 53 sites in the Cheshire and south Lancashire region. The site averages range from confined values of 1.2×10^{-5} through semi-confined values to rare low unconfined values of up to 0.09. The distribution of storage coefficient data (Figure 7.5.19) shows an approximately log-normal distribution, with a geometric mean of 1.1×10^{-3}. The interquartile range is 3.6×10^{-4} to 2.8×10^{-3}. There is no correlation from the data between pumping test length and storage coefficient value.

Changes in gradients of recovery or drawdown plots are common features in pumping tests in the region. Allen (1969) interprets them as being due to the influence of recharge or barrier boundary conditions. Alternative interpretations include delayed yield effects and vertical and lateral anisotropy of the sediments. Abstraction drawdown data show more deviations than recovery plots. These are caused by variable pumping rates and turbulent flow in the vicinity of the abstraction well.

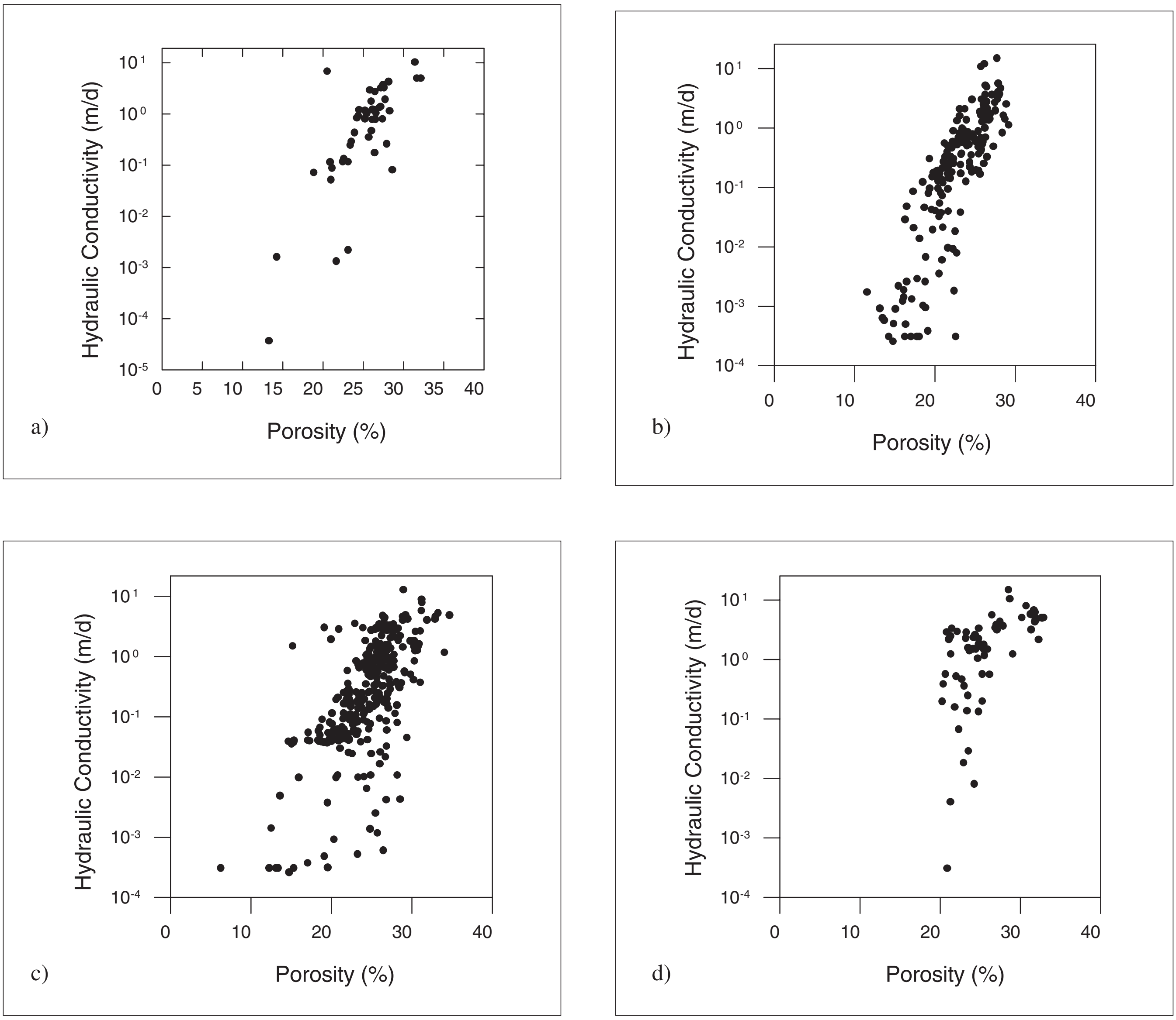


Figure 7.5.18 Plots of hydraulic conductivity against porosity for Permo-Triassic sandstone samples from the Cheshire and south Lancashshire region, a) Collyhurst–Kinnerton Sandstone Formation, b) Chester Pebble Beds Formation, c) Wilmslow Sandstone Formation, d) Helsby–Ormskirk Sandstone Formation.

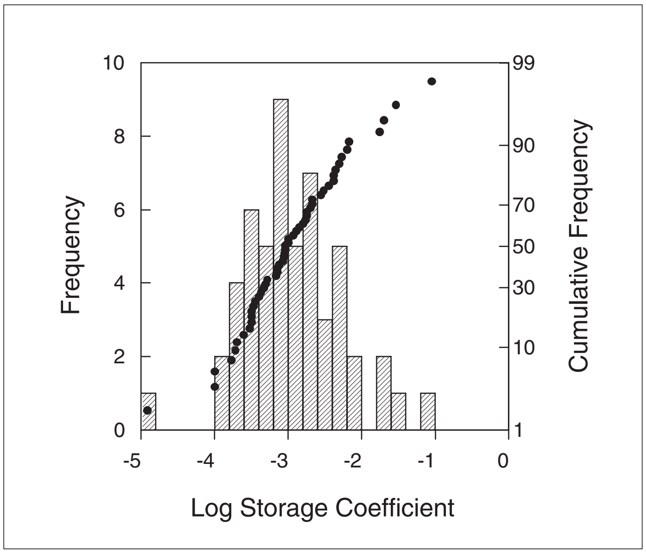


Figure 7.5.19 Distribution of storage coefficient data from pumping tests in the Permo-Triassic sandstones of the Cheshire and south Lancashire region.

Case studies

FOREST FARM [SJ 575 922], LOWER MERSEY BASIN

A 7 day abstraction test and a 7 day recovery test were carried out at Forest Farm Pumping Station, Lower Mersey Basin in order to obtain a reliable value of specific yield. The resultant value of 0.01 was lower than anticipated. The explanation given for this was that the observation well penetrates a depth of the saturated aquifer which is greater than the depth of the zone in which most of the flow occurs. Such observation wells, which are open through a considerable depth of the aquifer, can provide misleading results (University of Birmingham, 1981).

KENYON JUNCTION [SJ 648 965], LOWER MERSEY BASIN

Tests at Kenyon Junction made use of a series of vertically spaced piezometers in an observation borehole 34.5 m from the abstraction borehole. There was a significant variation between water levels at the free surface and those in deeper piezometers, indicating that permeability anisotropy is significant. The degree of response depends on the hydraulic conductivity of the zones which the piezometer samples.

The results were interpreted with an analytical model which could take account of the variations of head with depth. The best fitting model gave a storage coefficient of 2×10^{-4} to 4×10^{-4} and a specific yield of 6 to 12%. Porosity variations are independent of depth. University of Birmingham (1981) concluded that this technique of utilising piezometers at differing depths gives the most reliable pumping test interpretations.

ASHTON [SJ 505 689], WEST CHESHIRE

The Ashton pumping test is described in Section 7.5.2. At observation boreholes 2 and 4, there was no correlation between barometric pressure and water level, suggesting unconfined conditions. Early storage coefficients for the two boreholes, of 3×10^{-3} and 1×10^{-3} respectively, are higher than those calculated for the other observation holes, again suggesting that their overlying superficial deposits maybe relatively less confining (Mersey and Weaver River Authority, 1970).

Observation borehole 1 and observation borehole 3 had early storage coefficients of 7×10^{-4} and 4×10^{-4} respectively, indicating confined conditions. Late storage values were found to be greater than early ones. An early average of 6×10^{-4} increased with time to 3×10^{-3}.

SUMMARY

The Ashton pumping test used a selection of observation boreholes, which yielded different storage coefficients depending on the degree of confinement of the aquifer section sampled and on whether it was the early or the late data that were interpreted.

Observation wells which are open through a considerable depth of the aquifer may provide misleading results if the depth interval of the zone in which most flow occurs is less than the screened section. This was experienced at Forest Farm, but was avoided at Kenyon Junction because piezometers, which measure the piezometric head over much smaller intervals, were used instead. Interpreting nested piezometer levels with a radial flow model involves making fewer assumptions, and produces more accurate results, than traditional pumping test analysis. Unfortunately it is far more costly and has only been undertaken in a few instances.

Model storage

A regional Permo-Triassic specific yield of 14% was used to model the Lower Mersey Basin and north Merseyside by the University of Birmingham (1981 and 1984). This value is intermediate between the Kenyon Junction pumping test value of 6 to 12% and the mean core porosity of 22%. A value of 7×10^{-3} was used for the storage coefficient where the Permo-Triassic sandstones are overlain by drift. This relatively high value was chosen so that the contribution to storage from minor sands and gravels within the overlying clay could be incorporated. A storage coefficient of 5×10^{-4} was used where the aquifer is confined by the Mercia Mudstone Group.

Summary

Porosity varies slightly between formations, both in range and the nature of the frequency distribution. It reflects lithological variations such as grain size and shape, the degree of sorting and cementation. Porosity and hydraulic conductivity are roughly correlated. No porosity trend with depth within the top 100 m of aquifer is apparent

The highest values of core porosity are much greater than any values of storage coefficient derived from pumping tests. The latter consistently give confined and semi-confined values, but are considered unrepresentative in terms of specific yield. Radial flow model analysis of responses from nested piezometers, such as those at Kenyon Junction, provided the best specific yield results. Model values used are intermediate between porosity and pumping test values. Factors giving rise to these aquifer responses are detailed in Section 7.1.4.

7.6 FYLDE (NORTH-WEST LANCASHIRE)

7.6.1 Introduction

Geological and geographical setting

General description

The Fylde plain is located between Preston and Heysham. It lies to the west of the Bowland Forest, and includes Blackpool and Fleetwood (Figure 7.6.1). Covered by a thick sequence of Quaternary superficial deposits (drift), it has little topographic relief. The region lies within the North West Region of the Environment Agency and the Permo-

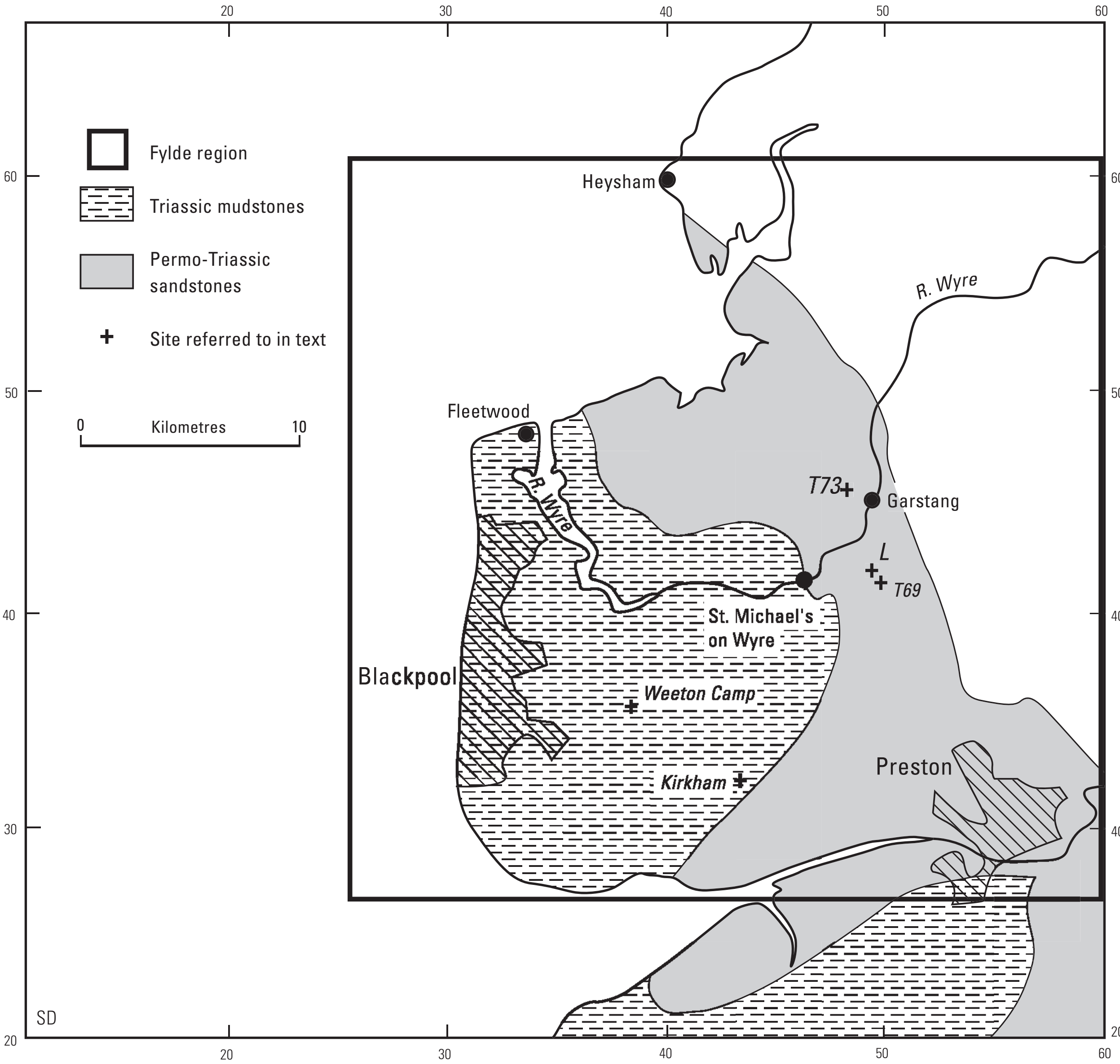


Figure 7.6.1 The Fylde — region covered and locations of places referred to in the text.

Triassic Sherwood Sandstone Group forms its major aquifer. The aquifer contains beds of poorly permeable mudstone which, together with marked fracturing in places, give rise to a significant heterogeneity in hydraulic properties.

Numerous boreholes have been drilled in the Sherwood Sandstone Group for water abstraction and monitoring purposes as part of a public water supply conjunctive use scheme. Abstraction is controlled in order to maintain river flows and to protect other abstractions (Peacock, A J, personal communication).

Regional structure

Structurally, the Fylde region is part of the West Lancashire Basin, an onshore extension of the Irish Sea Basin, which is connected *en echelon* to the Cheshire Basin to the south-east. Earth movements at the culmination of the Variscan Orogeny in late Carboniferous times resulted in local faulting and uplift associated with reactivated, basement structures. A long period of denudation then followed, forming a landscape of deeply eroded Carboniferous rocks with a relief not unlike that of the present day. The exposed land surface was deeply oxidised and reddened in the hot, arid climate. As sea level rose in the late Permian, the area was flooded from the north-west by the so-called Bakevellia Sea, and the mudstones of the Manchester Marl Formation were deposited on the faulted and folded Carboniferous 'basement'.

A phase of north–south-oriented rifting movements began in the early Triassic, producing a series of rapidly subsiding, fault-bounded basins that were to dominate and control palaeogeography and sedimentation in north-west England during the Triassic period. In the early Triassic, a major river system flowed northwards from the northern France–English Channel region via the Worcester and Cheshire Basins to the West Lancashire Basin and beyond. The sandy detritus transported and deposited by this river is preserved as the Sherwood Sandstone Group. Local thickness variations may well have been controlled by contemporary movements along growth faults and possibly along fold-axes (Wilson and Evans, 1990).

The river system gradually lost its power to transport sediment and, by the middle of the Triassic Period, when the Mercia Mudstone Group was deposited, the landscape was probably one of broad floodplains, mudflats and ephemeral lakes, at times briefly connected to the sea and at other times drying out, causing salt to be deposited.

Stratigraphy

The stratigraphical succession in the region, with its present and previous nomenclature, is shown in Table 7.6.1. The sequence below the Sherwood Sandstone Group consists predominantly of red-brown mudstones, assigned to the Manchester Marl Formation of late Permian age. These Permian strata are present at shallow depths in the east of the region, dipping westwards to greater depths near the Irish Sea coast. There is no equivalent in this region of the Collyhurst Sandstone, which underlies the Manchester Marl Formation in the Cheshire Basin.

Table 7.6.1 Permo-Triassic stratigraphy of the Fylde.

System and lithostratigraphical division	Previous division	Aquifer unit
TRIASSIC Mercia Mudstone Group	Keuper Marl	Aquitard
TRIASSIC Sherwood Sandstone Group	Bunter Sandstone	Aquifer
PERMIAN Manchester Marl Formation	Manchester Marls	Aquitard

Insufficient information is available in this region for the Sherwood Sandstone Group to be subdivided into formations. The sandstone is generally red to red-brown and fine to medium grained, with a few coarser bands. Rounded quartzite pebbles, common in the English Midlands succession, are rare here. Partings or beds of red silty mudstone, usually less than 0.6 m thick (although thicker beds have been proved), are commonly present; flakes or subangular clasts of similar mudstone are recorded at a few levels. The mudstone content and degree of carbonate cementation increases to the north-west.

The Sherwood Sandstone Group is overlain by the Mercia Mudstone Group in the west of the Fylde peninsula. Up to 50 m of Quaternary superficial deposits overlie the Permo-Triassic bedrock in the Fylde. The bedrock surface (rockhead) has considerably greater relief than the present Fylde plain.

Thickness

Many of the boreholes drilled in the subdrift outcrop penetrate over 150 m of the Sherwood Sandstone Group (Wilson and Evans, 1990), and some in the south-east and south-west of the basin have been thought to penetrate the underlying Manchester Marl Formation (However recent interpretation of seismic data suggests that these may in fact be persistent beds within the Sherwood Sandstone; this appears likely in the south-west, whereas in the south-east the presence of fault-bound horsts has been postulated (Seymour, K, personal communication)). Estimates based on gravity data indicate that the maximum depth to the base of Permo-Triassic strata may be about 3 km (Downing and Gray, 1986). Thickness variations in the region are mainly due to movement of syndepositional growth faults, which gravity and seismic evidence indicate to be present at the basin margins.

Faults

The Permo-Triassic rocks of the Fylde are gently folded and disrupted by a number of normal faults trending approximately NNE to SSE, and are either faulted against, or lie unconformably on, Carboniferous rocks.

There are indications that the Sherwood Sandstone Group was subjected to great tensional stress during deposition, resulting in growth faulting. The effects of this episode in the aquifer's structural history may have produced considerable inhomogeneities in sandstone permeability, both of the fractured and intergranular types (Brereton and Skinner, 1974). However the faults are obscured by the superficial deposits and consequently relatively little is known about them.

Hydrogeology

The Sherwood Sandstone Group aquifer is confined by the overlying Mercia Mudstone Group to the west, and by a thick layer of extensive superficial deposits cover to the east. Where glacial silty sands and gravels lie directly on top of the Sherwood Sandstone Group, they effectively form part of the aquifer. In most areas the permeable deposits are overlain by boulder clay, which acts as a confining layer. The sandstone is effectively unconfined where it is in direct contact with glacial sands and gravels, and the boulder clay is absent.

Glacial sand and gravels allow hydraulic connections between the underlying Permo-Triassic aquifer and rivers. There is significant leakage from certain stretches of the River Wyre and its tributaries when adjacent boreholes are pumped (Worthington, 1977). Windows in the superficial deposits permit limited groundwater recharge.

The Sherwood Sandstone Group of the Fylde has a low intergranular hydraulic conductivity and porosity. Fine-grained material is the most common, with laminations giving marked permeability anisotropy. The presence of thin marl bands gives rise to additional local anisotropy. Medium- and coarse-grained sandstones, where present, may be fairly clean, moderately well sorted and less cemented. The sandstones are almost entirely consolidated or well cemented; the friable types encountered further south are absent even close to the sub-drift surface (Lovelock, 1977). However, Worthington (1976) noted poor core sample recovery in some borehole sites, suggesting the presence of some unconsolidated material.

EFFECTIVE AQUIFER THICKNESS

Overlying glacial sand and gravels increase the effective thickness of the Sherwood Sandstone Group aquifer, increasing its apparent transmissivity and storage. Although the actual thickness of the Fylde Permo-Triassic Sandstone is up to 200 m (Brereton and Skinner, 1974) the effective thickness of the aquifer is, however, commonly considered to be equivalent to the maximum penetration of the pumping boreholes (Brereton and Skinner, 1974; Peacock, A J, personal communication) due to the presence of low hydraulic conductivity layers and the anisotropy shown by the core samples.

Conversely, Worthington (1977) argued that the effective aquifer thickness was greater than the depth of a partially penetrating borehole since the anisotropy ratio of intergranular horizontal to vertical hydraulic conductivity was only two. However this core-scale argument ignores the effect of low permeability layers, which significantly reduce aquifer-scale vertical hydraulic conductivity.

Previous hydrogeological investigations

An extensive investigation into the Fylde aquifer was carried out in the early 1970s as part of a study for the Lancashire Conjunctive Use Scheme. This comprised fieldwork undertaken by the Fylde Water Board and Lancashire River Authority and the development of a regional groundwater flow model by the Water Resources Board (Oakes and Skinner, 1975). As part of this investigation five group-pumping tests of the aquifer were conducted in order to gain more detailed information for the model. They were designed to stress the aquifer to assess the effect of pumping on the River Wyre, and to deduce the degree of leakage. Their durations ranged from 53 to 300 days.

The above investigation was complemented by core permeability measurement and geophysical work by the University of Manchester Institute of Science and Technology (Bow et al., 1970) and Birmingham University (Worthington, 1973).

The hydrogeology of the Sherwood Sandstone Group aquifer is currently being reviewed and remodelled by the Environment Agency in conjunction with North West Water plc and Mott MacDonald as part of the Fylde Aquifer and Wyre Catchment Water Resources Study.

7.6.2 Hydraulic conductivity and transmissivity

Hydraulic conductivity has been measured on a variety of scales on the Sherwood Sandstone Group aquifer. Laboratory permeametry provides the intergranular hydraulic conductivity of core samples. Down-hole geophysical logging shows where productive fractures occur. Bulk hydraulic conductivity values, combining both fracture and intergranular flow contributions averaged over a kilometre scale, can be obtained from the analysis of pumping tests. Regional scale values can be deduced from groundwater flow modelling. Results from these different techniques are considered in turn below.

Core data

Core hydraulic conductivity values for the Sherwood Sandstone Group held on the British Geological Survey's database tend towards a log-normal distribution (Figure 7.6.2a), with a pronounced negative skew. They span over four orders of magnitude, ranging from 1.8×10^{-4} to 4.1 m/d. The geometric mean is 0.08 m/d, the median is 0.14 m/d and the interquartile range is 0.02 to 0.52 m/d. There is no apparent trend of hydraulic conductivity variation with depth in the available core data, which correspond to depths of up to 110 m below ground level.

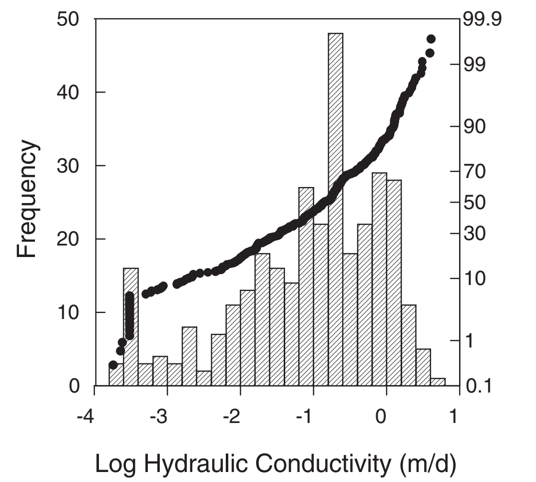
Permeametry was also conducted by Brereton and Skinner (1974) on 85 core samples, taken at 1 m intervals from the high-yielding borehole at site [SD 498 411]. Horizontal hydraulic conductivity was found to span three orders of magnitude, from 0.1 to 10 m/d.

Lithology has a major control on intergranular hydraulic conductivity. Less-permeable, fine-grained material is most common, with laminations giving marked permeability anisotropy. For fine-grained material the hydraulic conductivity data ranges from 0.006 to 0.06 m/d, and values in the horizontal direction may be up to 4 or 5 times the vertical values. Medium- and coarse-grained sandstones, where present, are an order of magnitude more permeable. Fairly clean, moderately well sorted and less cemented, they have a median hydraulic conductivity of 0.9 m/d in the horizontal direction and 0.02 m/d in the vertical direction (Lovelock, 1977).

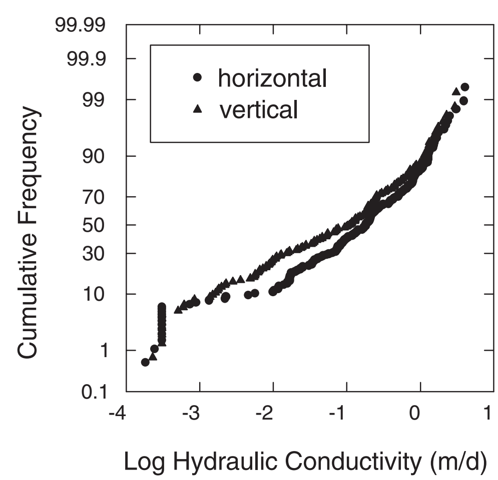
Horizontal hydraulic conductivity values from the database are usually greater than vertical values (Figure 7.6.2b). Statistics of the different distributions are given in Table 7.6.2. The ratio of the geometric means of horizontal values to vertical values, that is the mean core-scale anisotropy ratio, is 1.8. This core-scale anisotropy has the effect of enhancing the aquifer scale anisotropy, which arises from the layering of finer-grained (less permeable) and coarser-grained (more permeable) sediments.

From their data Brereton and Skinner (1974) assumed that a median value of 0.50 m/d was representative of bulk aquifer intergranular hydraulic conductivity, whereas Worthington (1977) argued that an arithmetic mean of 1 m/d was more appropriate. Lovelock's (1977) medium-grained sandstone median was 0.9 m/d. 'Representative' values for intergranular hydraulic conductivity therefore range from 0.1 to 1 m/d.

Relationships between hydraulic conductivity, resistivity and seismic velocity in core samples were investigated by Barker and Worthington (1973b). They were conducted with a view to applying the findings to resistivity sounding



a)



b)

Figure 7.6.2 Distribution of hydraulic conductivity data for Permo-Triassic sandstone samples from the Fylde, a) all samples, b) horizontal and vertical samples.

Table 7.6.2 Hydraulic conductivity data for the Permo-Triassic sandstones of the Fylde.

Orientation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
All	1.8×10^{-4}–4.1	0.02–0.52	0.14	0.08
Horizontal	1.8×10^{-4}–4.1	0.04–0.65	0.18	0.11
Vertical	2.3×10^{-4}–3.1	9.6×10^{-3}–0.4	0.10	0.06

and seismic refraction results within the Fylde, in order to determine regional hydraulic conductivity variations indirectly. This approach is most useful where intergranular flow predominates. Where fracture flow is dominant, the equations only allow an estimate of minimum field hydraulic conductivity. It was found that on a core scale, hydraulic conductivity (K) and p wave velocity (V) could be related by:

$$V = (1.4 \pm 0.1)–(0.38 \pm 0.07) \log K$$

and that:

$$F = (3.3 \pm 0.1)K^{-(0.17 \pm 0.02)}$$

where F is the formation factor, i.e. the ratio of the resistivity of saturated sandstone to that of the saturating solution. Velocity was measured in kilometres per second, and hydraulic conductivity in millimetres per second.

Geophysical logging

Brereton and Skinner (1974) describe the geophysical logging of a cored observation borehole [at SD 498 411]. It is located within a group of four high yielding abstraction boreholes (North West Water sites L1 to L4). Temperature logging in static conditions indicated natural inflows at 67 m and 84 m depth. Flowmeter and temperature logging, conducted whilst the adjacent wells were being pumped, revealed further anomalies indicative of fracture flow.

The presence of fractures at the inferred depths was confirmed by TV logging. Bedding planes appear locally as more fissile bands, cavities only developing if water has been drawn through at high velocity for some time. Only one of the fracture planes showed evidence of being connected to the pumping wells.

Pumping test transmissivity and bulk hydraulic conductivity

Transmissivity and specific capacity

Both transmissivity and specific capacity data vary widely, even over limited areas of the aquifer. As part of the Lancashire Conjunctive Use Scheme investigation certain proposed abstraction boreholes were found to produce low yields, even when sited on the basis of promising information from nearby trial boreholes. The interpolation of hydrological parameters between boreholes was therefore deemed inadvisable (Worthington, 1975).

The database has specific capacity records at three sites in the Fylde, with values of 100, 140 and 270 m^3/d/m, and a geometric mean of 150 m^2/d. Worthington (1977) showed that boreholes penetrating loosely cemented sandstones had higher specific capacities than those penetrating strongly cemented ones (Figure 7.6.3). It was inferred therefore that intergranular hydraulic conductivity has a control on aquifer production capacity.

The aquifer properties database contains transmissivity records from seven sites in the Fylde region. The site transmissivity values vary from 26 to 1100 m^2/d, with an interquartile range of 140 to 710 m^2/d. The geometric mean is 260 m^2/d, and the median is 360 m^2/d. Although the transmissivity values may vary randomly across the Fylde region, Reeves and Skinner (1974) suggested that, on a local (1 km^2 basis), it can be isotropic, presumably due to homogeneous and widespread fracturing.

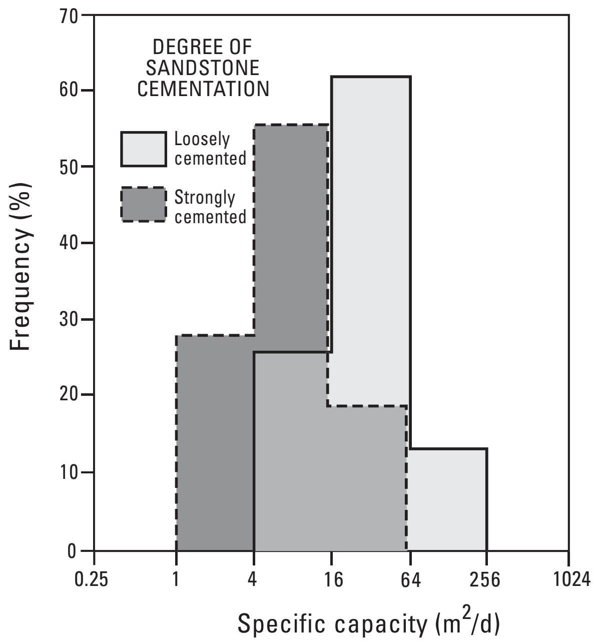


Figure 7.6.3 Distribution of specific capacity data for different degrees of sandstone consolidation (after Worthington, 1977).

An 8 day aquifer test was carried out by the Fylde Water Board at site L, Myerscough [SD 4979 4104]. The site was chosen because the four abstraction boreholes, all within 70 m of each other, were high yielding, and fracture flow was suspected. The boreholes were pumped simultaneously and the drawdowns were recorded at three observation wells, each about 500 m away. The drawdown-time response was similar at each observation borehole (Figure 7.6.4), (Brereton and Skinner, 1974), indicating that the bulk aquifer properties over the 1 km^2 study area are essentially isotropic. Fracturing was therefore assumed to be widespread and homogenously distributed over the test area. A transmissivity of 1100 m^2/d was calculated. This corresponds to a bulk hydraulic conductivity of 8.5 m/d if the effective aquifer thickness is taken as the borehole depth (Worthington, 1977).

Bulk hydraulic conductivity

Bulk hydraulic conductivity values have been calculated from the Aquifer Properties Database pumping test transmissivities for four sites in the Fylde region. The data range from 3.4 to 7.4 m/d, and have a geometric mean

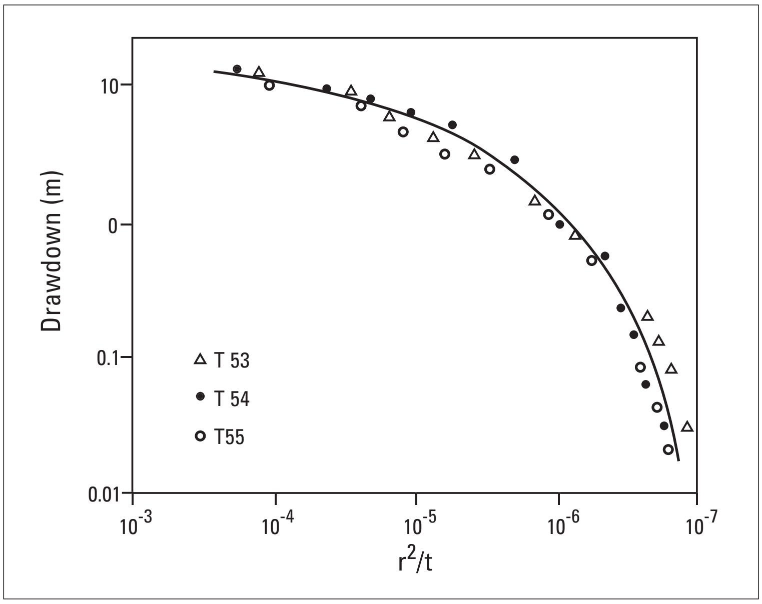


Figure 7.6.4 Drawdown curves for three observation boreholes at site L in the Fylde (after Brereton and Skinner, 1974).

of 5.3 m/d. When values of core (Table 7.6.3) and bulk hydraulic conductivity are compared, the bulk values are found to lie at and beyond the high end of the core hydraulic conductivity range. This suggests (albeit with very limited data) that the fracture flow contribution to the total hydraulic conductivity is clearly significant. At Crow Wood [SD 501 401] near Garstang, the bulk hydraulic conductivity is a factor of 13 times bigger than the core hydraulic conductivity geometric mean of 0.41 m/d, indicating the important contribution of fracture flow to the borehole.

Barker and Worthington (1973b) inferred from their data that a large overlap of bulk and core hydraulic conductivity suggested that intergranular flow is important in the Fylde's Sherwood Sandstone Group, although they recognised that it is locally supplemented by fracture flow. Reeves and Skinner (1974) believed that horizontal intergranular hydraulic conductivity is relatively uniform over the region and concluded that large variations in the bulk aquifer properties are likely to indicate the variation of fracture development in the sandstones.

Conversely, Worthington (1977) argued that it is laterally variable intergranular hydraulic conductivity which exerts a basic control on Fylde borehole productivity. Variations in localised fracture development are relatively unimportant unless the intergranular hydraulic conductivity is relatively high. This can allow a strong transmission of water to the fracture network which in turn supplements the intergranular flow across the well face. Maximum yields will occur where strong intergranular flow is enhanced by localized fracturing. Fractures can be regarded as extensions of the borehole face at which intergranular flow terminates rather than as a regional features which exert a primary control on aquifer productivity (Worthington, 1977).

Worthington (1977) compared arithmetically averaged core hydraulic conductivity with bulk pumping test derived hydraulic conductivity at several sites. At site T73 (Figure 7.6.1), the sandstone is coarse grained and loosely to moderately consolidated. Core hydraulic conductivity was 0.4 m/d, and pump test hydraulic conductivity ranged from 0.1 to 1.0 m/d, depending on the thickness used. Intergranular flow was presumed to be the dominant flow mechanism.

The horizontal intergranular hydraulic conductivity, at the high yielding borehole T69 [SD 498 411], is significantly lower than the pumping test derived bulk aquifer hydraulic conductivity. It is lower by a factor of 17, if median horizontal core hydraulic conductivity (0.50 m/d) and bulk hydraulic conductivity calculated with borehole penetration depth (8.5 m/d) are compared (Reeves and Skinner, 1974). However, the arithmetic mean core hydraulic conductivity (1 m/d) is just 5.5 times lower than the bulk hydraulic conductivity calculated using aquifer depth (5.5 m/d) (Worthington, 1977). Fracture flow is invoked as the dominant flow mechanism in this region, although the degree is controversial.

Model transmissivity

The Fylde aquifer was modelled for the Lancashire Conjunctive Use Scheme (LCUS) and is described by Oakes and Skinner (1975). The neat distribution of transmissivity contours (Figure 7.6.5) bears little relation to the randomly distributed pumping test values. In the east, lower transmissivities are used, in order to reflect the reduced thickness there. This gives rise to steeper hydraulic gradients towards the east. Overall, transmissivities range from 150 to 1500 m^2/day. This upper value is comparable with the maximum value in the aquifer properties database of 1100 m^2/d. Reeves et al. (1975) state that the modelled transmissivity distribution cannot be explained entirely in terms of varying aquifer thickness and lithology, but can be accounted for in terms of a variable density of fissuring.

The recent review and remodelling of the Sherwood Sandstone Group aquifer in the Fylde obtained good simulations of observed piezometry over a 20 year period using transmissivities predominantly in the range of 500 to 2000 m^2/d (corresponding to hydraulic conductivity values of 0.1 to 10 m/d). The aquifer was modelled as two-layer system, reflecting the presence of relatively persistent low permeability marl layers within the sequence. This was necessary to simulate the observed piezometry across the Fylde aquifer over the last 20 years of operation of the

Table 7.6.3 Comparison of hydraulic conductivities of the Permo-Triassic sandstones of the Fylde measured at different scales.

Measurement method	Scale	Hydraulic conductivity (m/d)	
		Range	Geometric mean
Core permeametry	Intergranular	10^{-4} to 4	0.08
Pumping test	Borehole	3 to 7	5.3

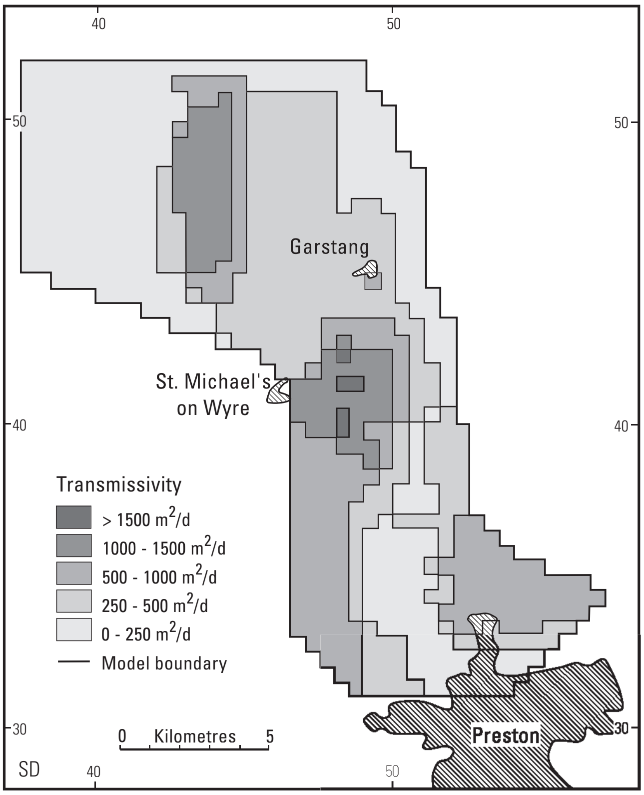


Figure 7.6.5 Model transmissivity distribution for the Permo-Triassic sandstones in the Fylde (after Oakes and Skinner, 1975).

LCUS. The presence of sands with high storage and permeability in hydraulic continuity with rivers may also account for the apparently high sandstone transmissivity values (Seymour, K, personal communication).

Summary

The Permo-Triassic Sandstone of the Fylde has a much lower intergranular hydraulic conductivity and porosity than that of Nottinghamshire and of the central Midlands. It is almost entirely consolidated and well cemented. The distribution of core hydraulic conductivity is significantly lower for Fylde core samples (Figure 7.6.2) than Cheshire core samples (Figure 7.5.7). The trend of intergranular hydraulic conductivity decreasing northwards corresponds to the decreasing grain-size of the sediments.

Groundwater flow in the Fylde region was initially thought to be predominantly of an intergranular nature. However further studies have shown that this assumption cannot be made and that fracture flow is highly significant in the Triassic Sherwood Sandstone Group. Differences in the areal distribution of transmissivity cannot be explained by thickness changes alone. Closed circuit television techniques have confirmed the presence of fracture flow in high discharging boreholes. Bulk hydraulic conductivities obtained from pumping test analyses are typically two orders of magnitudes greater than intergranular hydraulic conductivity (Table 7.6.3); again, this can be attributed to fracture flow.

Recent modelling has suggested regional transmissivity values lie mainly in the range 500 to 2000 m^2/d, and may be affected by the presence of rivers in hydraulic continuity with the sandstone as well as glacial sands directly above rockhead.

7.6.3 Porosity and storage

Storage, like hydraulic conductivity, can be measured at a range of scales. Microscopic analysis reveals the nature of porosity, and core permeametry gives its magnitude. Pumping test analysis gives confined storage coefficients.

Core porosity

A frequency histogram of porosity values of all the Sherwood Sandstone Group values in the Aquifer Properties Database is shown in Figure 7.6.6. These range from 5.4% to 31%, with an arithmetic mean of 23% and with a standard deviation of 5%. It is a negatively skewed normal distribution, with an interquartile range of 20 to 26%. There is no apparent trend of porosity with depth within the 120 m below ground level from which the samples were taken. Lovelock (1977) noted a variation of porosity with grain size: coarse-grained sands have a porosity range of 24 to 28%, which is higher than the 15 to 20% range of fine-grained sediments.

Analyses of samples from boreholes at Kirkham [SD 4324 3247] and Weeton Camp [SD 388 360] were undertaken by Strong (1993) using optical microscopy, electron microscopy and image analysis techniques. The present high porosity characteristics of some of these sandstones are considered to be the result of early cementation and preservation of a primary porosity by early calcite, non-ferroan dolomite, possibly halite, anhydride and gypsum cements, followed later by cement dissolution, leaving remnants of calcite and non-ferroan dolomite.

Minor ferroan dolomite, some calcite, illite and kaolinite cements which now occur are generally considered to be later cements. The distinctive quartz arenite units were cemented by early quartz cements, probably before significant burial and compaction. The different authigenic clay assemblages appear to be the result of different fluid-flow histories in later diagenesis, possibly structurally controlled (Strong, 1993).

Porosity generally increases with hydraulic conductivity (Figure 7.6.7) but the hydraulic conductivity value associated with a particular porosity can vary by four or five orders of magnitude, because pore throat sizes affect hydraulic conductivity. The sizes of the pores and their

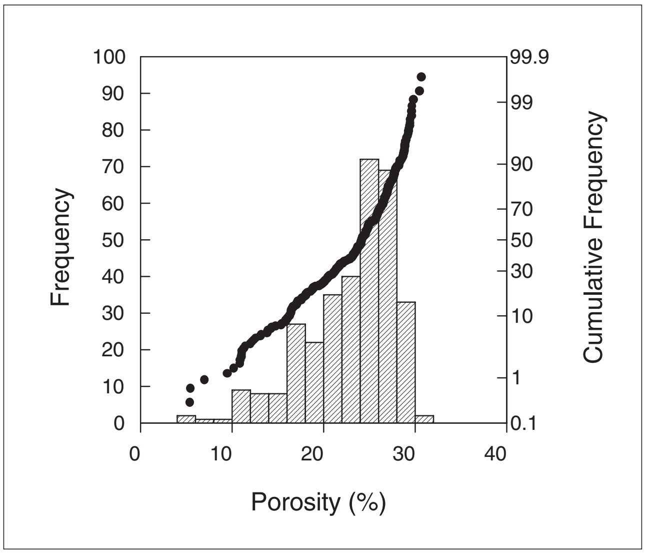


Figure 7.6.6 Distribution of porosity data for Permo-Triassic sandstone samples from the Fylde.

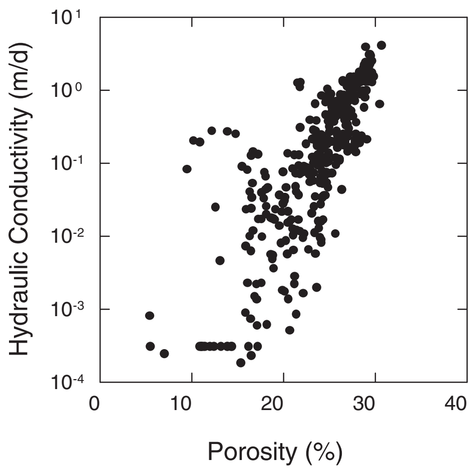


Figure 7.6.7 Plot of intergranular hydraulic conductivity against porosity for Permo-Triassic sandstone samples from the Fylde.

throats are in turn influenced by the degree and type of cementation, varying grain size, grain shape and sorting.

After working on core samples, Barker and Worthington (1973b) deduced relationships between porosity, seismic velocity, and resistivity. This work was conducted with a view to applying the findings to resistivity sounding and seismic refraction results within the Fylde, in order to determine regional porosity variations indirectly. It was found that Fylde porosity (n) can be calculated from p wave velocity (V) (km/s) by:

$$V = (0.43 \pm 0.13) - (2.99 \pm 0.24) \log_{10} n.$$

A relationship between the porosity and the formation factor (F), which is ratio of the resistivity of saturated sandstone to that of the saturating solution, was also determined:

$$F = (1.05 \pm 0.08)\, n^{-(1.47 \pm 0.05)}.$$

Pumping test storage

Storage coefficient records in the database are available for 5 sites in the Fylde region, with values ranging from 8.1×10^{-5} to 0.17. The latter is atypically large and represents an unconfined specific yield value, (possibly reflecting overlying sand storage characteristics). The interquartile range is 2×10^{-4} to 2×10^{-3} and both the geometric mean and the median are 0.0015.

A confined storage coefficient of 2×10^{-3} was calculated from the three observation borehole pumping test at site L, [SD 498 411]. The aquifer remained fully confined throughout the test. Five weeks after pumping started, TV logging at an observation well adjacent to the abstraction wells revealed flow from fractures above the water level, illustrating the slow rate of gravity drainage (Brereton and Skinner, 1974).

Model storage

Oakes and Skinner (1975) describe the Lancashire Conjunctive Use Scheme's model. The confined storage coefficient is estimated to range from 8×10^{-5} to 7×10^{-3}. These values are applied where confinement by superficial deposits occurs. A specific yield value is used when water levels fall below the clay base; this is taken as 0.015 where the water table remains within the drift, and as 0.09 when the water table is within the Permo-Triassic sandstones. These specific yield values are intermediate between the low end of core porosity values and the higher pumping test storage values.

The recent modelling of the Fylde aquifer used a confined storage coefficient of 5×10^{-5} and a specific yield of 0.06 (Seymour, K, personal communication).

Summary

The porosity of the Sherwood Sandstone Group appears to be controlled by the primary lithology, rather than secondary cementation. Finer-grained horizons have lower porosities than the medium- to coarse-grained layers. There are no marked trends of porosity with depth, but porosity and hydraulic conductivity are positively correlated. Porosity can be related to resistivity and seismic velocity in core samples. Unconfined storage coefficient values used in the original (WRc) Lancashire Conjunctive Use Scheme model are intermediate between porosity and pumping-test values whereas confined storage values used for the model are similar to pumping-test values.

7.7 NORTH-WEST ENGLAND

7.7.1 Introduction

Geological and geographical setting

General description

This region encompasses a number of basins surrounding much of the Lake District massif (Figure 7.7.1). The Permo-Triassic aquifers of the Vale of Eden and Carlisle areas occur within adjacent, connected basins and have experienced a similar geological history. The west Cumbria and Furness sequences were deposited at the margin of the East Irish Sea Basin. There are significant differences in the stratigraphy present in the three basins. This, taken with the geographical separation of the west Cumbria and Furness areas, makes it appropriate to consider the detailed aquifer properties on a sub-regional basis, rather than taking the more general view employed for other regions. An overview, highlighting similarities and differences in the aquifer properties of the Permo-Triassic sediments is presented in this introduction. More detailed discussions of the properties and stratigraphy attributable to specific lithological units are by sub-region; namely the Carlisle Basin (7.7.2), the Eden Basin (7.7.3), west Cumbria (7.7.4) and the Furness area (7.7.5).

Regional structure and depositional history

Structurally the region is dominated by the Lake District massif, which consists of rocks of Lower Palaeozoic age. The massif is encircled by the outcrop of younger Carboniferous and Permo-Triassic rocks. Permo-Triassic strata occur to the north-east, north and south-west of the Lake District massif and generally dip away from it. They are preserved within the Vale of Eden, Carlisle and East Irish Sea Basins, which were formed by extension and rifting in early Permian times. The aeolian Penrith Sandstone Formation and contemporaneous alluvial fan conglomerates and breccias (Brockram) were deposited during the early Permian in a dominantly arid climatic regime. In the late Permian, global sea level rise led to marine flooding of the deeper parts of these basins and the deposition of mudstones and associated evaporites (St Bees Shale, Eden

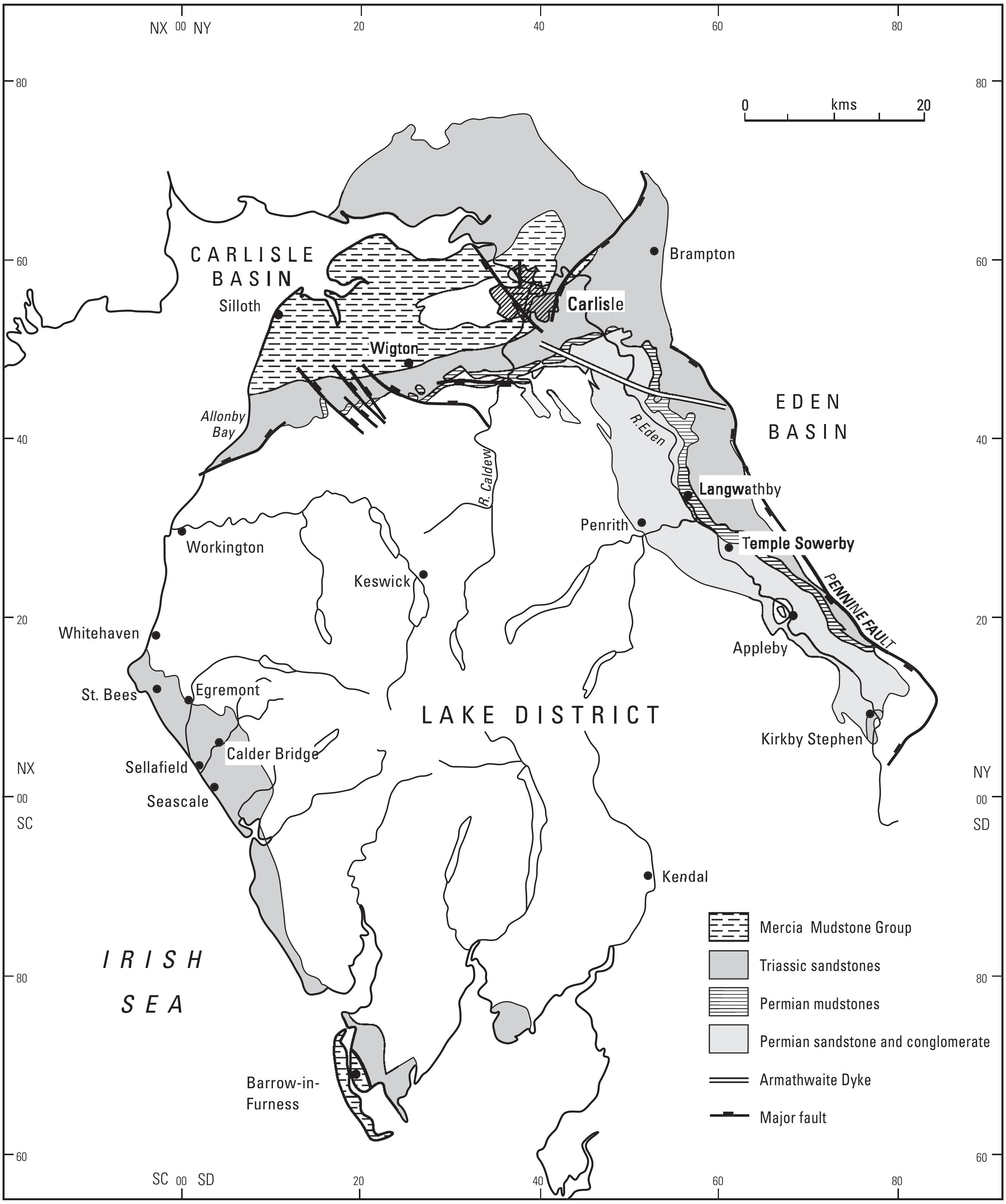


Figure 7.7.1 General setting of the Permo-Triassic sandstones of north-west England.

Shale, St Bees Evaporite formtions). Brockram continued to be deposited towards the basin margins. The early Triassic saw the establishment of a major river system flowing across the region, with the deposition of the predomnantly fluvial sandstones of the lower part of the Sherwood Sandstone Group (St Bees Sandstone Formation). More arid conditions returned later in the Triassic, firstly resulting in deposition of the predominantly aeolian sandstones of the upper part of the Sherwood Sandstone Group (Calder, Ormskirk and Kirklinton Sandstones) and later the deposition of the alluvial plain/saline mudflat deposits of the Mercia Mudstone Group. The general stratigraphy of the region is shown in Table 7.7.1.

General hydrogeology

The groundwater in the Permo-Triassic sandstones is widely used for water supply. Near the outcrop, the chemical quality of the groundwater in the Permo-Triassic

Table 7.7.1 Permo-Triassic stratigraphy of the north-west (after Warrington et al., 1980 and Nirex, 1993a).

Age	Group	Formation						Aquifer unit
		West Cumbria	Thickness (m)	Carlisle Basin	Thickness (m)	Vale of Eden	Thickness (m)	
Triassic	Mercia Mudstone		<3700		<400	absent	—	Aquitard
	Sherwood Sandstone	Ormskirk Sandstone	250	Kirklinton Sandstone	10–100			
		Calder Sandstone	650–1000					Aquifer
		St Bees Sandstone	<1000	St Bees Sandstone	<500	St Bees Sandstone	<350	
Permian		St Bees Shale	0–200	St Bees Shale	<90	Eden Shale	<180	Aquitard
		St Bees Evaporite	0–200					
		Brockram/ Collyhurst Sandstone	0–220	Penrith Sandstone (present at depth)	0–?	Penrith Sandstone	<900	Aquifer

sandstones is generally good, particularly in the Penrith Sandstone Formation. The total dissolved solid content is only about 200 mg/l, but the sulphate concentration can be high where flow is from the evaporites in the Eden and St Bees Shale Formations. In the west along the Irish Sea coast there is only limited saline intrusion, which occurs mainly in the south of Cumbria.

Around the Sellafield area rivers are locally in contact with the aquifer and some water pumped from the aquifer comes indirectly from the rivers. In the northern Carlisle and Eden basins drift cover locally separates rivers from underlying aquifers, but there is some connection.

Aquifers

The main aquifer in the region is the early to mid-Triassic Sherwood Sandstone Group (Table 7.7.1). The lowest formation of the Sherwood Sandstone Group, the St Bees Sandstone, is present throughout the region. Other, overlying formations are recognised within the group in the Carlisle Basin (Kirklinton Sandstone) and on the Cumbrian coast (Calder and Ormskirk Sandstone formations). The early Permian Penrith Sandstone Formation is present in both the Carlisle and Vale of Eden basins, but is only exploited, significantly, as an aquifer in the latter, where it is important.

Aquitards

The aquitards within the sequence are formed by the Permian Brockram Formation (except in the Eden Basin), St Bees Shale and Eden Shale formations, and the Triassic Mercia Mudstone Group. The Brockram Formation comprises a strongly cemented calcareous breccia which has a very low permeability. It forms an aquitard, which interdigitates with the Penrith Sandstone Formation in the southern part of the Eden basin and the St Bees Sandstone Formation in west Cumbria along the basin margins. The St Bees Shale Formation, of late Permian age, forms an aquitard below the Sherwood Sandstone Group throughout much of west Cumbria and the Carlisle Basin. The equivalent Eden Shale Formation of the Vale of Eden separates the Penrith Sandstone Formation and St Bees Sandstone aquifers. The Mercia Mudstone Group overlies and confines the Sherwood Sandstone Group aquifer in the central part of the Carlisle Basin and in parts of the Furness area (Table 7.7.1).

Faults

The St Bees Sandstone is exposed on the edge of the Manx Basin along the west Cumbrian coast and dips toward the Irish Sea. Faults commonly occur as discrete planes of dislocation rather than broad deformation bands. Faults strike roughly east-west and form two conjugate sets dipping north and south. Deformation zones associated with the faults vary in thickness from 1 to 370 mm. Generally, the sediment has been sheared and crushed in the deformation zone, leading to significant reduction in grain size and permeability compared to the unfaulted rock (Knott, 1994). Vertical joints are also present and parallel to one set of faults.

Faults are also present in the Vale of Eden. The two main sets trend west-north-west and north-north-east and are extensional normal faults (Knott, 1994). These faults are likely to have a low permeability across their shear zones, though they may rapidly transmit water parallel to any associated fracturing. This may result in regional anisotropy of permeability, with a decrease the regional permeability in a north-south direction across the trend of the faulting. Faults with large displacements have thicker sheared zones and are likely to be more impermeable to flow across them. However boreholes in the St Bees Sandstone Formation which intersect fault zones have higher yields, suggesting that generally the fracturing increases the permeability of the sandstones at least in some directions. Fault zones may be detected in the Vale of Eden where there is no drift cover, but the more general drift cover in the Carlisle Basin obscures faults within the sandstone. Very detailed mapping of west Cumbria has revealed many faults within the Sherwood Sandstone Group and suggests that faulting is prevalent throughout the formation but is frequently obscured by drift and weathering of the sandstones at outcrop.

Anisotropy

Generally the Sherwood Sandstone Group forms one aquifer, however with depth its matrix permeability decreases and fractures are less transmissive. In consequence the effective aquifer thickness is confined to the top few hundred metres. In addition the considerable interlayering found in nearly all the Sherwood Sandstone Group gives an overall anisotropy to the aquifer.

Previous hydrogeological investigations

There have been a number of investigations in this region. Much work has been carried out by UK Nirex Ltd (1993a and 1993b) and a number of sub-contractors in the Sellafield region investigating a site for a potential waste repository. This has included extensive geological characterisation of the area including the St Bees Sandstone Formation, with borehole logging and core permeability and porosity measurements. Modelling of the groundwater flow has also been carried out. There has been limited work on the St Bees Sandstone Formation west of Carlisle and in the Eden Valley including BGS investigation in the Penrith Sandstone aquifer at Cliburn (Lovelock et al., 1975; Price et al., 1982); and a brief water resources study in the Furness area in the south (Brassington and Campbell, 1979).

Regional aquifer properties

Core data

Comparison of the median core hydraulic conductivity between regional subdivisions (Table 7.7.2) indicates that the Penrith Sandstone Formation is more permeable than the St Bees Sandstone Formation. The St Bees Sandstone Formation appears to be more permeable in the north than the south. However, this could however be a function of the depth at which the core samples are taken, as the permeability is likely to decrease with depth.

Core horizontal and vertical permeabilities are generally similar, there appears to be little core-scale anisotropy (Table 7.7.3). The St Bees Sandstone Formation in Cumbria shows a small degree of anisotropy, with greater horizontal permeability. The wide range of permeabilities: from 1.9×10^{-6} m/d to 0.94 m/d in the St Bees Sandstone Formation in Cumbria, and 5.5×10^{-3}–4.46 m/d in the St Bees Sandstone Formation in the Carlisle Basin and Vale of Eden, indicates that there is potential for overall anisotropy within the aquifers due to lithologies of differing permeabilities.

Porosity values show a wide range, corresponding to the wide range of permeability values. The highest porosities are seen in the north of the region, with an arithmetic average of 27% in the St Bees Sandstone Formation in the Carlisle Basin and the Vale of Eden, and an average of 24% in the Penrith Sandstone Formation (Table 7.7.4). The Penrith Sandstone Formation has in general a slightly lower porosity than the northern St Bees Sandstone Formation. In contrast in the south of the region, the Cumbrian St Bees Sandstone Formation has lower porosity average of 16%, which is mirrored by lower permeability values in this area.

Transmissivity and storage coefficients

At relatively shallow depths (of the order of 100 m), both the Triassic Sherwood Sandstone Group (the St Bees Sandstone Formation) and the Permian Penrith Sandstone Formation are good aquifers. Typical values for field transmissivities are 100 to 300 m^2/d but values can be much higher reaching 1000s m^2/d (Lovelock, 1977). Generally the transmissivity obtained from pumping tests in the west Cumbria area is of the order of hundreds of metres squared

Table 7.7.2 Permo-Triassic sandstone core hydraulic conductivity data, north-west England.

Group or Formation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Penrith Sandstone: Vale of Eden	3.5×10^{-5}–26.2	0.3–3.95	1.35	0.8
Sherwood Sandstone				
St Bees Sandstone: Carlisle Basin and Vale of Eden	5.5×10^{-3}–46	0.14–0.39	0.23	0.24
St Bees Sandstone: West Cumbria	1.9×10^{-6}–0.94	1.9×10^{-4}–0.014	1.3×10^{-3}	1.3×10^{-3}

Table 7.7.3 Horizontal and vertical core hydraulic conductivity data for the Permo-Triassic sandstones, north-west England.

Group or Formation	Orientation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Penrith Sandstone	Horizontal	2.6×10^{-4}–22.3	0.28–3.9	1.1	0.71
	Vertical	3.5×10^{-5}–14.7	0.07–2.8	0.37	0.3
St Bees Sandstone: Carlisle Basin and Vale of Eden	Horizontal	5×10^{-3}–4.4	0.16–0.41	0.26	0.26
	Vertical	0.01–4.5	0.12–0.37	0.21	0.21
St Bees Sandstone: Cumbria	Horizontal	1.93×10^{-6}–0.94	3×10^{-4}–0.025	2.9×10^{-3}	2.3×10^{-4}
	Vertical	1.9×10^{-6}–0.21	1.4×10^{-4}–5.5×10^{-3}	7×10^{-4}	7.2×10^{-4}

Table 7.7.4 Permo-Triassic sandstone core porosity data, north-west England.

Group or Formation	Range (%)	Interquartile range (%)	Median (%)	Arithmetic mean (%)
Penrith Sandstone	5.6–35.1	21.1–27.8	24.1	24.1
Sherwood Sandstone:				
St Bees Sandstone: Carlisle Basin and Vale of Eden	19.3–34.9	25.3–30.1	26.9	27.4
St Bees Sandstone: Cumbria	3.7–27.2	12.9–20.2	15.2	16

per day and the geometric mean of transmissivity for all the aquifers of the whole north-west region is 240 m^2/d (Figure 7.7.2, Table 7.7.5). The large difference between the intergranular and field transmissivities reflects the extent that fractures control the rate of flow through the aquifers (at least on a local scale).

The pumping test transmissivities of the St Bees Sandstone Formation in west Cumbria appear to be fairly constant. This suggests that the effective hydraulic conductivity of the freshwater aquifer sampled by boreholes is similar throughout the formation. By contrast, in the Carlisle Basin the Sherwood Sandstone Group (Kirklinton Sandstone and St Bees Sandstone formations) has a wide range of transmissivities from tens to hundreds of metres squared per day with exceptional borehole transmissivities of up to thousands of metres squared per day. In the north of the Vale of Eden the St Bees Sandstone Formation has transmissivities of a similar range to the St Bees Sandstone Formation in West Cumbria, with transmissivities of tens to hundreds of metres squared per day. In contrast to the St Bees Sandstone Formation, the Penrith Sandstone Formation in the south of the Vale of Eden has higher transmissivities which are generally up to 1000s m^2/d (Figure 7.7.3). Generally the storage values obtained from pumping tests are confined to semi-confined values, with a geometric mean of 1.7×10^{-4} (Figure 7.7.4, Table 7.7.5).

Established large diameter boreholes in the Penrith Sandstone Formation typically yield 3000 m^3/d compared with 2000 m^3/d in the St Bees Sandstone Formation with draw-

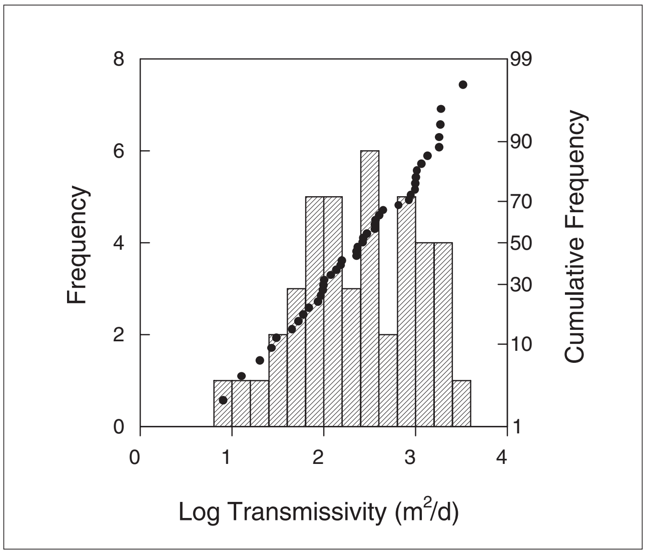


Figure 7.7.2 Distribution of transmissivity data from pumping tests in the Permo-Triassic sandstones of north-west England.

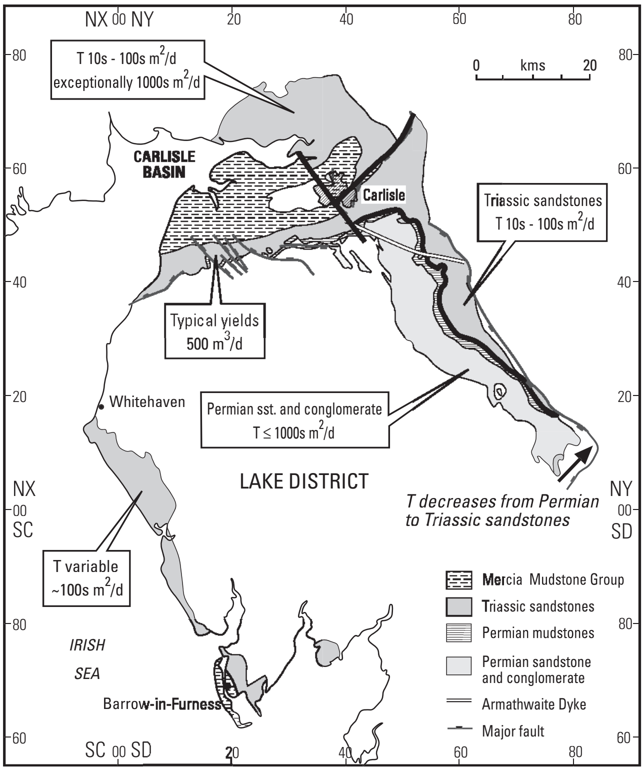


Figure 7.7.3 Transmissivity trends in the Permo-Triassic sandstones of north-west England.

Table 7.7.5 Summary of aquifer properties data for the Permo-Triassic sandstones in north-west England from pumping tests.

Permo-Triassic sandstones (all data)	Range	Interquartile range	Median mean	Geometric
Transmissivity (m^2/d)	8–3300	93–984	263	240
Storage coefficient	4.5×10^{-8}–0.12	7.2×10^{-5}–0.002	4×10^{-4}	1.7×10^{-4}

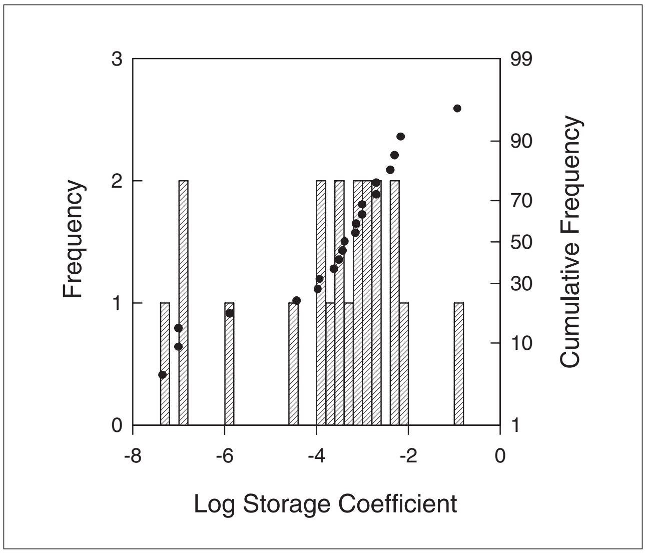


Figure 7.7.4 Distribution of storage coefficient data from pumping tests in the Permo-Triassic sandstones of north-west England.

downs of 10 to 20 m (Monkhouse and Reeves, 1977). However these conditions do not always hold: yields from investigation boreholes to the west of Carlisle have been very low, especially where situated in the lower, more argillaceous sandstones. Higher in the formation at Scales Demesne [NY 184 461], yields from abstraction boreholes constructed to similar specification were found to vary greatly over short distances. A short-term discharge in excess of 6000 m^3/d from one borehole was observed within 500 m of another borehole yielding only 500 m^3/d for some 70 m drawdown (Ingram, J A, personal communication).

Summary

Generally the transmissivity of the St Bees Sandstone Formation depends on fracture intersection, with tighter fractures deeper in the aquifer, resulting in progressively smaller increases in yield with depth. The Penrith Sandstone Formation has greater matrix permeability, except in the silicified horizons, and yields continue to increase with depth: the effect of fracture closure with depth is not generally seen (Ingram, J A, personal communication).

In all the aquifers throughout the region, the average values of permeability which are obtained from core samples are generally lower than pumping test and packer test derived bulk hydraulic conductivities, and are also lower than values used in modelling. Poorly cemented sandstones have high permeability and porosity values, which are much closer to the values used for modelling. On a regional scale the poorly cemented, coarse, well-sorted sandstone horizons dominate groundwater flow, and the less permeable horizons are of less significance. On a local scale (hundreds to a few thousand metres) groundwater flow into boreholes via fractures gives much higher transmissivity values, but such values are not applicable on the regional scale.

7.7.2 Carlisle Basin

Geological and geographical setting

The Carlisle Basin lies to the north of the Lake District and to the north and west of the Vale of Eden Basin (Figure 7.7.1). Permo-Triassic strata within the basin are gently folded into a shallow syncline with an axis running from west of Carlisle to the coast at Silloth.

Permo-Triassic sandstones in the Carlisle Basin occur in two main units, the early Permian Penrith Sandstone Formation and the early to mid Triassic Sherwood Sandstone Group. These are separated by the late Permian St Bees Shale Formation, and overlain by the mid- to late Triassic Mercia Mudstone Group. The Sherwood Sandstone Group includes two formations, the St Bees Sandstone and Kirklinton Sandstone (Table 7.7.1).

The Penrith Sandstone Formation is present at depth in the west of the Carlisle Basin but thins considerably to the east and pinches out towards the south, where it is overlapped by younger deposits. At outcrop in the south of the basin, the St Bees Shale Formation lies directly on a thin, basal Permian breccia. The Penrith Sandstone Formation is not greatly exploited as an aquifer in the Carlisle Basin.

The Sherwood Sandstone Group forms the principal aquifer within the basin. It crops out between Allonby Bay and Carlisle on the southern side of the basin and along the Solway coast of Scotland on the northern side. These outcrops join to the east of Carlisle. To the west of Carlisle, the Sherwood Sandstone Group is confined beneath the Mercia Mudstone Group, a thick succession of mudstones and siltstones that are effectively impermeable.

St Bees Shale Formation

The maximum thickness of the St Bees Shale Formation in the Carlisle Basin is approximately 90 m. The formation consists of red-brown mudstone, siltstone and subordinate fine sandstone, originally deposited on extensive coastal mudflats in an arid, highly evaporitic climate. Beds of gypsum and anhydrite are present and have been mined at Cocklakes.

St Bees Sandstone Formation

The maximum thickness of the St Bees Sandstone Formation is about 500 m. The formation consists predominantly of red-brown and grey, very fine- to fine-grained cross-bedded sandstone with thin beds of mudstone and siltstone. 'Flakes' of mudstone are present throughout the formation and micaceous laminae are fairly common. The boundary with the underlying St Bees Shale Formation is gradational and diachronous. The sandstones were deposited in braided river or stream channels crossing a broad alluvial plain; the mudstone beds were laid down by periodic flood events. The sandstone is generally hard or very hard and is strongly cemented by a combination of calcite, silica and iron oxide. At outcrop, it is generally sufficiently hard and weather-resistant to be quarried for building stone.

Kirklinton Sandstone Formation

The Kirklinton Sandstone Formation has a maximum thickness of about 100 m. It is most easily distinguished from the St Bees Sandstone Formation in the east of the basin (Ingram, 1978) in the Carlisle area itself. The Kirklinton Sandstone Formation may extend as far west as Wigton where up to 10 m was seen in British Sidac Ltd boreholes. The formation was originally deposited mostly as aeolian, dune sands. It differs from the St Bees Sandstone Formation in that it contains no mudstone or siltstone, is generally softer, more friable and slightly coarser grained and is more fractured. The Kirklinton Sandstone Formation thus has better aquifer properties than the St Bees Sandstone Formation, at least near boreholes where flow will preferentially enhance fractures, though this effect will not be significant regionally (Peacock, 1992).

Mercia Mudstone Group

The Mercia Mudstone Group consists dominantly of red-brown and green siltstones and mudstone, known locally as the Stanwix Shales. The maximum thickness is unknown but is probably at least 400 m in the centre of the basin. Some calcareous bands and dolomite nodules are present, as are lenses of gypsum.

Jurassic Penarth and Lias Groups

In the axis of the basin, latest Triassic to early Jurassic mudstones and limestones (Penarth and Lias Groups) overlie the Mercia Mudstone Group. In the late eighteenth century, an exploratory borehole for coal at Great Orton [NY 330 542] proved 64 m of Jurassic mudstones (Dixon et al., 1926).

Drift

Most of the Carlisle Basin is covered with thick, Quaternary drift deposits consisting mainly of boulder clay, sand and gravel. They cover 95% of the outcrop of the Sherwood Sandstone Group aquifer (Ingram, 1978). The drift deposits are generally 10–30 m thick, reaching a maximum of 60 m in a deep glacial channel between Wigton [NY 250 480] and Abbeytown [NY 174 507], possibly extending to the Solway Firth. The stratigraphy of the drift sequence is variable and complex, though sand and gravel tends to be more common towards the middle with boulder clay at the base and top. Fine-grained glacio-lacustrine deposits occur locally (Eastwood et al., 1968) and peat deposits are fairly common throughout the area. The sandier parts of the drift sequence are permeable and form minor aquifers; they have been exploited locally for water supply, especially along the sides of rivers.

Structure and faulting

The long axis of the Carlisle Basin trends east–west, running from just north of Carlisle were towards Silloth [NY 115 535] on the coast. The south and south-east parts of the basin are extensively disrupted by a series of northwest to south-east-trending faults, with a second set trending south-west to north-east. A series of faults with the latter trend separate the Carlisle and Vale of Eden Basins, about 4 km south-east of Carlisle. The Penrith Sandstone Formation is very thin or absent in the boundary zone between the two basins, which thus formed an area of attenuated deposition in early Permian times. The overlying St Bees Shale/Eden Shale and St Bees Sandstone formations straddle the boundary between the basins.

Hydrogeology

The St Bees and Kirklinton Sandstone Formations of the Sherwood Sandstone Group form a single continuous aquifer up to 1000 m thick. The St Bees Sandstone Formation has the lowest intergranular porosity and permeability values found in the Permo-Triassic sandstones investigated by Lovelock (1977). In the Kirklinton Sandstone Formation, porosity, permeability and specific yield values are likely to be generally higher than those in the St Bees Sandstone Formation. At Wigton boreholes drilled to depths in excess of 200 m have produced good supplies of water from the St Bees Sandstone Formation for industrial purposes. Typical borehole yields are 500 m^3/d.

Groundwater flow

Groundwater flow in the Carlisle basin is towards the centre of the basin (Ingram, 1978). Between Allonby and Carlisle groundwater flows north-north-west across the sandstone outcrop, discharging through permeable drift as springs and river baseflows. In the east of the basin flow occurs west towards the Solway Firth, with groundwater flow influenced by discharge to local rivers. Small rivers crossing the outcrop may lose water to the aquifer in their upper reaches in areas with little drift.

It is likely that the effective thickness of the St Bees Sandstone aquifer is around 100 m, because at greater depths the fractures are increasingly closed and the lithology becomes more fine grained and argillaceous. The aquifer is strongly anisotropic and rarely shows any effects of unconfined storage in pumping tests (Peacock, 1992).

Groundwater chemistry

Generally water in the Permo-Triassic sandstones in the Carlisle Basin is of calcium, magnesium, sodium, bicarbonate type. This groundwater is different from that in the Penrith Sandstone Formation of the Eden Valley Basin its higher proportion of sodium and magnesium. The total hardness varies from 145 to 358 mg/l. At the top of the sequence water in the sandstone immediately beneath the Stanwix Shales (Mercia Mudstone Group) shows an increase in the proportion of sulphate. This effect is also seen along the feather edge of the Sherwood Sandstone Group in Yorkshire and in the south-west of England. Nitrate values were low at 0 to 1.24 mg/l (Ingram, 1978).

Aquifer properties

St Bees Sandstone Formation

HYDRAULIC CONDUCTIVITY AND TRANSMISSIVITY

Lovelock (1977) analysed 16 outcrop samples of the St Bees Sandstone Formation from the Carlisle Basin. Values of intergranular hydraulic conductivity varied between 0.17 m/d and 0.5 m/d. These samples were poorly cemented, unlike much of the sandstone in the basin, and it is likely that the values at depth in the centre of the basin are much lower. The average horizontal hydraulic conductivity for core samples from the BGS database for the St Bees Sandstone Formation in both the Carlisle and the Eden Basins is 0.21 m/d. The maximum value is 4.4 m/d (Figure 7.7.5, Table 7.7.3). The hydraulic conductivity distribution follows an approximately log-normal distribution. There appears to be a some correla-

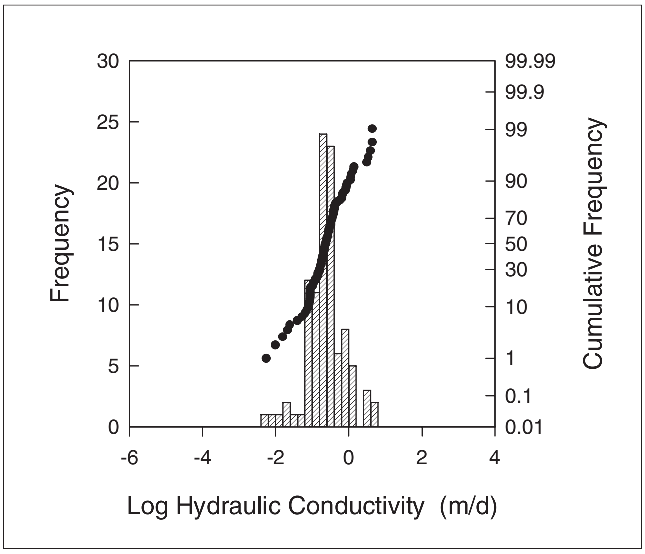


Figure 7.7.5 Distribution of hydraulic conductivity data for Sherwood Sandstone Group samples from the Carlisle Basin and the Vale of Eden.

tion of horizontal and vertical hydraulic conductivities (Figure 7.7.6, Figure 7.7.7), with the horizontal conductivity usually slightly higher than the vertical. The friable sandstones with less cement are significantly more permeable than those which are well cemented, and the flow of water to a borehole is likely to be concentrated along the more permeable horizons, or along fractures.

There are only seven sites in the Carlisle Basin with pumping test data on the Aquifer Properties Database. Transmissivity values vary from tens of m^2/d up to 2000 m^2/d, with a geometric mean of 100 m^2/d (Figure 7.7.8). Values may be lower near the confining Stanwix Shales. Very high transmissivity values at Scales Demesne [NY 184 461] may be partly due to induced leakage via fracture systems from overlying permeable drift deposits and should be taken in the context of much lower values supported by other investigation boreholes in the area.

POROSITY AND STORAGE

Lovelock (1977) estimated a porosity between 24 to 27% for fairly uncemented sandstones. The average porosity calculated from the BGS database for all the St Bees Sandstone Formation samples in the Carlisle and Vale of Eden areas is 27% (Figure 7.7.9, Table 7.7.4). The distribution again illustrates the importance of the local cementation on the aquifer properties of the sandstone. There is a general correlation between the permeability and porosity of the St Bees Sandstone Formation samples in this region (Figure 7.7.10).

There are limited data for storage coefficient in the Carlisle Basin. The storage coefficient values are confined to semi-confined.

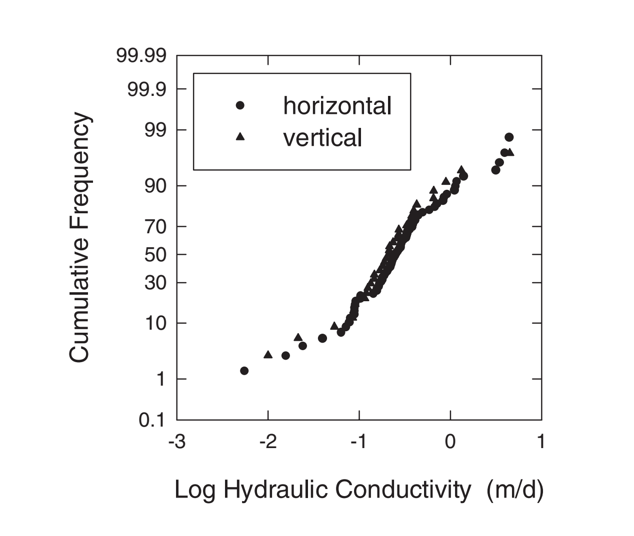


Figure 7.7.6 Distribution of hydraulic conductivity data for horizontal and vertical samples of the Sherwood Sandstone Group from the Carlisle Basin and the Vale of Eden.

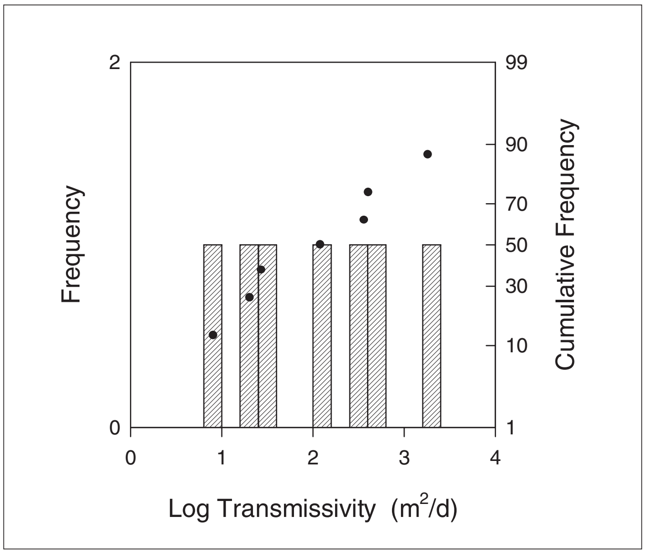


Figure 7.7.8 Distribution of transmissivity data from pumping tests in the Sherwood Sandstone Group of the Carlisle Basin.

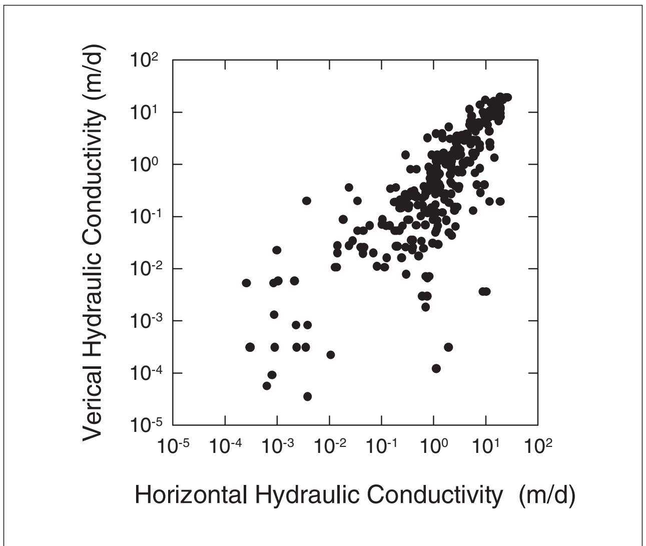


Figure 7.7.7 Plot of vertical against horizontal hydraulic data for Sherwood Sandstone Group samples from the Carlisle Basin and the Vale of Eden.

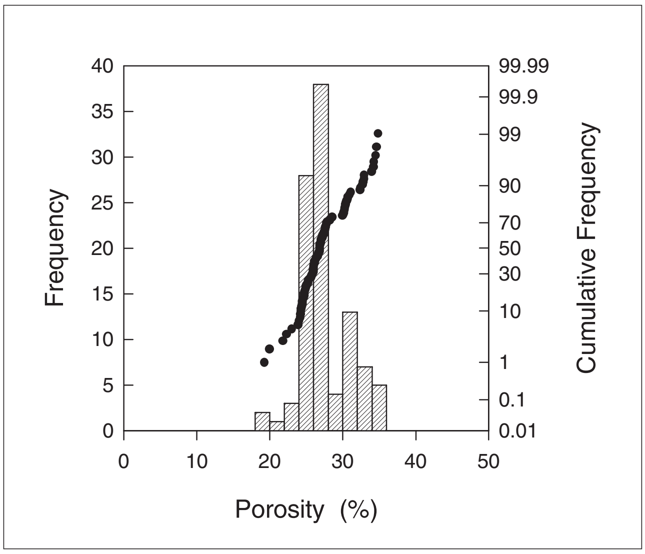


Figure 7.7.9 Distribution of porosity data for Sherwood Sandstone Group samples from the Carlisle Basin and the Vale of Eden.

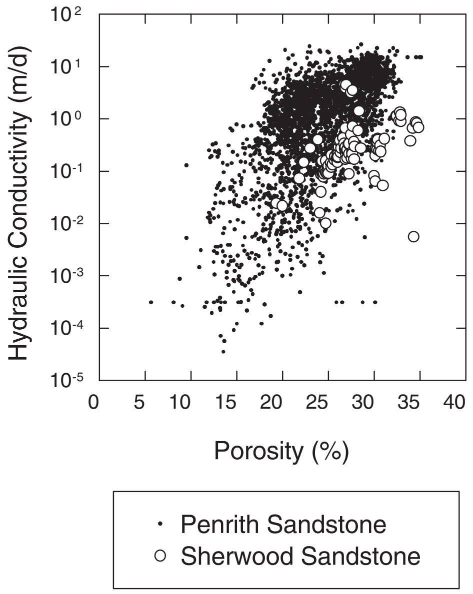


Figure 7.7.10 Plot of hydraulic conductivity against porosity data for Permo-Triassic sandstone samples from the Carlisle Basin and the Vale of Eden.

Kirklinton Sandstone Formation

There are few data for aquifer properties solely for the Kirklinton Sandstone Formation. High yields in the Carlisle city area, where the sandstone occurs, suggest that it is more permeable than typical St Bees Sandstone material in the area. Borehole yields vary from 1000 m^3/d to 1750 m^3/d for drawdowns of 20 to 45 m. However one pumping test specifically testing the Kirklinton Sandstone Formation (Pirelli No 2. [NY 387 540]) in Carlisle, gave a transmissivity of only 8 m^2/d which is thought to be atypically low. Geophysical logging at Scales Demesne along with visual examination of the core suggests the Kirklinton Sandstone Formation to be represented in the upper part of the borehole, which may further explain its higher transmissivity values (Ingram, J A, personal communication).

Summary

General regional transmissivity values for the Carlisle Basin are estimated to be around 30 to 50 m^2/d with a confined storage coefficient of $<10^{-4}$, a specific yield of 0.02, and a saturated thickness of 100 m for both the St Bees Sandstone Formation and the Kirklinton Sandstone Formation (Peacock, 1992). Pumping of some boreholes such as that at Scales Demesne, lead to sand influx and well development, suggesting that pumping can lead to development of fractures that are penetrated by the borehole (Vines, 1988). No regional groundwater models have been developed for this area.

7.7.3 Vale of Eden

Geological and geographical setting

The Vale of Eden lies on the northeast of the Lake District massif. The Vale of Eden Basin is a mainly fault-bounded trough about 50 km long and 5–15 km wide and contains Permian and Triassic strata which dip gently to the north-east. The Pennine Fault and associated escarpment form its north-eastern boundary, and the Permo-Triassic succession wedges out south-westwards against Carboniferous strata (Figure 7.7.1).

There are two aquifer systems and an aquitard unit within the Permo-Triassic sediments of the Vale of Eden and north Cumberland area. The Penrith Sandstone Formation and St Bees Sandstone Formation form the aquifers and are separated by the Eden Shale Formation, which constitutes an effective aquitard (Table 7.7.1).

Penrith Sandstone Formation

The early Permian Penrith Sandstone Formation was deposited in a structurally controlled, intermontane basin that was broadly coincident with the present Vale of Eden. The eastern and southern margins of this basin cannot have lain far beyond the limits of the present Permo-Triassic outcrop. To the west, however, the Penrith Sandstone Formation probably extended well beyond its present outcrop. The formation tends to thicken into depressions on the underlying, late Carboniferous to earliest Permian land surface. A ‘saddle’, characterised by attenuated deposition, separated this basin from the Carlisle Basin to the north and north-west. Gravity estimates indicate that the formation is locally about 900 m thick in the centre of the basin (Bott, 1974). The sandstone is largely aeolian in origin, the cross-bedding foresets indicating the accumulation and migration of barchan-type sand dunes. Towards the margins of the basin the aeolian sandstones pass laterally into water-lain, alluvial fan sandstones with lenses of breccia (Macchi, 1991; Holliday, 1993). Breccia (known locally as Brockram) becomes progressively more dominant southwards so that, in the south of the basin, the sandstones are absent and the early Permian is represented entirely by brockram.

The Penrith Sandstone is red-brown to brick red in colour, consisting of well-rounded and well-sorted, medium to coarse grains. Less well-sorted, fine- to coarse-grained sandstone beds with thin mudstone intercalations are common at some levels and indicate episodes of fluvial deposition; these occur mainly near the top of the sequence and at the margins of the basin. Brockram lenses, present within the sandstone towards the basin margin, consist largely of angular fragments of dolomitised limestone in a strongly cemented calcareous sandstone matrix.

In the northern part of the basin, parts of the top 100 m or so of the Penrith Sandstone Formation have been secondarily cemented by silica, producing quartz overgrowths with well-developed crystal faces. In places these overgrowths fill up to 70% of pore space. The extent of silicification is reflected in the local geomorphology on the formation outcrop: where the silica cement is sparse the outcrop has low relief and is commonly drift covered, but where the cement is abundant the relief is strong with prominent scarps and dip slopes. Silicification was probably penecontemporaneous with deposition (Waugh, 1970). It most likely resulted from the production of silica dust by abrasion of sand grains in the desert environment, followed by solution in alkaline groundwaters and subsequent precipitation by capillary evaporation. These siliceous sandstones are very indurated and poorly permeable, and have been used locally as a building stone. They typically occur in layers up to 10 m thick, separated by less well-cemented sandstone. Beneath this silicified zone, the Penrith Sandstone Formation is only moderately cemented and in parts completely uncemented (Ingram, 1978), forming some of the most permeable strata of the Permo-Triassic sandstones of the Vale of Eden. Other cements include calcite, gypsum and anhydrite. These are present locally at depth but have been dissolved at outcrop.

Eden Shale Formation

The Penrith Sandstone Formation is overlain by the Eden Shale Formation which is up to 180 m thick. The formation is broadly equivalent to the St Bees Shale Formation of west Cumbria and the Carlisle Basin. It consists mainly of mudstone and siltstone; sandstone, breccia and conglomerate intercalations are subordinate, though they increase in abundance towards the south of the basin. The strata are mainly red in colour with brown, green and grey beds in places. Gypsum and anhydrite are present as beds, scattered nodules, cements and gypsum veins. These evaporites have been dissolved in places and are likely to be responsible for high groundwater salinities in the sandstone aquifers above and below. The gypsum and anhydrite has been mined at Kirkby Thore, Glassonby and Cocklakes. Dolomite beds are also present locally. The Eden Shale Formation sediments were deposited in the late Permian on a continental alluvial plain or sabkha, on which saline lakes periodically developed (Holliday, 1993).

St Bees Sandstone Formation

This formation is very similar in depositional environment and lithology to its equivalent in the Carlisle Basin (Section 7.7.2). It has a maximum thickness of around 350 m in the Vale of Eden Basin. It consists mainly of very fine to fine-grained, indurated sandstone. Mudstone beds are generally subordinate, though increase in abundance towards the boundary with the underlying Eden Shale Formation.

Drift deposits

Drift deposits resemble those in the Carlisle Basin, but are less extensive and thinner, typically being around 10 to 20 m thick with a maximum of 30 m. The stratigraphy of these deposits is complex. Interdigitations of sand, gravel, silt and clay each develop their own piezometric level, resulting in complex perched water tables above the Penrith Sandstone Formation.

Structure and faulting

The eastern edge of the Vale of Eden is bounded by the Pennine Fault system, which throws the Permo-Triassic rocks against Carboniferous or Lower Palaeozoic rocks. The Pennine Fault follows the foot of the Pennine escarpment from near Brampton [NY 530 610] in the north to Stainmore [NY 830 130] in the south. There it is joined by another major structure, the Dent Fault, which trends north-east to south-west through Kirkby Stephen [NY 780 085].

Hydrogeology

The Penrith Sandstone Formation is a major aquifer from which large quantities of groundwater for public supply are obtained from a number of boreholes located in the northern part of the outcrop. The formation is confined by the Eden Shale Formation to the east of the River Eden and by drift cover over much of the area to the west. Boreholes which intersect the silicified part of the formation tend to have very low yields. The friable nature of other layers of the formation may cause borehole construction problems. Generally the groundwater within the Penrith Sandstone Formation is of calcium bicarbonate type, however the water immediately underlying the Eden Shale Formation is of calcium sulphate type. Generally total hardness is around 40 to 170 mg/l. Very hard water may be found near the Brockram Formation due to its high calcite and dolomite content (Ingram, 1978). The St Bees Sandstone Formation has generally calcium-, magnesium-, sodium- and bicarbonate-rich groundwater but immediately above the Eden Shale Formation increased sulphate concentrations may occur. High nitrate concentrations (from agricultural input) occur in outcrop areas (Ingram, 1978).

Groundwater flow

In the Penrith area hydraulic gradients are shallow and predictable, generally towards the rivers Eamont and Eden (Ingram, J A, personal communication). Water may be encountered at depths of over 100 m when drilling at high elevations. Steeper hydraulic gradients in the northern part of the Penrith Sandstone Formation may reflect the lower permeability of the sandstone in this area. Areas with water levels above the silicified bands may act as a number of aquifers with perched water tables (Ingram, 1978). The aquifer is anisotropic due to its interlayered nature. Laterally groundwater may be transferred from the Carboniferous Limestone where the Penrith Sandstone Formation lies directly on the limestone to the south of Penrith. Along the Pennine Fault the are many springs indicating that much of the lateral inflow to the basin is from surface flow rather than between aquifers across the fault zone.

The groundwater flow in the Vale of Eden is dominated by the river Eden. The river Eden gains over most of its length, (between Langwathby and near Temple Sowerby the river is underlain by the Eden Shale Formation and is not in contact with the aquifer). The water table lies at around 50 m below ground level in the north of the basin, however the water level is closer to the surface near the river Eden.

Hydraulic conductivity and transmissivity

Penrith Sandstone Formation

CORE DATA

Most of the core data in the Eden Valley is derived from the Cliburn boreholes [about NY 585 260], from which over 2000 samples have been obtained. Very few samples are available from other sites. These data indicate that hydraulic conductivities range from 3.5×10^{-5} m/d to 26.2 m/d, with a median of 1.35 m/d, the great range in permeability reflecting the variable degree of cementation of the sandstone. The core data indicates a general anisotropy of the sandstone: horizontal permeability is generally around 10 times that of vertical permeability. This can be attributed to lamination within poorly sorted horizons (Figure 7.7.11, 7.7.12, Table 7.7.2, Table 7.7.3).

Lovelock (1977) found that well-sorted sandstone outcrop samples had intergranular hydraulic conductivity values of greater than 7.5 m/d while less well-sorted units had hydraulic conductivities of 0.28 m/d to 1.3 m/d. Within the silicified units values decreased to less than 3×10^{-4} m/d.

At Cliburn the geometric mean value of vertical hydraulic conductivity was approximately 0.6 m/d with a mean horizontal hydraulic conductivity of 2.6 m/d. This resulted in an estimated matrix transmissivity of 128 m^2/d assuming an aquifer thickness of 49 m (Lovelock, 1975).

PUMPING TEST TRANSMISSIVITIES

There are around 15 different pumping test sites in the Penrith Sandstone Formation. They have transmissivities ranging from tens of metres squared per day to nearly 2000 m^2/d at Cliburn. This transmissivity variation reflects the variation in transmissivity with cementation of the

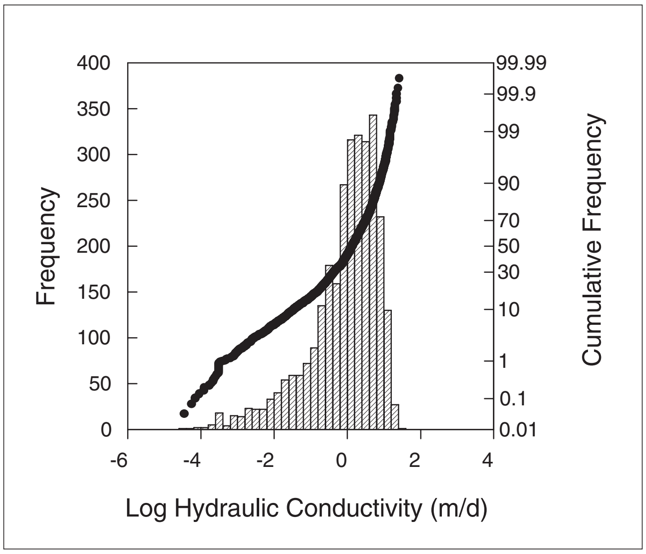


Figure 7.7.11 Distribution of hydraulic conductivity data for Penrith Sandstone samples from the Vale of Eden.

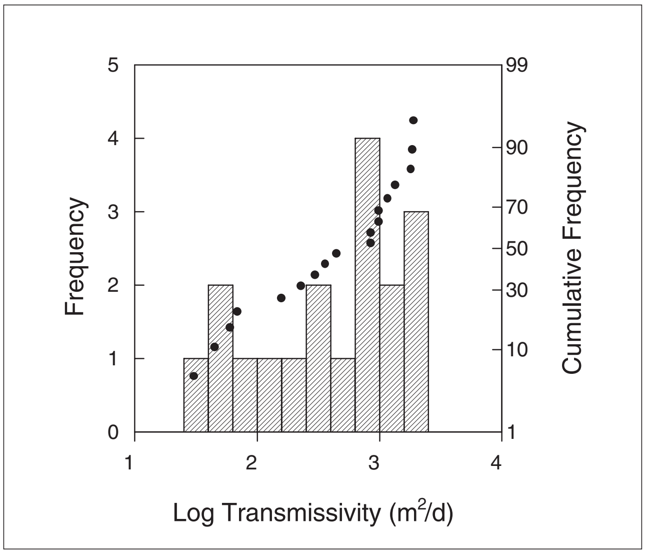


Figure 7.7.13 Distribution of transmissivity data from pumping tests in the Penrith Sandstone of the Vale of Eden.

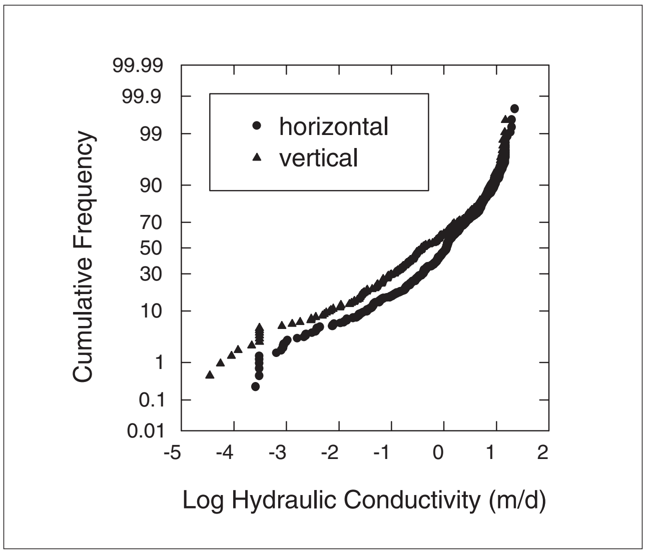


Figure 7.7.12 Distribution of hydraulic conductivity data for horizontal and vertical samples of Penrith Sandstone from the Vale of Eden.

sandstone. In general the values for the Penrith Sandstone Formation are of the order of hundreds of metres squared per day, with a geometric mean of 390 m^2/d (Figure 7.7.13).

PUMPING TEST CASE STUDIES

Cliburn [NY 585 260]

At Cliburn, south of Penrith, transmissivities of around 1900 m^2/d were found; much greater than those calculated from matrix permeability (128 m^2/d), indicating preferential flow. This preferential flow could come from either more permeable horizons or from fractures. Sub-horizontal bedding plane fractures are likely to provide most of this flow, amounting to about 90% of flow to the borehole (Ingram, 1978). A more detailed analysis of the permeability distribution in a research borehole in the Penrith Sandstone Formation at Cliburn (Price et al., 1982), indicated that, although probably of limited extent, two fractures contributed 85% of the total transmissivity, intergranular transmissivity being only 175 to 200 m^2/d.

Holmwrangle [NY 518 492]

Pump testing at Holmwrangle Fish Hatchery gave a transmissivity of around 60 m^2/d, with much of the water coming from the River Eden nearby. There is a steep hydraulic gradient in the aquifer near this borehole, indicative of low permeability. High hydraulic gradients and artesian conditions indicate little natural flow of groundwater, typical of poorly permeable areas.

Fairhill [NY 512 314]

At Fairhill, near Penrith, the Penrith Sandstone Formation was penetrated from 1 m below the surface to a maximum depth of 150 m, hard cemented layers were encountered in the upper 100 m. The sandstone was dry in the top 105 m whilst drilling was carried out, however once water was struck the rest water level subsequently rose to 74 mbgl, reflecting the consistent groundwater level across the area. Very similar conditions were encountered to the east of the town.

The results of step tests in boreholes 1 and 2 were analysed using a radial flow model. A hydraulic conductivity of the order of 29 m/d was used to fit the data, with a confined storage coefficient of 2×10^{-6} (from fitting well Nos 1 and 2), and 4×10^{-5} (from fitting data from an observation borehole).

Radial flow modelling of a constant rate test on No. 2 borehole used the same hydraulic conductivity values for fitting observations from boreholes 1 and 2, but a lower hydraulic conductivity of 18 m/d and a higher storage coefficient of 1×10^{-3} fitted measurements from the observation borehole.

Transmissivities of around 2000 m^2/d were obtained from recovery analysis using Jacob's method, and very low storage coefficient values were obtained. This is compatible with an effective aquifer thickness of T/K = 2000/30 = 67 m. This is of a similar order to the saturated aquifer thickness penetrated by the borehole (76 m), and the saturated aquifer thickness penetrated below the water strike level (45 m).

The rise in water level during drilling and the low values of storage coefficient suggests that the aquifer responds in a confined manner, despite the lack of cover over the Penrith Sandstone Formation. The permeability values derived from the radial flow model are very high for sandstone, indicating that fracture flow is significant in the aquifer. One possible explanation of the lower transmissivity and higher storage from the observation borehole is that it was drilled a year before the test, whereas the pumping boreholes were drilled just before the test. During that year water is likely to have flowed up the borehole from the deeper confined layers to more shallow horizons. Water may have drained from these upper layers on pumping thereby producing an increased value of storage coefficient (Campbell, 1992).

Packer tests

Packer tests were carried out at various intervals in the Cliburn research borehole. Each interval (except that at the base of the borehole), was isolated by two packers. There was evidence for considerable anisotropy of the sediments (K_h>K_v), which, when corrected for, lead to an increase in the estimated horizontal permeability (Price et al., 1982). This anisotropy is evidence for the lack of permeable vertical fracturing in the area.

Packer and laboratory permeability measurements show good agreement in most of the Cliburn borehole, indicating that generally the small fractures seen in the borehole wall are not permeable. The exceptions are the two intervals with flowing fractures 0 and 13 (Figure 7.7.14). These have a much higher field permeability.

From a total pumping test transmissivity of 1350 m^2/d between the water table and 60 mbgl, 85% appears to come from zones containing two main fractures, leaving a transmissivity of only around 200 m^2/d attributable to the essentially unfractured zones. This was found to agree well with estimates from laboratory measurements on core samples. It is likely that minor fracturing near the top of the borehole increases the injection transmissivity slightly above the laboratory intergranular values. These results suggest that the Penrith Sandstone Formation has limited hydraulic conductivity that is attributable to matrix flow over much of its thickness, and zones of very high local flow when fractures are present.

Geophysical logs: flow logs

Fluid logging at Cliburn indicated numerous fractures mainly above 30 mbgl. Closed circuit TV (CCTV) showed a major fracture at 29.3 m (over 1 cm wide). Another major fracture near the base of the hole was indicated by heat pulse flow measurements and was seen on CCTV, but was not picked up by the temperature and conductivity logs. Flow logging suggested that water was entering the borehole near the water table (with a major contribution from the fracture at 29.3 m) travelling down the borehole and leaving via a fracture at 58.5 mbgl. CCTV indicated suspended particles following this path down the borehole. The many small fractures between the water table and the fracture at 29.3 m did not appear to contribute much water when the borehole was logged (Price et al., 1982).

This evidence suggests that in some boreholes much of the water is derived from only a small number of active fractures whilst many fractures have little or no contribution to flow. This also indicates incipient vertical hydraulic gradients maintained within the Penrith Sandstone Formation: probably on account of variable cementation and associated anisotropy. This in turn suggests that vertical

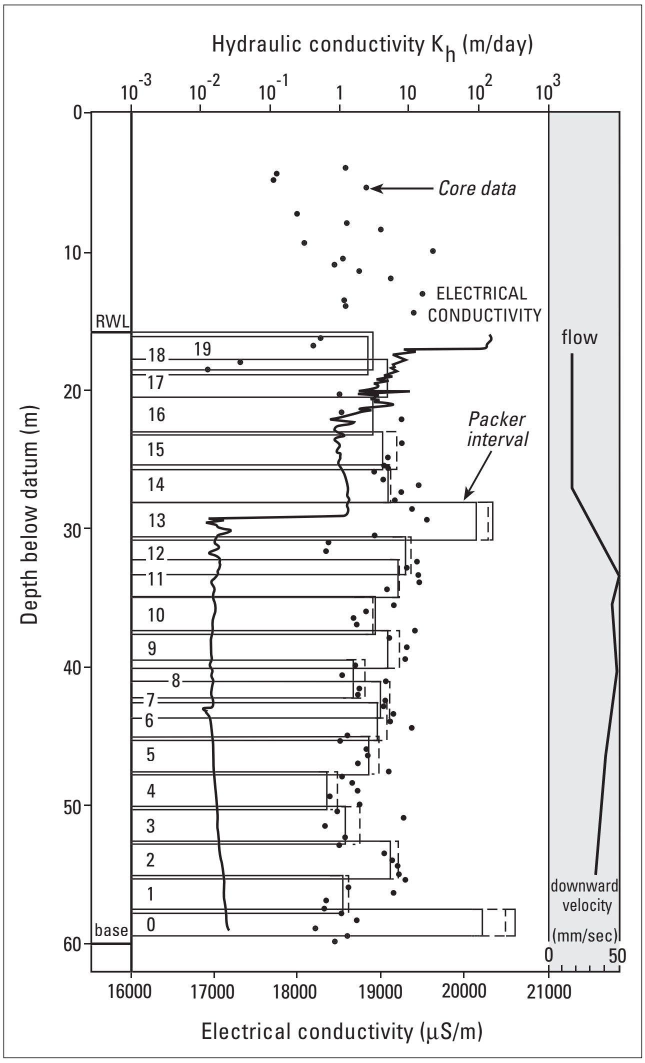


Figure 7.7.14 Comparison of core hydraulic conductivity, packer test hydraulic conductivity, electrical conductance and flow logging in the Penrith Sandstone (after Price et al., 1982).

fractures (or jointing) are not important in transmitting water, fractures detected within the borehole being mainly associated with horizontal bedding planes.

St Bees Sandstone Formation

Core data

There are fewer samples taken from the St Bees Sandstone Formation than the Penrith Sandstone Formation in the Vale of Eden. The permeability of the St Bees (Sherwood) Sandstone varies from 0.048 to 3.5 m/d, with a median of 0.16 m/d. The St Bees Sandstone Formation shows a much closer grouping of data than the Penrith Sandstone Formation, perhaps because of the great variability in cementation of the latter. The sandstone shows some anisotropy on the core plug scale, vertical permeability being perhaps being around half that of horizontal permeability. The effect however is much less marked than that in the Penrith Sandstone Formation (Figures 7.7.5, 7.7.6, 7.7.7).

Pumping test transmissivity

There are very limited pumping test data for the St Bees Sandstone Formation in the Vale of Eden. Transmissivity values are in the range 167 to 276 m^2/d (Ingram, J A, personal communication). Skirwith observation borehole [NY 613 325] had an airlift yield of around 200 m^3/d, and an observation borehole at Ousby Moor [NY 596 358], drilled through a fault zone had a higher artesian flow of 470 m^3/d. Thus it may appear that some fault zones in this region are permeable, however the sustainability of these yields is unknown (Ingram, 1978).

Porosity and storage

Penrith Sandstone Formation

CORE DATA

Core porosities of the Penrith Sandstone held in the Aquifer Properties Database vary from 5 to 36% with a median of 24% (Figure 7.7.15, Table 7.7.4). Lovelock (1977) determined that well-sorted outcrop samples had porosities of around 30%, with values of 25 to 30% for less well-sorted units. In more silicified sandstones porosities fell to 5 to 8%. Laboratory values of specific yield of the more porous sandstones at Cliburn (BH 2) were in the range 10 to 17%. Generally core with a higher porosity also has a higher permeability (Figure 7.7.10).

Local cementation of the upper part of the Penrith Sandstone Formation in the form of quartz overgrowths reduces the porosity of the sands. Maximum porosities of 30% are reduced to 27% by incipient quartz growth that has little effect on the permeability of the aquifer. Greater cementation, reducing porosity to 15% in places reduces the permeability to only a few tenths of a metre per day, material with low porosities of 5 to 8% having very low permeabilities of less than (3×10^{-4} m/d). Gypsum cement where present reduces the permeability even more (Gale et al., 1990).

PUMPING TEST STORAGE COEFFICIENT

The Penrith Sandstone Formation is unconfined along the southern edge of the Vale of Eden Basin, and confined in the northern side of the basin by the St Bees Shale Formation. The geometric mean of the storage coefficient (8 values) is 1.1×10^{-4} (Figure 7.7.16).

The generally confined nature of the pumping test storage coefficients is due to the lack of vertical flow and dewatering of the matrix on the timescale of the tests. For example at Cliburn a cemented horizon near the water table prevented dewatering of the aquifer and effectively confined the aquifer (Ingram, 1978).

St Bees Sandstone Formation

POROSITY AND STORAGE

The St Bees Sandstone Formation generally has a higher porosity than the Penrith Sandstone Formation; ranging from 19 to 34% with a median of 27%. This reflects the locally higher degree of cementation in the Penrith Sandstone Formation. The limited data for the St Bees Sandstone Formation suggests that matrix material with a higher porosity generally has a higher permeability.

Values of storage coefficient from very limited data are in the range 5×10^{-3} to 2×10^{-5} (Ingram, J A, personal communication).

Summary

The limited amount of aquifer properties information for the Vale of Eden is mainly concentrated in the northern part of the Vale. The Penrith Sandstone aquifer has high porosity and intergranular permeability values where the sandstones consist of non-cemented and poorly cemented (iron oxide), coarse- to very fine-grained 'millet seed' quartz sands. Silica cementation reduces inter-granular porosity as do gypsum and calcite cements near contacts with the Eden Shale and Brockram formations. Aquifer transmissivity is dominated by fracture flow whereas the storage coefficients are controlled by intergranular porosity. Fractures 1 to 3 mm wide contribute <1% of total porosity, but can contribute over 90% of total transmissivity. The presence of extensive subhorizontal fracturing through which most of the groundwater flow occurs has been determined by conventional borehole logging and observed by use of downhole television techniques.

Summary of aquifer properties

Estimates of regional aquifer properties for the Penrith Sandstone aquifer suggest a regional transmissivity of 300 m^2/d and a storage coefficient of 0.0005, with an effective porosity of 15% and a saturated thickness of 200 m. This further suggests a regional effective permeability of 1.5 m/d

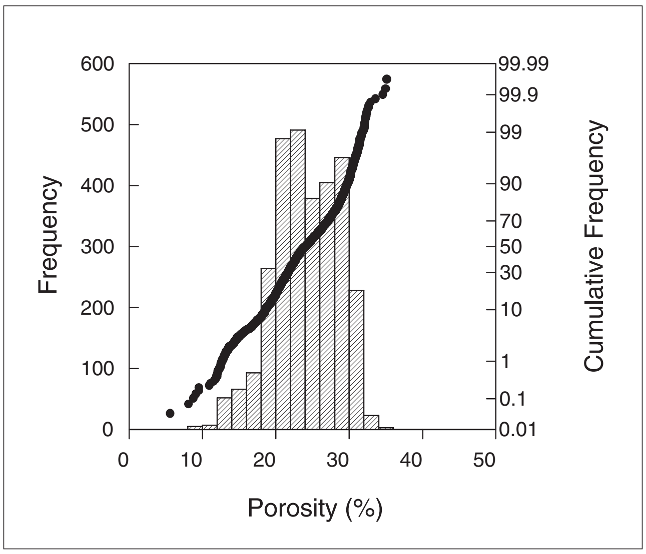


Figure 7.7.15 Distribution of porosity data for Penrith Sandstone samples from the Vale of Eden.

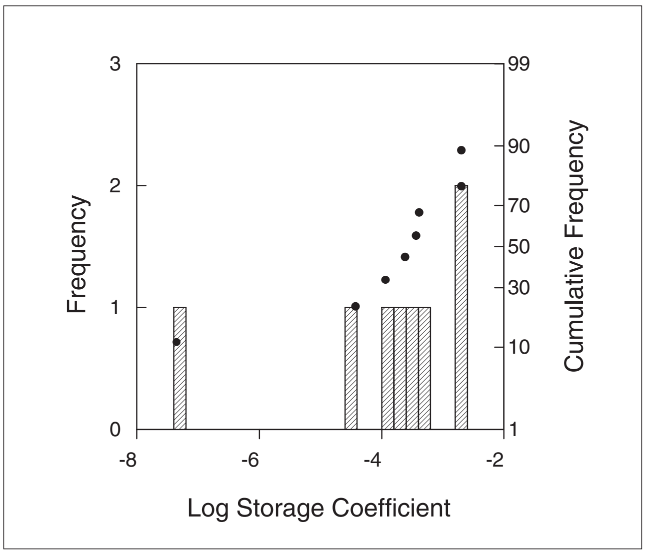


Figure 7.7.16 Distribution of storage coefficient data from pumping tests in the Penrith Sandstone of the Vale of Eden.

(Peacock, 1992). However locally in some boreholes, such as the Cliburn borehole, greater transmissivities are obtained from fractures. General well yields are around 2300 m^3/d for approximately 10 m of drawdown (Ingram, 1978).

The Cliburn constant rate and packer tests illustrate a number of features often present in the Permo-Triassic sandstones. Increases in drawdown towards the end of a pumping test may be interpreted in a variety of ways. Such an increase in drawdown can be attributed to the cone of depression in the borehole intersecting a boundary. Alternatively such an effect could be caused by the inherent low vertical permeability and high anisotropy of the sandstone caused by the interlayering of sediments and variable cementation.

There is considerable discussion of whether the Permo-Triassic Sandstones are confined or unconfined in the areas where they occur at outcrop. At the Cliburn site it is possible that the highly silica cemented layer within the Penrith Sandstone Formation acts as a confining layer.

The Permo-Triassic sandstones were deposited in fluvial or aeolian conditions and all exhibit interbedding, often at a variety of scales. This may give rise to directional permeability depending on the bedding inclination and the cross-bedding of the sandstone. The effect of cross-bedding on the overall permeability of a Permo-Triassic aquifer is not fully known.

The (vertical) anisotropy of the sandstones determines the effective aquifer thickness. In an aquifer with a high vertical permeability the effective aquifer thickness would be the whole aquifer thickness. In the Permo-Trias this is often reduced to the borehole depth as water is not drawn from deeper in the aquifer when the borehole is pumped due to anisotropy.

Generally the aquifer properties of the St Bees Sandstone Formation in the Vale of Eden are very similar to those of the formation in the Carlisle Basin.

7.7.4 West Cumbria

Geological and geographical setting

Permo-Triassic sandstone crops out along the West Cumbrian coast between Whitehaven and Barrow-in-Furness (Figure 7.7.1). The strata generally thicken and dip in an offshore direction.

The principal sandstone aquifer within the region is the Sherwood Sandstone Group of early to mid-Triassic age. The early Permian is represented by the breccias and conglomerates of the Brockram Formation. These are overlain by the late Permian St Bees Evaporite and the St Bees Shale formations. Both these formations pass laterally into the Brockram Formation north-eastwards towards the Lake District massif, which formed the eastern boundary of the East Irish Sea Basin throughout the Permo-Triassic.

The Permo-Triassic stratigraphy of the region is shown in Table 7.7.6. Three formations are recognised within the Sherwood Sandstone Group, namely the St Bees Sandstone, Calder Sandstone and Ormskirk Sandstone formations. The latter is overlain by the Mercia Mudstone Group.

Brockram Formation

The basal Permian unit is the Brockram Formation, a poorly bedded and poorly sorted breccia or conglomerate. The clasts are generally pebble-sized and angular in shape. They are mainly derived from the Borrowdale Volcanic Group but clasts of limestone are common in the lowest few metres in areas where the Brockram Formation directly overlies the Carboniferous Limestone. The matrix varies from mudstone to very poorly sorted, fine- to coarse-grained sandstone; it is generally weakly calcareous (Nirex, 1993a).

St Bees Evaporites Formation

The St Bees Evaporite Formation consists of a lower dolomite unit, a middle siltstone and dolomite unit and an upper anhydrite unit (Nirex, 1993a).

St Bees Shale Formation

The lithology of the St Bees Shale Formation varies from massive mudstone, siltstone or very fine sandstone to inter-laminated claystone, siltstone and very fine sandstone with some breccia clasts. The formation was deposited on extensive coastal mudflats in an arid, highly evaporitic climatic regime. Occasional sandy beds were deposited by episodic sheetfloods. The St Bees Shale Formation interdigitates with the Brockram Formation towards the boundary with the Lake District massif (Nirex, 1993a).

St Bees Sandstone Formation

This formation is the lowest of the Sherwood Sandstone Group. Though predominantly fluvial in origin, it is largely pebble-free and finer grained than its equivalent in the Cheshire Basin, the Chester Pebble Beds.

The formation is composed of pale reddish brown, very fine- to medium-grained sandstone. The sandstones are lithic, subarkosic arenites, composed dominantly of mono-

Table 7.7.6 Permo-Triassic stratigraphy in the West Cumbria area (after Nirex, 1993a).

System	Group	Formation	Lithology	Thickness (m)
Triassic	Mercia Mudstone Group		Red mudstones, siltstones and halite	<3700
	Sherwood Sandstone Group	Ormskirk Sandstone	Sandstones, mainly red, fine-grained to medium-grained	250
		Calder Sandstone		485
		St Bees Sandstone		500
Permian		St Bees Shale	Red mudstones and siltstones	0–200
		St Bees Evaporite	Anhydrite, halite and dolomitic limestone	0–200+
		Brockram	Breccia sandstone	0–220

crystalline quartz, feldspar and, in the lower part, lithic fragments derived from the Borrowdale Volcanic Group. The formation, which averages around 550 m thick, has a gradational lower boundary with the underlying St Bees Shale Formation but a sharp upper boundary with the Calder Sandstone Formation. Syndepositional fault activity within the basin controlled local thickness variations. The St Bees Sandstone Formation consists mainly of fluvial channel deposits with less common sheetflood and aeolian intervals. Palaeocurrent studies in the fluvial sandstones show a dominant flow direction to the north-west (Nirex, 1993a).

Calder Sandstone Formation

This formation takes its name from exposures in the River Calder. It consists mainly of dark reddish brown, fine- to coarse-grained sandstone with common well-rounded and frosted aeolian grains. It is poorly cemented and approximately 485 m thick. The base of the Calder Sandstone Formation is sharp and marked by changes in colour, lithology and sedimentary structures. The upper boundary is not well defined at outcrop. The formation was deposited mainly as aeolian sand dunes with localised reworking by braided fluvial channels (Nirex, 1993a).

Ormskirk Sandstone Formation

Offshore, this sandstone formation is 250 m thick, but has been poorly characterised onshore. The formation is mainly of aeolian origin with some fluvial intervals (Nirex, 1993a).

Drift

The area is extensively mantled by Quaternary drift deposits, though some of the river valleys are drift free. The drift includes boulder clay, sands and gravels and has a complex internal stratigraphy.

Structure and faulting

The West Cumbrian Permo-Triassic strata were deposited on the edge of the East Irish Sea Basin. Following the end of the Variscan orogeny an extensional stress regime prevailed in north-west England and adjacent offshore areas during most of the Permo-Trias. This resulted in episodes of rifting and subsidence of fault-bounded sedimentary basins, in which large thicknesses of Permo-Triassic deposits accumulated. The Permo-Triassic sequence of the West Cumbrian coast lies on the margin of the East Irish Sea Basin, and wedges out rapidly against the Lower Palaeozoic rocks of the Lake District massif to the north-east.

There has been extensive faulting in the West Cumbria area. Faulting is generally in a northerly to northwesterly direction parallel to the boundary of the East Irish Sea Basin with the Lake District Massif (Nirex, 1993a).

Cementation

Porosity in the Permo-Triassic sequence is variable, but appears to be mainly controlled by primary lithology, ranging from tight mudstones and siltstones to very porous open-framed sandstones. The porosity in the Brockram, St Bees Evaporite and St Bees Shale formations is negligible (<1%). The aeolian intervals within the Sherwood Sandstone Group (generally prevalent towards the top) are usually more porous than those of fluvial origin. Porosity is around 15% to 25% in the St Bees Sandstone Formation. Most of this is considered to be secondary, attributed to removal of carbonates by present-day groundwaters, but ultimately due to early preservation of non-compacted, open fabrics. This could have occurred due to the presence of an early, pre-compaction evaporite cement, probably anhydrite, which was subsequently removed during diagenesis (Strong et al., 1994). Some secondary dissolution of detrital grains, particularly feldspars, has also occurred (Nirex, 1993a).

Hydrogeology

Water resources

Groundwater is used for a variaty of purposes (potable, industrial and agricultural) throughout the West Cumbria area. Springs are used extensively for private water supply (NRA, 1992).

Groundwater chemistry

The waters are mainly of calcium-bicarbonate type. The chemistry of the groundwater is controlled by input of sodium chloride dominated salts from marine aerosols, blown in from the Irish Sea. Dissolution of diagenetic minerals, dominantly calcite with some gypsum, from the St Bees Shale Formation in the north of the Sellafield area is also important. Approximately the upper 200 m of the Sherwood Sandstone Group forms the effective freshwater aquifer. A saline interface exists at a depth of around 300 to 700 m. Generally, the saline interface is situated at a formational boundary, such as at the base of the Calder Sandstone Formation or is positioned within the St Bees Sandstone Formation or the Brockram Formation (Nirex, 1993a).

Groundwater flow

Natural recharge to the St Bees Sandstone Formation takes place mainly in the outcrop areas, with only limited recharge in areas with recent and drift deposits. It is estimated (Ireland and Avery, 1976) that around 70% of 'effective rainfall' (i.e. rainfall less evapotranspiration), recharges the aquifer in the outcrop area, while only 10% recharges in the drift covered areas. Recharge generally occurs in the east and flows through the sandstone aquifers to discharge in the west into streams, rivers and the sea. Spring discharge is locally important.

The groundwater table is usually above the base of the drift. The permeability of the drift is variable, but generally it does not effectively confine the Sherwood Sandstone Group aquifer. The St Bees Sandstone Formation is apparently unconfined but exhibits tidal influence for some distance inland and barometric efficiency. There is possibly some influence of mine water from the Becker Mine on the groundwater levels in the Calder Sandstone Formation and the St Bees Sandstone Formations (Nirex, 1993a).

Groundwater flow in the Calder Sandstone Formation and the St Bees Sandstone Formations is driven by recharge in areas of higher topography inland to the east (Nirex, 1993a). Natural flow in the Calder area occurs as base flow to the River Calder to the east of Calder Bridge, where the river is in direct contact with the aquifer, and westward towards the sea. Flow is subhorizontal when considered over a regional scale due to the low vertical permeability of the St Bees Sandstone Formation. However, away from the recharge areas, comparison of deep and surface head within the aquifer as a whole indicates that there is a general upward hydraulic gradient within the sandstones. This is enhanced by the anisotropy of the system (Nirex, 1993a), an effect seen in the aquifer elsewhere. Groundwater flow occurs mainly in fractures, at least on a local scale, and the aquifer has a low storage coefficient 10^{-4} to 10^{-5} on the timescale of pumping tests. Reasonable yields are only obtained when boreholes intersect fractures.

River/aquifer interaction

In the upper Calder valley there is a high degree of connection between the St Bees Sandstone Formation (where it outcrops inland) and the river. The groundwater flow to the river can be seen in water levels near the top of the Sherwood Sandstone Group, but is not seen in deeper water levels, illustrating the anisotropic nature of the aquifer. If groundwater is pumped for river augmentation then the initial net gain to the river flow declines with time. It is thought that water enters the aquifer where fault and fracture zones intersect the river bed (Ireland and Avery, 1976). A North West Water Authority investigation around Egremont (Figure 7.7.1) identified induced effects on small rivers during pumping tests on investigation boreholes (Ingram, J A, personal communication).

Groundwater investigations

The main hydrogeological investigation in this area has been that at Sellafield, where between 1991 and 1997 UK Nirex Ltd (Nirex, 1993a and 1993b) conducted a detailed study to investigate the suitability of the site for a deep repository for solid intermediate and low-level radioactive waste. Although the investigations focused on the properties of the Borrowdale Volcanic Group, a substantial amount of research was carried out on other, shallower material, including the Permo-Triassic sandstones. The aquifer properties information presented here is taken from a published intermediate report (Nirex, 1993a) which included analysis of investigations by North West Water Authority in the St Bees and Egremont areas (Figure 7.7.1).

There are also limited NRA internal reports of pumping tests and water development in the Furness region (Brassington and Campbell, 1979), and an MSc thesis on the river Calder area (Kirk, 1986).

Hydraulic conductivity and transmissivity

Calder Sandstone Formation

CORE DATA

Results from work undertaken by Nirex in the Sellafield area have provided core permeability data with a range of over three orders of magnitude for the Calder Sandstone Formation. The median value of horizontal core hydraulic conductivity is 0.043 m/d and 0.017 m/d for vertical hydraulic conductivity (Figure 7.7.17, Table 7.7.7). This suggests that the intergranular hydraulic conductivity is anisotropic with a slightly higher horizontal hydraulic conductivity parallel to bedding (Nirex, 1993a).

ENVIRONMENTAL PRESSURE MEASUREMENTS

Field hydraulic conductivities measured using environmental pressure measurement (EPM) tests vary over nearly three orders of magnitude with a median of 8.6×10^{-3} m/d (Table 7.7.7). The median value for core hydraulic conductivity (measured by gas) is higher than the median value of field hydraulic conductivity, suggesting that the Calder Sandstone Formation has mainly matrix flow and acts as an intergranular medium (Nirex, 1993a).

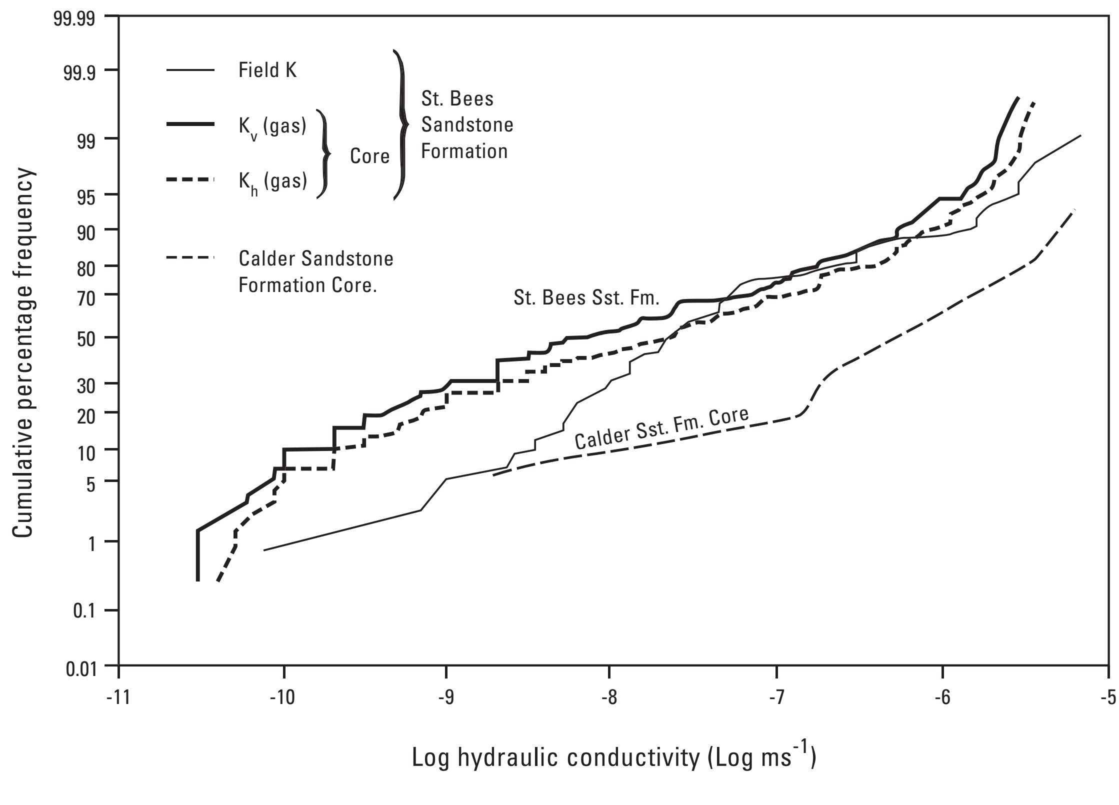


Figure 7.7.17 Cumulative frequency distributions of hydraulic conductivity data for St Bees Sandstone and Calder Sandstone core samples and field data from the St Bees Sandstone of the Sellafield area, West Cumbria (after Nirex, 1993a).

Table 7.7.7 Hydrogeological properties of the Calder Sandstone Formation (after Nirex, 1993a).

	No. samples	Min.	Median	Max.
Field EPM K (m/d)	9	2.7×10^{-3}	8.6×10^{-3}	1.37
Core K_h gas (m/d)	8	1.72×10^{-4}	0.0433	0.545
Core K_v gas (m/d)	8	1.72×10^{-4}	0.0172	0.545
Core porosity (%)	10	13.4	19.5	26.3

There are no direct pumping test transmissivity measurements solely for the Calder Sandstone Formation.

St Bees Sandstone Formation

Core data

Much core characterisation has been carried out in the St Bees Sandstone Formation by Nirex in the Sellafield area. Core hydraulic conductivity values range over five orders of magnitude, with a median horizontal core hydraulic conductivity of 1.7×10^{-3} m/d (170 samples) (Nirex, 1993a). The horizontal core hydraulic conductivity is between 0.25 and 0.5 orders of magnitude greater than vertical core hydraulic conductivity. The St Bees Sandstone Formation matrix appears to be have an anisotropy ratio (K_h/K_v) of 4:1 with higher permeability parallel to bedding (Nirex, 1993a) (Figure 7.7.17).

Permeability and porosity data in the Upper Calder region (Lovelock, 1970) have median values of 4×10^{-3} m/d for hydraulic conductivity and 15% porosity. In the St Bees Sandstone Formation in west Cumbria (Lovelock 1971) analysed 73 core samples from two boreholes (No 1 [NY 058 073] and No 2 [NY 046 075]). Hydraulic conductivity values from borehole 1 averaged 1.1×10^{-3} m/d with a porosity of 15.4%, and for borehole 2, average values of 3.6×10^{-3} m/d and 15.8% were obtained.

BGS core data from a number of sites throughout the west Cumbria area have a median horizontal hydraulic conductivity of 2.91×10^{-3} m/d, with an interquartile range of 2.98×10^{-4} to 0.0246 m/d. The median vertical hydraulic conductivity is 7.18×10^{-4} suggesting an anisotropy ratio (K_h/K_v) of around 4:1 and (Figure 7.7.18, 7.7.19, Table 7.7.3).

Environmental pressure measurements

Hydraulic conductivity values for the St Bees Sandstone Formation at the Sellafield site measured in the field (using Environmental Pressure measurement, or EPM tests) vary over five orders of magnitude with a median value at 2.6×10^{-3} m/d. Large-scale K_h/K_v anisotropy was calculated to be around 50:1 from estimates of the total thickness of sandstone and siltstone within the sequence, (assuming that the lowest 10% of the core sample hydraulic conductivities represented siltstone and the rest sandstone). This ratio is likely to increase near to the base of the St Bees Sandstone Formation where siltstone beds are more frequent.

Such a degree of anisotropy is much greater than indicated by core data (which is related only to small-scale laminations and mineral alignment). Vertical fractures, where present and open, will reduce the anisotropy by allowing flow to bypass the matrix. In general however, matrix conductivities of greater than 8.6×10^{-3} m/d had field conductivities of a similar value (Nirex, 1993a) (Figure 7.7.17).

Pumping test transmissivities

The transmissivity depends on the degree of fault and fracture intersection in the boreholes; the highest yields are obtained for boreholes located in a fault zone. Groundwater flow occurs predominantly in fractures, the degree of fracture intersection in a borehole determining the local transmissivity. The aquifer shows signs of being fairly anisotropic, and there is local connection between surface water and the aquifer. Transmissivities range from less than 10 to several hundreds of m^2/d (BGS database) with a geometric mean of 160 m^2/d (Figure 7.7.20). In the Brow Top region in

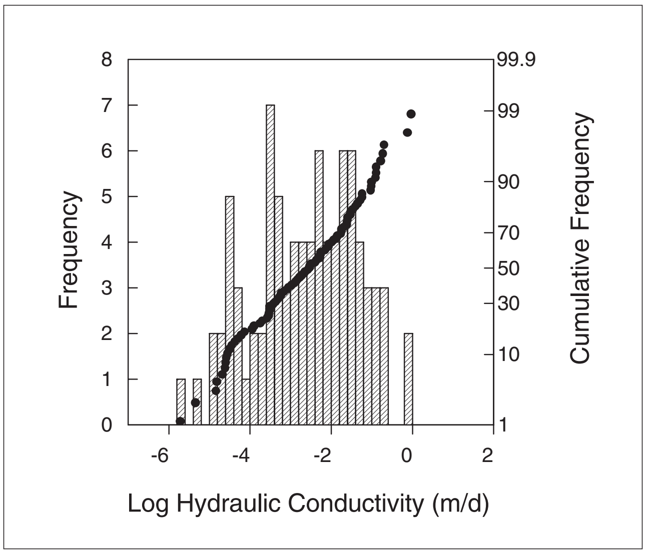


Figure 7.7.18 Distribution of horizontal hydraulic conductivity data for St Bees Sandstone samples from West Cumbria.

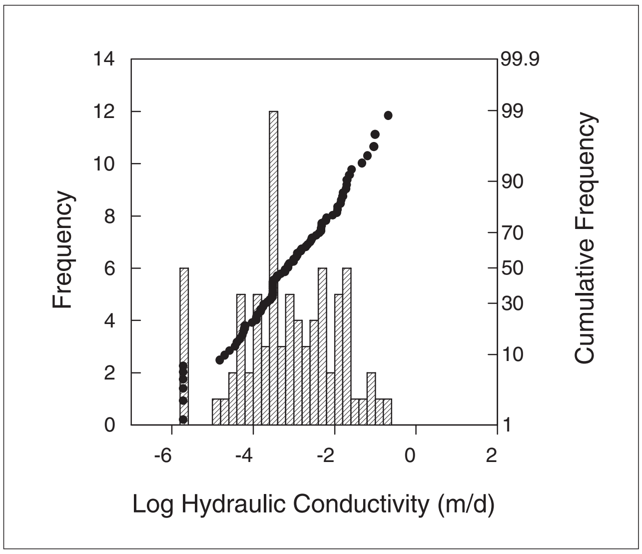


Figure 7.7.19 Distribution of vertical hydraulic conductivity data for St Bees Sandstone samples from West Cumbria.

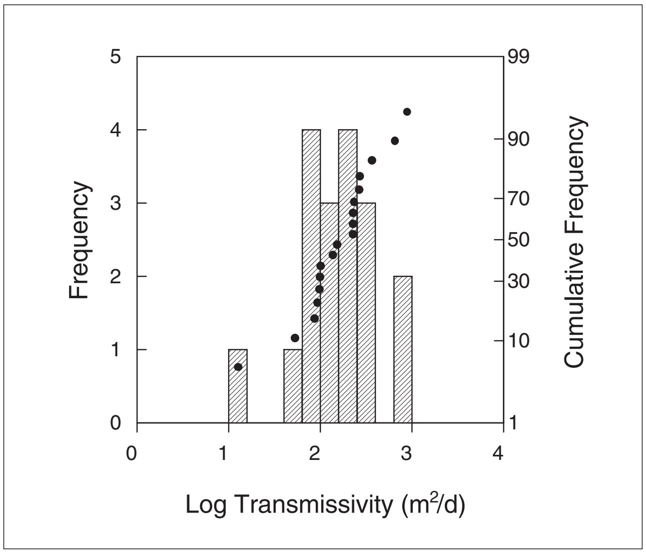


Figure 7.7.20 Distribution of transmissivity data from pumping tests in the St Bees Sandstone of west Cumbria.

the Calder Valley [NY 03 06], transmissivity values are variable, transmissivities, (on pumping wells without observation wells), are in the range 65 to 370 m^2/d with estimated confined storage (Ireland and Avery, 1976).

MODEL HYDRAULIC CONDUCTIVITY

Areal modelling of the Sherwood Sandstone Group in the Sellafield region using MODFLOW has been carried-out and NAMMU was used for sensitivity analysis. The simplest MODFLOW model used a hydraulic conductivity of 0.3 m/d, based on field measurements by Nirex and the water industry. Recharge to the model was controlled by the vertical hydraulic conductivity of the drift set at 0.05 m/d. It appears that locally there may be possible transfer of water from the Sherwood Sandstone Group to the Carboniferous Limestone, but this was not likely to be occurring over the whole area of mine workings.

Vertical modelling, using a finite element grid, was performed on two vertical sections through Seascale and Sellafield to investigate the possible dominance of horizontal flow. The same hydraulic conductivity values as in the MODFLOW model were used, (Calder Sandstone Formation 0.3 m/d, St Bees Sandstone Formation 8.6 × 10^{-3} m/d) except where the St Bees Sandstone Formation was less than 200 m from the ground surface in which case a value of 0.3 m/d was used. The effect of anisotropy was investigated by performing simulations with the ratio of horizontal to vertical hydraulic conductivity set to 10 and 100 for the Calder Sandstone Formation and between 1 and 1000 for the drift. The results suggested that the model was not very sensitive to anisotropy. The differences in the water table elevation between this vertical model and the MODFLOW model were fairly small, less than 7 m (Nirex, 1993a).

A two-dimensional finite element SUTRA model was constructed of the Sellafield groundwater flow system. The aquifer parameters used were: drift $K_h = K_v = 4.3 \times 10^{-4}$ m/d, Calder Sandstone Formation, K_h = 0.011 to 0.017 m/d and K_h/K_v = 10, St Bees Sandstone Formation $K_h = 2 \times 10^{-3}$ to 6.9×10^{-3} m/d and K_h/K_v = 10.

A three dimensional model was developed using the model code SWIFT to look at the variable direction of flow, (not purely towards the coast), that was indicated by the MODFLOW modelling. The aquifer properties values used are indicated in Table 7.7.8.

Generally the model permeabilities seem to suggest that the Calder Sandstone Formation is one or two orders of magnitude more permeable than the St Bees Sandstone Formation as a whole. However it appears that the upper horizons of the St Bees Sandstone Formation resemble the Calder Sandstone Formation. The implications of this for the aquifer properties of the freshwater aquifer is that the Calder Sandstone Formation properties are likely to dominate, with the deeper layers of the St Bees Sandstone Formation of less significance. This is borne out by the chemistry and the presence of saline water at depth beneath the more permeable freshwater horizons. The anisotropy the Calder Sandstone Formation is fairly low, whereas modelling indicates that vertical anisotropy is important in the St Bees Sandstone Formation. The low vertical permeability of the latter is thought to retard recharge.

Table 7.7.8 Model aquifer properties data for the Sellafield area of west Cumbria (after Nirex, 1993a).

			Area modelling	Vertical modelling		3D modelling
Model			Modflow	Finite element modelling	SUTRA	SWIFT
Hydraulic conductivity (m/d)	Drift	K_h	—	0.1	0.00043	—
	Drift	K_v	0.05	—	0.00043	—
	Sherwood Sandstone Group	K_h	0.3	—	—	—
	Calder Sandstone Formation	K_h	—	0.3	0.011–0.017	0.3
		K_h/K_v	—	—	10	—
	St Bees Sandstone Formation	K_h	—	0.0086	0.002–0.007	0.00086
		K_h/K_v	—	model not very sensitive to anisotrop	10	—

Porosity and storage

Core data

CALDER SANDSTONE FORMATION

Porosity estimates (10 samples) from Nirex data range from 13.4 to 26.3% with a median of 19.5% (Nirex, 1993a). This formation has a much greater porosity than the St Bees Sandstone Formation (Figure 7.7.21).

ST BEES SANDSTONE FORMATION

Core porosities from Nirex data (179 samples) from the Sellafield area range from 1.5% to 21.6% with a median value of 11.6% (Nirex, 1993a) (Figure 7.7.21). Core permeability has a moderate correlation with porosity within the St Bees Sandstone Formation. Vertical core permeability appears to correlate better with porosity than horizontal permeability but the reason for this is unclear (Nirex, 1993a).

BGS core data for the west Cumbria area have a median value of porosity of 15% and an interquartile range of 13% to 21% (Figure 7.7.22). Again this is lower than the porosities obtained for the Calder Sandstone Formation. The base of the St Bees Sandstone Formation is less porous than the cleaner, coarser sediments near the top of the formation. There appears to be some correlation between core permeability and porosity (Figure 7.7.23).

Beneath the St Bees Sandstone Formation the St Bees Shale Formation has porosities in the range from 1.1% to 11.2% with a median value of 2.8%. This low porosity combined with median low field hydraulic conductivities of 1.7×10^{-4} and low median core permeabilities of 7×10^{-6}, means that the shales form an effective hydraulic base for the fresh water aquifer.

Pumping test storage coefficients

Storage coefficient values obtained from pumping tests, in the Sherwood Sandstone Group generally, are mainly confined (Figure 7.7.24). The geometric mean of storage coefficient values (9 values) is 8.6×10^{-5}, with a range from 1×10^{-7} to 0.12.

Model storage coefficient values

Model storage values used in the SWIFT model are 0.2 for the Calder Sandstone Formation, and 0.1 for the St Bees Sandstone Formation (Nirex, 1993a).

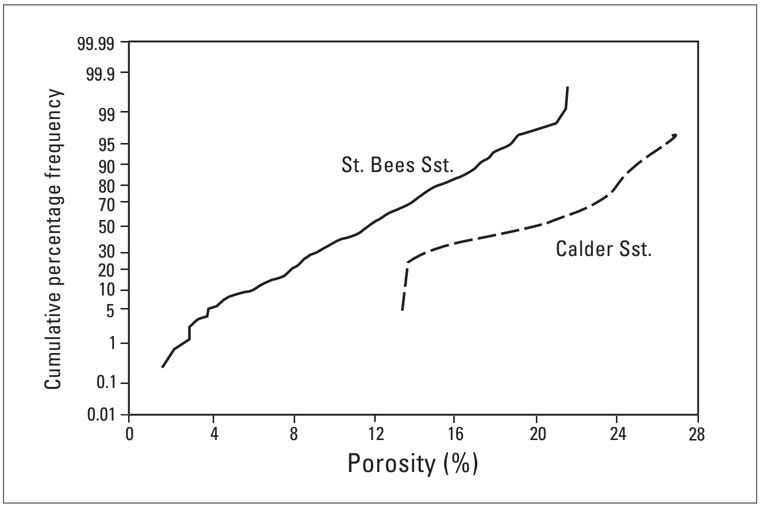


Figure 7.7.21 Cumulative frequency distribution of porosity data for St Bees Sandstone samples and Calder Sandstone samples from the Sellafield area, west Cumbria (after Nirex, 1993a).

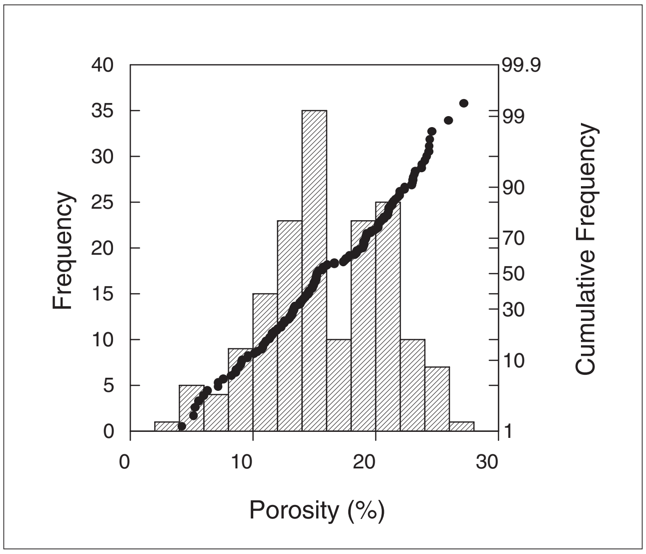


Figure 7.7.22 Distribution of porosity data from Sherwood Sandstone Group samples from west Cumbria.

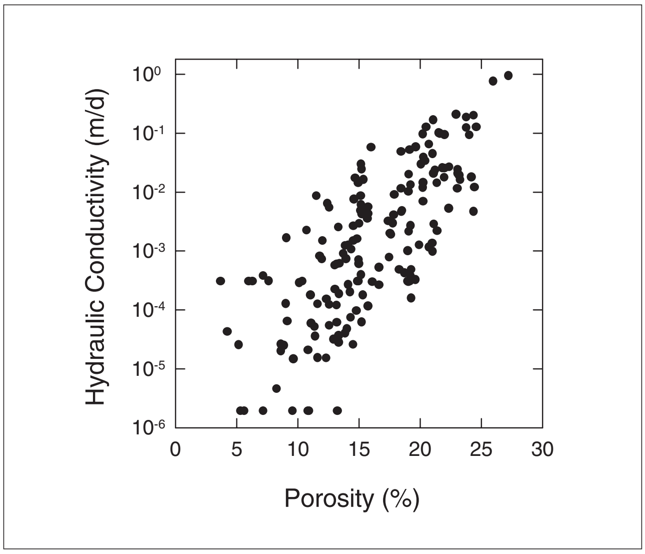


Figure 7.7.23 Plot of hydraulic conductivity against porosity data for Sherwood Sandstone Group samples from west Cumbria.

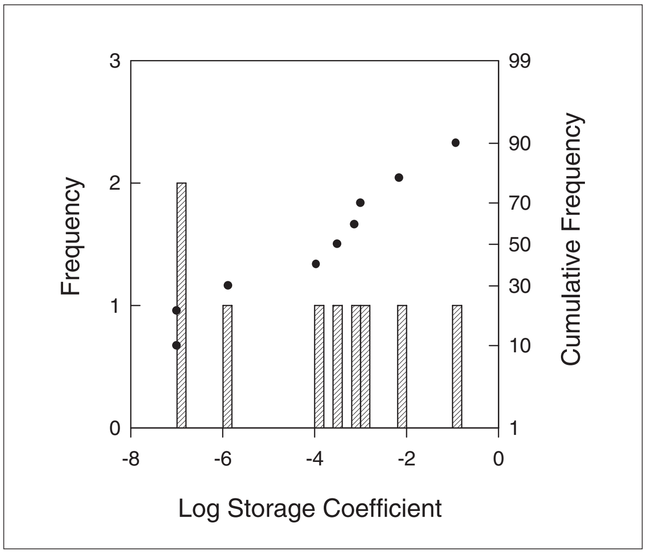


Figure 7.7.24 Distribution of storage coefficient data from pumping tests in the St Bees Sandstone, west Cumbria.

Aquifer response times

In the Calder area hydrographs indicated an annual water level fluctuation of between 0.5 and 6 m. Several boreholes exhibit barometric effects indicating that the aquifer is responding in a confined manner on a daily time scale. Some boreholes up to a couple of miles from the coast have a daily water level fluctuation which is attributed to tidal effects (Ireland and Avery, 1976).

Summary

The field permeabilities measured in boreholes are on average of similar or slightly higher permeability than the core measurements. The upper part of the Sherwood Sandstone Group is more conductive and has core and field permeabilities that are similar, indicating that flow occurs predominantly through the matrix rather than fractures. The lower part of the Sherwood Sandstone Group (especially towards the base of the St Bees Sandstone Formation) is less permeable and has field permeabilities that are around two orders of magnitude greater than core permeabilities indicating that fracture flow dominates over matrix flow in the deeper layers (Nirex, 1993b). Model permeabilities confirm this view of groundwater flow. Table 7.7.9 summarises permeability values for the Calder and St Bees Sandstone formations in west Cumbria.

Models use unconfined storage coefficients for both the Calder Sandstone and the St Bees Sandstone formations, of similar values to those obtained for core porosity. This is in contrast to the confined specific storage values obtained in pumping tests, and the confined response indicated by barometric and tidal effects. This variable aquifer response is typical of the Permo-Triassic sandstones, especially those which have interlayered sediments and which exhibit anisotropy. The aquifer responds in a confined or semi-confined manner over a short time scale, but in an unconfined manner over a longer time scale of months or years.

7.7.5 The Furness area

Geological and geographical setting

In this area the St Bees Shale Formation consists of 80 to 215 m of unfossiliferous mudstones with subordinate thin limestones and sandstones. A 10 m-thick anhydrite bed occurs at the base with thinner beds higher up in the sequence. The formation grades up into the St Bees Formation, the base of which is taken arbitrarily as the base of the Triassic.

The St Bees Sandstone Formation is about 700 m thick in this area, being composed mainly of cross-stratified, red sandstones with many thin intercalations of red mudstone. The grain size varies from fine to medium and, in general, the sandstone is well cemented by calcite (Brassington and Campbell, 1979).

The St Bees Sandstone Formation is overlain by the Mercia Mudstone Group, the basal 10 to 20 m of which is assigned to the grey, Hambledon Mudstone Formation. This is overlain by 150 to 180 m of dominantly red Singleton Mudstone, which contain a few thin beds of salt.

Glacial drift is present over much of the area, mainly as boulder clay, but with intercalated sands and gravels. The drift generally thickens to the south and west away from the higher ground around Dalton-in-Furness [SD 230 735] (Brassington and Campbell, 1979). Most of the St Bees Sandstone Formation outcrop is mantled by drift, but there are a few drift-free areas along the Vale of Nightshade north of Furness Abbey at Ormsgill [SD 185 720] and at the base of the cliffs north-west of Rampside [SD 230 665]. The coastal area and Walney Island have extensive spreads of marine alluvium and raised beach deposits.

Structure

The area is disrupted by a series of NNW- to SSE-trending faults, each of which are normal with downthrows to the west. The Yarlside Fault, which throws the Permo-Triassic against Carboniferous strata in the east of the region, has a throw of around 600 m. A major syncline is present in the west of the area, with its axis plunging south-south-east along the Walney channel.

Table 7.7.9 Summary of permeability values for drift, Calder Sandstone Formation and St Bees Sandstone Formation, west Cumbria (sources: Nirex, 1993a and water industry data).

Hydraulic conductivity (m/d)	Calder Sandstone Formation		St Bees Sandstone Formation	
	K	K_h/K_v	K	K_h/K_v
Core	0.0414	2.3	0.0017	4
EPM	0.0086	—	0.0026	50
Pumping test bulk K	—	—	0.07–3.7 (~2)	—
Model	0.3–0.017	10	$0.3–8.6 \times 10^{-4}$	10

Hydrogeology

Water resources

The development of groundwater resources in the St Bees Sandstone Formation of the Furness region occurred in two main periods. Boreholes were constructed around 1900 in the town centre and dock areas for industrial supply, and between 1955 and 1965 to the north of the town for greater industrial and domestic supply (Brassington and Campbell, 1979). Saline groundwater intrusion is a problem along the coast.

Chemistry

There are a number of different types of water chemistry in the area. Modern Permo-Triassic sandstone groundwater, calcium-bicarbonate rich and low in chloride and sulphate, is present over much of the area. Waters rich in sodium, potassium and chloride are present in the north (British Cellophane boreholes [SD 194 737]) and in the south at Barrow Paper Mills [SD 216 688]. The southern high chloride waters are due to recent coastal saline intrusion, while the northern case is possibly due to saline intrusion into the Carboniferous limestone. Older waters, evolved from calcium bicarbonate water, are richer in sodium at the expense of magnesium and calcium as a result of ion exchange in the aquifer with time. Deep in the sandstones more calcium bicarbonate and sulphate rich water is present, the sulphate probably being derived from the St Bees Shale Formation beneath the sandstones, which contain gypsum and anhydrite deposits. These findings of recent recharge in the outcrop area and older water away from this are corroborated by tritium data. High tritium values (<20 TU) are found in the recharge area grading to low values (<3 TU) away from the outcrop (Brassington and Campbell, 1979).

Groundwater flow

Prior to the commencement of abstraction, the water table generally followed the ground surface with a 'mound' coinciding with the drift free area of Hawcoat [SD 205 720]. The natural groundwater flow was to the south towards the sea in the area of the docks. Locally at British Cellophane Boreholes [SD 194 737] connection was found between the St Bees Sandstone Formation and the Carboniferous Limestone. When the limestone was pumped, drawdown was seen in an observation hole open only to the St Bees Sandstone Formation.

Simple water balance calculations in this area indicate that there is only limited recharge through the drift-free areas with no substantial flow in from the surrounding areas such as the Carboniferous Limestone to the east.

High abstraction rates have resulted in lowering of groundwater heads and a decline in the water quality due to migration/leakage of deeper and older water into the abstraction boreholes. In addition, along the coast, there is some saline intrusion which as led to abandonment of the Barrow Paper Mills borehole [SD 216 688] (Brassington and Campbell, 1979).

Groundwater investigations

The general groundwater resources of the area are summarised in a North West Water Hydrogeological report (Brassington and Campbell, 1979). There has been little pump testing in the area and there are only limited core data and no modelling work. Generally however the area is similar to the Sellafield area further north, though the sediments may be slightly more permeable and porous in the Furness region. The effects of saline intrusion are more evident than further north. This area appears to be intermediate between the north-west Cumbria region and the Fylde Permo-Triassic Sandstones.

Hydraulic conductivity and transmissivity

Core data

The average hydraulic conductivity of core taken from the Sherwood Sandstone Group at two sites in Barrow in Furness is 0.049 m/d at one site and 6.7×10^{-4} m/d at the other site (source BGS core data). This is similar to the values obtained further north in west Cumbria, and less than that obtained further south in the Fylde.

Pumping test transmissivity

Pumping tests at Schneider Road [SD 196 707] and Thorncliffe Road [SD 196 709] gave transmissivity values of 1000 m^2/d.

The Bowater Scott Works Borehole [SD 199 725] was cored from 44 m to 166 m through St Bees Sandstone Formation which was fractured near its top but appeared to have little permeability at depth.

Specific capacity and borehole yields

The Leece borehole [SD 241 685] had an artesian head when unpumped (1976) but had a drawdown of 59 m for a discharge of 650 m^3/d (specific capacity 11 m^3/d/m) indicating a low transmissivity (the borehole is considered to be in a faulted block where the aquifer is thin; Ingram, J A, personal communication). The high water level in this area is indicative of low regional permeability in relatively thin sandstones, with low fracture connection, which allows high heads to develop.

Ratio intergranular K to pumping test K: fractures

Laboratory tests on core from Hawcoat quarry (Barrow in Furness) gave an estimated matrix transmissivity value of 8 m^2/d (Brassington and Campbell, 1979), in an area where pumping test results reach 1000 m^2/d, indicating more than 99% fracture flow. Correspondingly the low transmissivities determined in some pumping tests, mainly to the east of Furness (Leith Brow [SD 214 715] and Furness Abbey [SD 217 717] and Leece [SD 241 685]) indicate a lack of fracture intersection and low permeabilities typical of matrix values.

Porosity and storage

Core data

Laboratory core data (BGS database) in the Barrow in Furness area had an average porosity of around 20%. This is generally higher than in the St Bees Sandstone Formation further north.

Pumping tests

Pumping test storage coefficients have confined to semi-confined values, with a value of 1×10^{-3} in the Schneider Road and Thorncliffe Road boreholes.

Aquifer response times

Continuous water level records in the area all show barometric and tidal effects, the barometric efficiency of the area varying between 45–65%. Assuming a mean barometric efficiency of 55%, a porosity of 20% (Lovelock, 1977) and an aquifer thickness of 500 m, a storage coefficient of 8×10^{-4} may be calculated. This is similar to that calculated from pumping tests and represents a high confined value and an aquifer that is responding mainly in a confined manner but which has unconfined areas (Brassington and Campbell, 1979).

Summary

The permeability of the St Bees Sandstone Formation appears on the basis of very limited data to be generally similar to that further north at Sellafield.

Generally the aquifer behaves in a similar manner to the Sherwood Sandstone Group further north. The aquifer responds in a confined manner over a short time scale, but in a more semi-confined manner over longer times. In the Furness region the drift cover is more complete than further north and so the aquifer may respond in a more confined manner.

7.8 VALE OF CLWYD

7.8.1 Introduction

Geological and geographical setting

General description

The Vale of Clwyd is flanked to the east by the Clwydian Range and to the west by the Denbigh Moors (Figure 7.8.1). Permo-Triassic sandstone is the region's principal aquifer, which falls within the jurisdiction of the Welsh Region of the Environment Agency. The sandstone is preserved within a north–south-trending, down-faulted block or graben. The sandstones mostly subcrop beneath thick superficial deposits, and in consequence exposures are scarce. The Permo-Triassic sandstone has not been subdivided into formations in the Vale of Clwyd; it consists of homogeneous, cross-bedded, generally well-cemented, fine- to medium-grained sandstone with a few mudstone horizons and no pebble beds (Lewis et al., 1989).

Artesian heads of over 6 m above ground level cause overflowing conditions over a large area in the centre of the main basin (Lewis et al., 1989). Boreholes in the Permo-Triassic sandstones have an average yield of approximately 3000 m^3/d, although yields exceeding 7000 m^3/d have been obtained (Monkhouse and Richards 1979). The Vale contains three pumping stations: Efail Newydd, Llandyrnog and Llwyn Isaf; commercial users own the other boreholes.

Regional structure

The Permo-Triassic sandstone aquifer of the region is preserved in a fault-bounded basin or graben. The Vale of Clwyd fault, which forms the eastern boundary, is a major structure with a downthrow to the west of 1500 m. This fault juxtaposes the sandstones against Lower Palaeozoic or, locally, Carboniferous rocks. The western boundary is mostly defined by an *en chelon* series of north–south-trending faults, each with throws up to 300 m. Geophysical evidence indicates that the aquifer thickens considerably towards the east across these faults. South of Ruthin, the Permo-Triassic lies unconformably on Carboniferous rocks with no apparent faulted contact (Warren et al., 1984).

The Permo-Triassic sandstones occur within two main structural basins and unconformably overlie Carboniferous Limestone in both. They are up to 300 m thick in the northern basin, and up to 525 m thick in the southern, with greatest thicknesses towards the basin centres. Over 90% of the southern basin and the whole of the northern basin are covered with drift deposits, which locally exceed 90 m in thickness (Lewis et al., 1989).

Stratigraphy

Uncertainty surrounds the age and lithostratigraphy of the Permo-Triassic sandstones of the Vale of Clwyd. Warren et al. (1984) consider that they are likely to be Upper Permian or Triassic in age, perhaps spanning the boundary between the two periods. Warrington et al. (1980) suggest that they are possibly the lateral equivalents of the Kinnerton Sandstone Formation of the Cheshire Basin, and of the Collyhurst Sandstone and Manchester Marl formations of the West Midlands, but imply that application of any formal stratigraphical name would be wholly speculative. No formation names are applied, therefore, in this account. The sandstone is assigned to the Lower Mottled Sandstone on Institute of Geological Sciences 1:50 000 geological sheets 107 and 108 (1973 and 1972). Outcrops are found south of Ruthin, on the left bank of the River Clwyd south-east of St Asaph, and on the eastern margin of the Vale (Lambert et al., 1973).

The lithology of the sandstones is described by Warren et al. (1984). They are mainly fine to medium grained with subordinate coarser beds; a few silty beds occur at some levels. No basal conglomerate has been recorded. The colour is mainly red, less commonly yellow and grey. The sand grains vary from well rounded to subangular and consist predominantly of quartz with subordinate feldspar and lithic grains. The sandstone is generally friable. Much of it is cross-bedded and probably of aeolian origin, the red colour being due to grain coatings of haematite. Other parts of the succession have probably been deposited sub-aqueously, as suggested by argillaceous and micaceous laminae, mud-flake breccias, graded bedding and rare pebbles. The depositional environment was likely to have been a desert with local, ephemeral lakes or watercourses (Warren et al., 1984).

Previous hydrogeological investigations

The aquifer was the subject of a detailed study by the Dee and Clwyd River Authority and the Water Resources Board (Lambert et al., 1973) which provided information on the hydrology, hydraulic properties, groundwater resources and groundwater quality. During the investigation three abstraction boreholes, (referred to as A, B and C), and associated observation boreholes were drilled and test-pumped for periods ranging from three days to two months. The tests were complemented with geophysical logging and laboratory studies on core samples taken from the observation wells.

Worthington (1976), Reeves et al. (1975) and Lovelock (1977) have all studied the hydraulic properties of the sandstones in the Vale of Clwyd. Detailed gravity and seismic geophysical surveys have been undertaken by Collar (1974) and Wilson (1959) in order to determine the extent and depth of the Permo-Triassic basins along the Vale of Clwyd. No groundwater models of the region have been published.

7.8.2 Hydraulic conductivity and transmissivity

Core data

Frequency distributions of core hydraulic conductivity data from the Aquifer Properties Database are given in Figure 7.8.2a. They range from 3×10^{-4} to 3.0 m/d and have a geometric mean of 0.21 m/d. Table 7.8.1 gives further statistics. The most permeable sands are those which are either clean, well-sorted medium sands, or poorly sorted and laminated types in which the coarse laminae have clean

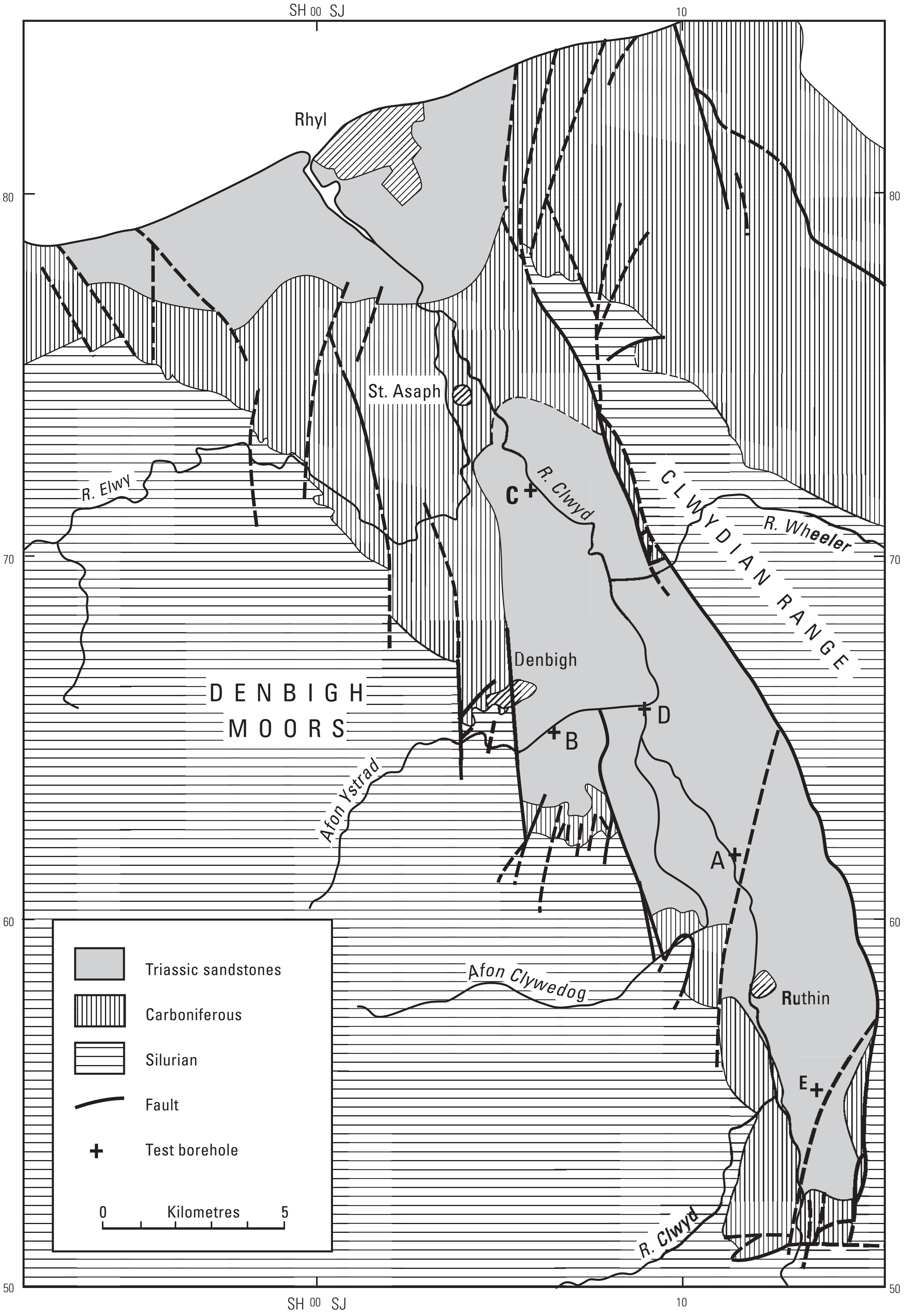


Figure 7.8.1 Vale of Clwyd — region covered, locations of places referred to in the text, and geology.

'millet seed'-type grains, with high horizontal conductivities. The lowest values can be attributed to subordinate well-cemented, compacted fine-grained sands (Lovelock, 1977).

Thin-section analysis by Lambert et al. (1973) revealed that, for a given borehole, there is an inverse correlation between matrix (cement) fraction and permeability. However there was no significant correlation between the grain-size distribution and the laboratory-determined physical properties. Core-scale anisotropy, although common is not ubiquitous. Vertical and horizontal hydraulic conductivity values from the Aquifer Properties Database are plotted in Figure 7.8.2b, and their statistics are given in Table 7.8.1. The horizontal hydraulic conductivity median value, 0.29 m/d, is double the vertical median value. The horizontal hydraulic conductivity of cores from boreholes A1 [SJ 112 618] and B1 [SJ 063 652] is generally four to eight times vertical values, whereas for borehole C1 [SJ 057 721] the factor is close to unity (Lambert et al., 1973).

The core samples are biased towards more cemented horizons. Poor core recovery was noted at site C [SJ 057 721], where the strata appeared to be weakly cemented (Reeves et al., 1975). At site C, the maximum value for hydraulic conductivity derived from laboratory tests on cores, 0.63 m/d, is much higher than that obtained at the other boreholes. A high intergranular flow would be consistent with the low degree of cementation.

Geophysical logging

The occurrence of fracture flow was established at site A [SJ 112 618] by geophysical logging techniques. Flow logging showed that about 80% of the total flow is achieved at a depth of 58 m. Television inspection of the borehole showed a small horizontal fracture at this depth. The caliper and differential temperature logs also highlighted this fracture, along with smaller ones at greater depths (Lambert et al., 1973). The fracture horizons were of similar orientation to the observed bedding surfaces. Surface geophysical surveys show that a major fault passes close to site A and it is possible that the fracturing is associated with this tectonic disturbance (Reeves et al., 1975).

Pumping test transmissivity and bulk hydraulic conductivity

Pumping tests were conducted at eight sites as a component of the Groundwater Resources study by the Dee and Clwyd River Authority and the Water Resources Board (Lambert et al., 1973). Both the geometric mean and median of the values are 130 m^2/d. They range from 20 to 1200 m^2/d and have an interquartile range of 56 to 310 m^2/d. The lowest values probably result from intergranular flow alone. The large range is most likely to relate to the degree of fracturing present at each site, as it cannot be explained by differing borehole saturated depths alone. However, where core samples and downhole logs are absent, the precise nature of groundwater flow to these boreholes is unknown.

Bulk aquifer hydraulic conductivities have been computed by Lambert et al. (1973) for the eight pumping tests. The depth of penetration of the borehole into the aquifer, rather than the total aquifer thickness, was taken as the saturated thickness value, because of the high anisotropy observed in core samples. Bulk hydraulic conductivity values were found to range from 0.17 m/d to 20 m/d. The minimum values are consistent with mean intergranular hydraulic conductivity values obtained from the core samples. The geometric mean of the borehole values is 2.4 m/d, and the median is 2.3 m/d.

Mean core intergranular hydraulic conductivity can be compared with computed bulk pumping test derived hydraulic conductivity at two sites. At site A, the intergran-

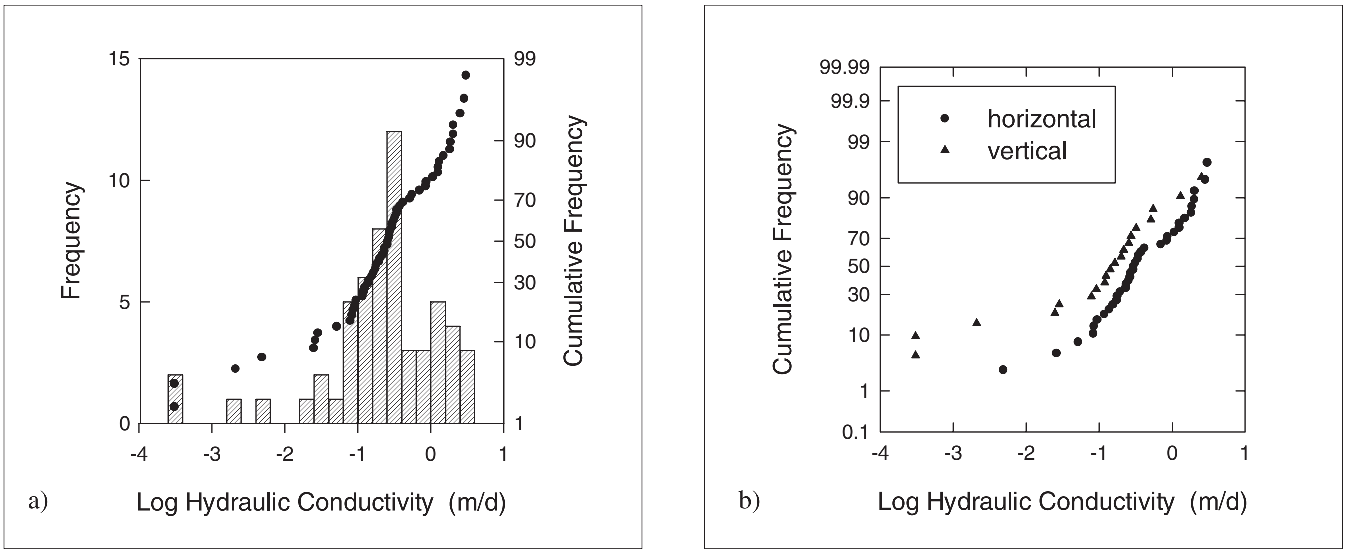


Figure 7.8.2 Distribution of hydraulic conductivity data for Permo-Triassic sandstone samples from the Vale of Clwyd, a) all samples, b) horizontal and vertical samples.

Table 7.8.1 Core hydraulic conductivity data for the Permo-Triassic sandstones of the Vale of Clwyd.

Orientation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
All	3.0×10^{-4}–3.0	0.12–0.78	0.26	0.21
Horizontal	4.8×10^{-3}–3.0	0.16–1.16	0.29	0.34
Vertical	3.0×10^{-4}–2.5	0.03–0.31	0.15	0.83

ular and bulk values were 0.53 and 19.6 m/d respectively, suggesting that fracture flow is substantial, contributing 97% of the borehole discharge. This is consistent with the prolific fractures observed during borehole logging and the evidence of faulting nearby. At site B the pumping test derived bulk hydraulic conductivity was 2.1 m/d, a factor of eight times larger than the mean horizontal intergranular hydraulic conductivity. Here, the intergranular flow contribution is more significant than at site A.

Summary

Although the Permo-Triassic sandstone is homogenous, and fine to medium grained with few mudstone horizons and no pebble beds, it has a wide range of both intergranular and bulk hydraulic conductivity values (Table 7.8.2), spanning over two orders of magnitude. The lowest values of transmissivity are of the order of 10 to 50 m^2/d and probably represent intergranular flow. Under such conditions borehole depth exerts a strong control on transmissivity. Values in excess of 1000 m^2/d occur in localised areas, which may be associated with faulting. Borehole logging confirms that fracture flow is locally significant.

Table 7.8.2 Comparison of hydraulic conductivities for the Permo-Triassic sandstones of the Vale of Clwyd measured at different scales.

Hydraulic conductivity type	Measurement method	Interquartile range (m/d)	Geometric mean (m/d)
Intergranular	Permeametry	0.12–0.78	0.21
Bulk	Pumping test	0.76–11.3	2.4

7.8.3 Porosity and storage

Core porosity

Figure 7.8.3 shows the frequency distribution of core porosity measurements held on the British Geological Survey's database. The data tend to a normal distribution, with an arithmetic mean of 23.6%. The median is similar at 23.3%. There is a moderate variation of core porosity values in the sandstone, with an interquartile range of 21 to 25% and a total range of 19 to 31%. The variability can be attributed to the differing grain-size, degree of sorting of the sediments, degree of grain roundness and the extent of weathering and diagenesis. Elsewhere in the country, porosities can be much lower, for instance 6% in Cheshire and south Lancashire. The lack of low porosities in the Vale of Clwyd is likely to result from a lesser degree of cementation.

Porosity and hydraulic conductivity are positively correlated (Figure 7.8.4), although the hydraulic conductivity associated with a particular porosity can vary by up to three orders of magnitude. Pore throat size is likely to have a stronger influence on hydraulic conductivity than it has on porosity. Specific yield, determined from core samples by centrifuge techniques, is estimated as 4 to 17% by Lambert et al. (1973).

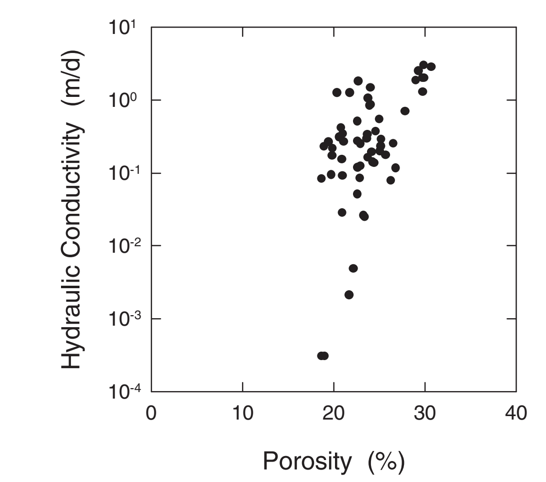


Figure 7.8.4 Plot of hydraulic conductivity against porosity for Permo-Triassic sandstone samples from the Vale of Clwyd.

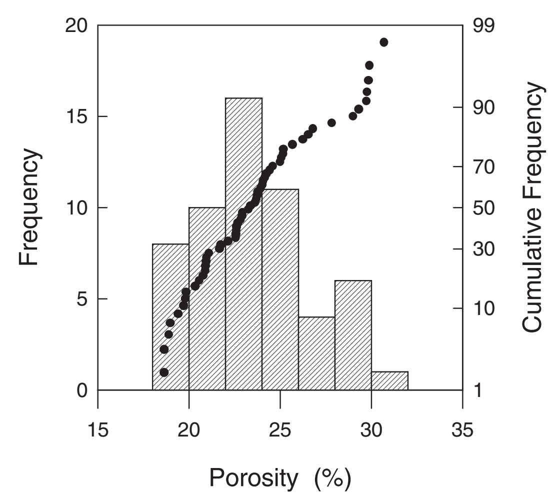


Figure 7.8.3 Distribution of porosity data for Permo-Triassic sandstone samples from the Vale of Clwyd.

Pumping test storage

Storage coefficients calculated from pumping tests in the Vale of Clwyd range from 1×10^{-4} to 2×10^{-3} (six values). The higher values indicate the semi-permeable nature of the overlying superficial deposits. When abstraction takes place from the aquifer, downward leakage from these deposits is induced. The geometric mean of values is 3.8×10^{-4}; a representative confined value of 4×10^{-4} has been suggested by Monkhouse and Richards (1979).

Summary

The Permo-Triassic sandstones are confined by superficial deposits, causing artesian conditions in the centre of the southern basin. Confinement is not total, since leakage occurs through the superficial deposits, which can hydraulically connect the aquifer to rivers. The porosity range is moderate, from 19 to 31%. Values of specific yield are intermediate between confined storage values and the porosity values.

7.9 SOUTH-WEST ENGLAND

7.9.1 Introduction

Geological and geographical setting

General description

Permo-Triassic sandstones and breccias form the principal aquifers of west Somerset and east Devon, and fall within the jurisdiction of the South West region of the Environment Agency. These strata crop out in a belt extending from Exmouth and Paignton in the south to Minehead in the north, with a 'finger' of Permian deposits extending west of this belt towards Crediton and beyond (Figure 7.9.1).

The region is composed of a number of catchment areas. The Tone catchment area drains the north-east of the region, and the Otter Valley drains the south-east. In the west of the region, where the Permian strata outcrop, the rivers Exe, Clyst and Cred drain the area towards the south down the Exe estuary. Generally there is little superficial material and the rivers are in hydraulic connection with the aquifers over which they flow (Figure 7.9.2).

Regional structure

The Permo-Triassic strata lie unconformably on folded Carboniferous, Devonian and Lower Palaeozoic basement, infilling a variable buried topography (Sherrell, 1970). The sequence generally becomes younger towards the east and is divided into four major divisions, the Permian Exeter Group and the Triassic Aylesbeare Mudstone, Sherwood Sandstone and Mercia Mudstone groups.

The Permo-Triassic sequence in the main outcrop area (Figure 7.9.1), consists of sedimentary rocks dipping gently 10–12° to the east, unconformably overlying the Palaeozoic basement which outcrops to the west. Minor faulting is present, usually with the downthrow to the east. The Permian sequence is representative of an intermontane or alluvial fan type of sedimentary environment and shows considerable and rather unpredictable lithological variation (Henson, 1970). The deposits consist of the

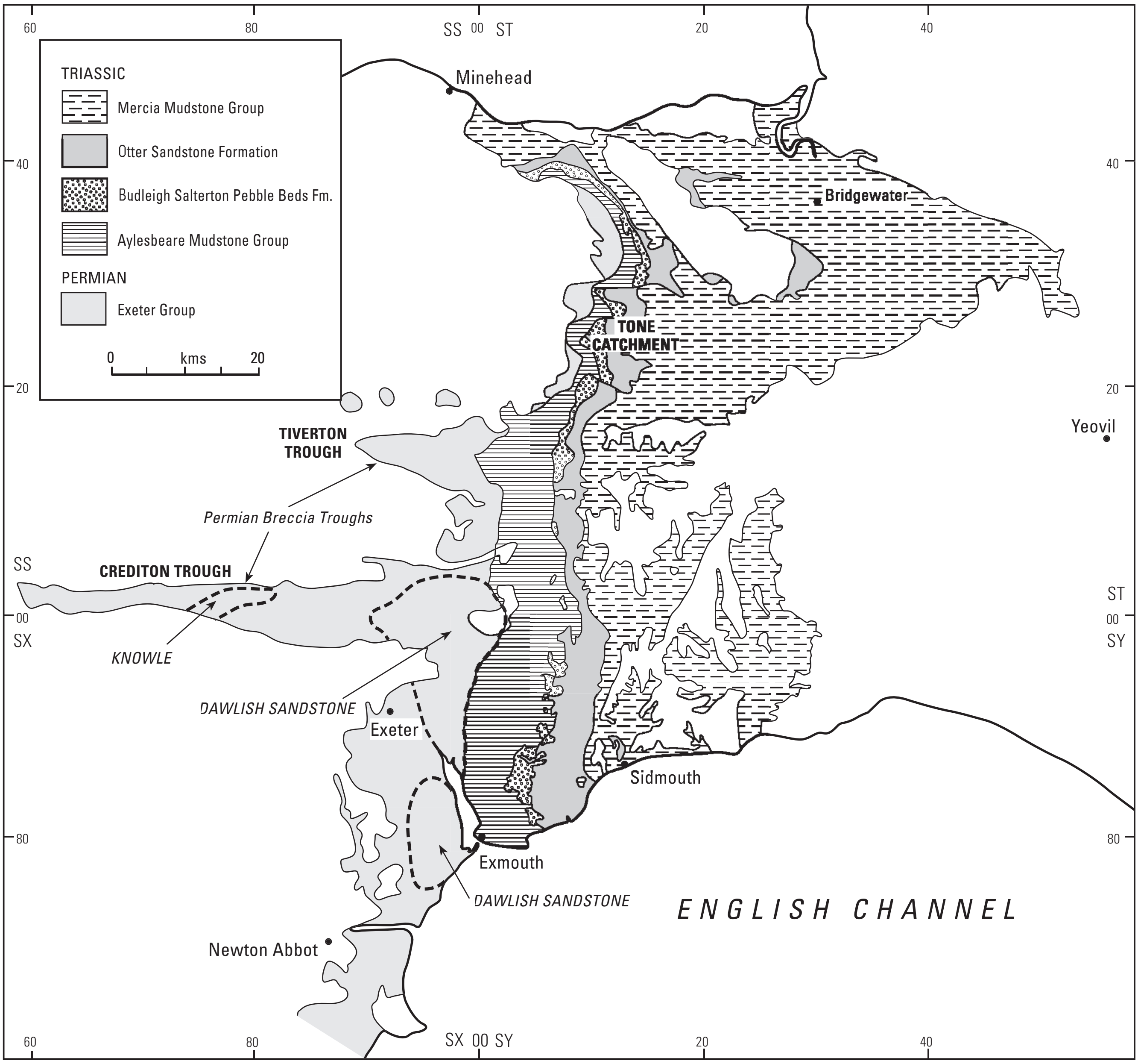


Figure 7.9.1 General geology of the Permo-Trias in south-west England.

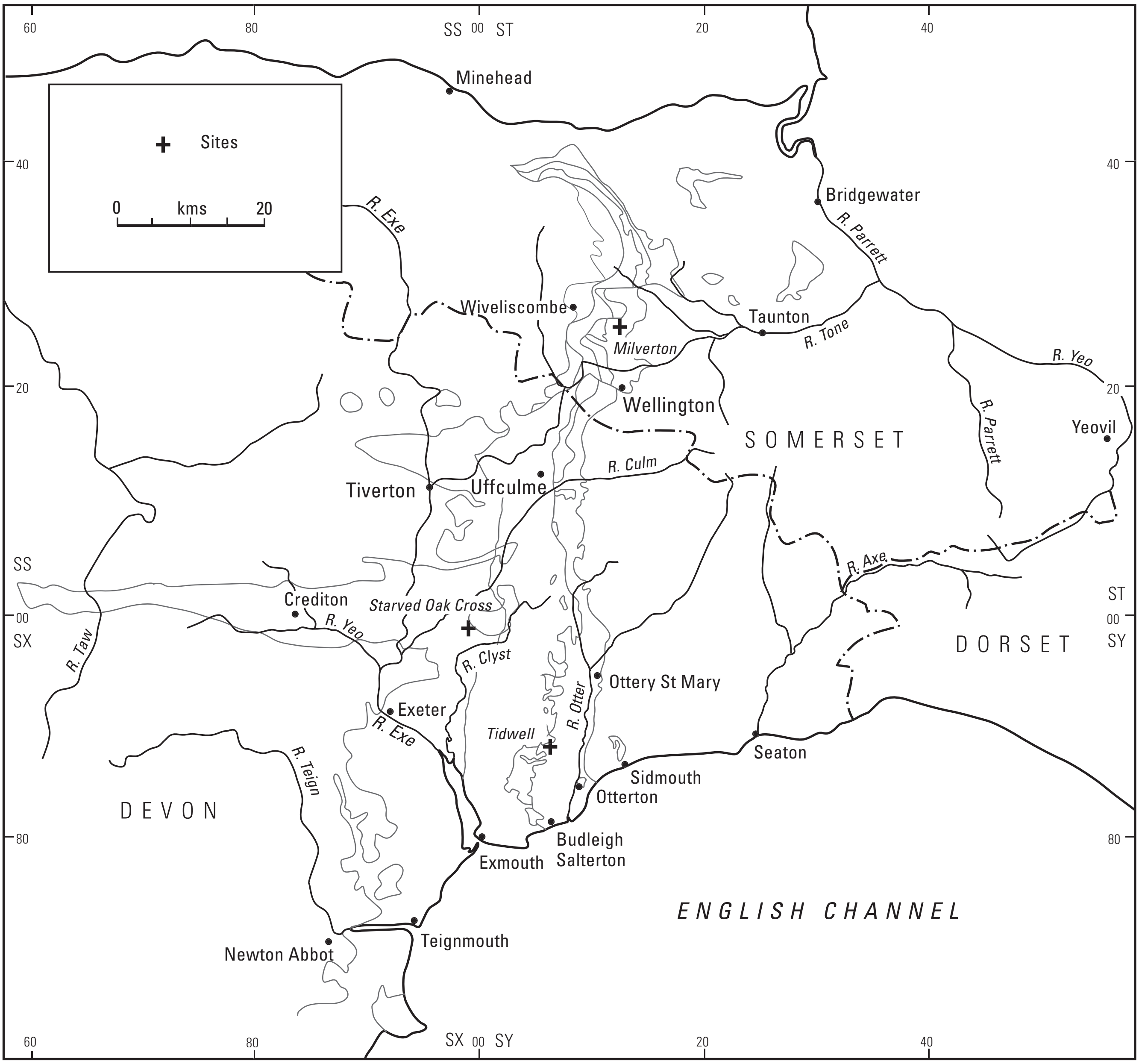


Figure 7.9.2 Geographical setting of the Permo-Triassic aquifer in south-west England.

erosional products of the original Palaeozoic basement, the topography of which influenced the patterns of deposition in Permian times. The Palaeozoic basement forms the hydraulic base to the aquifer.

The Permian deposits in the north and west (Figure 7.9.1) occur as infills to large fault-controlled troughs, and form narrow fingers of outcrop towards the west away from the main Permo-Triassic rocks. The troughs are bounded by east–west-trending normal faults which underwent substantial syndepostitional movement. Later faulting has a north-west to south-east trend and has some associated manganese mineralisation, with additional north–south fractures resulting from east–west extension in the Triassic. The Tiverton Trough has a depth of 300 m, declining to the east, whilst the Crediton Trough has a depth of over 800 m (Bott et al., 1958).

The Triassic sandstones and pebble beds are situated along the valley of the River Otter in a north–south band from Budleigh Salterton in the south to Uffculme to the north of the Otter Valley. The Sherwood Sandstone Group is composed of the Otter Sandstone and the Budleigh Salterton Pebble Beds formations and is underlain by the Aylesbeare Mudstone Group. It is overlain to the east by the Mercia Mudstone Group.

To the north of Uffculme, a number of faulted blocks of aquifer lie within the River Tone catchment. The Otter Sandstone Formation thins from about 140 m thick to the east of Uffculme to about 70 m near Wellington. The aquifer is divided into several blocks by east–west-trending faults, for example the Wellington, Halse and Bishop's Lydeard blocks. Cementation progressively increases northward and to the north of the Preston–Bowyer Fault the deposits become more massive conglomerates.

Stratigraphy

A revised nomenclature for the Permo-Triassic deposits in south-west England has recently been introduced with the publication of the revised 1:50 000 scale Geological Sheet 325: Exeter (British Geological Survey, 1994). An examination of the earlier published map of 1912 indicates that the revised nomenclature approximately equates to that previously used as listed below.

New nomenclature	Old nomenclature
Mercia Mudstone Group	Upper Marls (Keuper)
Otter Sandstone Formation	Upper Sandstone
Budleigh Salterton Pebble Beds Formation	Pebble Beds
Aylesbeare Mudstone Group	Lower Marls
Exeter Group	Lower Sandstone Breccia and Conglomerate

Adjacent map sheets 326, 310 and 311 (Institute of Geological Sciences 1974, 1976 and 1974 respectively), all use the 'old' nomenclature, but no division between Permian and Triassic strata is defined, as is the case in the 'new' nomenclature, (the Exeter Group being Permian and the remainder Triassic). For the purpose of this section the nomenclature established for Geological Sheet 325 will be utilised over the whole of the region. It should however be recognised that as other areas are revised in the future, alternative local formational names may be established. The Permian Exeter Group in particular contains a wide range of local formational names which have been applied to various sandstone and breccia units which may be of limited lateral extent. In addition a number of formations (Alphington Breccia, Heavitree Breccia and Monkerton), formerly treated as members of the Teignmouth Breccia Formation (Laming, 1969; Davey, 1981), are now considered as formations within the Exeter Group and the term Teignmouth Breccia is no longer used. The term Clyst Sandstone was applied to Permian sandstones to the north of the Exe estuary which are now included as members of the Dawlish Sandstone Formation and the name is no longer used.

The Permo-Triassic stratigraphy of the region is presented in Table 7.9.1 and the distribution of the strata illustrated in Figure 7.9.1.

Exeter Group

The Exeter Group, which is of Permian age, crops out in a north–south-trending belt to the west of the outcrops of the Aylesbeare Mudstone and Sherwood Sandstone groups. Finger-like outcrops also extend westwards into a number of narrow, fault-bounded basins, such as the Crediton and Tiverton troughs. The group reaches a maximum of 1000 m in thickness in the eastern part of the Crediton Trough, but elsewhere is typically 200–400 m thick. The breccias and sandstones of this group were sourced from the basement rocks to the west and transported eastward, and thus become better sorted and finer grained in that direction. The breccias contain (in their various locally named units) fragments of locally derived slate, limestone, sandstone, igneous rocks (including quartz porphyry) and vein quartz. They probably represent alluvial fan deposits; those in the Tiverton and Crediton troughs may have accumulated at the foot of fault scarps bounding these basins. Sandstones, locally up to 200 m thick, occur at several levels in the Exeter Group, but are more common in the upper part (for example the Dawlish Sandstone Formation of the Exeter area). They include lenses of breccia and are mostly of fluvial origin, though aeolian dune sandstones also occur.

The breccias of the Exeter Group commonly range from fine to coarse grained and are usually made up of fining-upwards, planar-bedded sedimentation units overlying erosional bases. The coarser clasts near the bases of the unit commonly show imbrication. The matrix is of silty sand or sandy silt grade, composed of haematite-stained quartz grains and lithic fragments with silt and clay minerals and forms up to 30 per cent of the rock. Alternating coarse and fine breccias and sandstones in the basal part of the formation pass upwards into more uniform sediments of mean grain size. Some planar-bedded sandstones and mudstone lenses occur. Sandstone units 0.2 m to 2 m thick are commonly interbedded with breccia towards the top of the formation and show characteristics of both aeolian and fluvial deposition (Yeandle Whittaker Partnership, 1994).

The Dawlish Sandstone Formation, (also referred to as the Clyst Sandstone by some authors), overlies and interdigitates with the breccias and generally comprises poorly cemented fluvial and aeolian cross-bedded sandstones with breccia lenses. The sandstone is reasonably well defined in cliff section, with a 260 m thick zone of cross-bedded, fine to medium sandstone with occasional lenses of breccia (<5% of total) and local thin bands of marls and carbonaceous bands. These breccia lenses are best developed in

Table 7.9.1 Permo-Triassic stratigraphy in south-west England (after Warrington, 1980 and BGS, 1995)

Age	Group	Formation	Lithology	Thickness (m)	Aquifer unit
TRIASSIC	Mercia Mudstone		Mudstone, siltstone	360	Aquitard
	Sherwood Sandstone	Otter Sandstone	Sandstone	100–170	Aquifer
		Budleigh Salterton Pebble Beds	Sandstone, conglomerate	20–30	
	Aylesbeare Mudstone	Littleham Mudstone	Mudstone	70–530	Aquitard
		Exmouth Mudstone and Sandstone	Mudstone, Sandstone		
PERMIAN	Exeter	numerous local names, including the Dawlish (Clyst) and Knowle Sandstones, Cadbury, Bow and Crediton Breccias	Breccias, sandstones	up to 1000	Aquifer

the upper parts of the formation and are locally aggregated to form units up to 10 m thick. Typically the sandstones are 65 to 80 per cent quartz, up to 20 per cent orthoclase, up to 3 per cent plagioclase and around 10 per cent lithic fragments. To the east of Exeter the sediments are thinly bedded, moderately well-cemented, fine- to coarse-grained sandstones interbedded with common siltstones, clays and occasional fine breccias.

Aylesbeare Mudstone Group

The Aylesbeare Mudstone Group, formerly termed Lower Marls, is now thought to be mostly early Triassic in age, rather than late Permian. It is typically about 300 m thick, varying locally from 70 to 530 m. It is composed of reddish brown mudstones with intercalated beds of silty sandstone and sandy siltstone. Beds of red and green cross-bedded sandstone are common locally in the lower part of the Group.

Sherwood Sandstone Group

The main outcrops of the Sherwood Sandstone Group are centred on the Otter Valley in the south and in the Tone catchment area in the north of the region. The Sherwood Sandstone Group lies conformably on the Aylesbeare Mudstone Group. It is typically about 150 m thick in the region, locally thickening to about 200 m. It consists of two formations, separated by a minor but widespread unconformity. The lower formation, the Budleigh Salterton Pebble Beds, is typically 20 to 30 m thick. It consists dominantly of brown sandy conglomerates containing rounded metaquartzite clasts of pebble, cobble and boulder size. Beds of cross-stratified sandstone occur throughout. Lenses of pebble free silt occur towards the top of the sequence. There is a decrease in sediment size towards Wellington and Uffculme, away from the sediment source in the west. The formation was probably deposited in a high-energy, braided river system flowing generally towards the north. To the north of Uffculme, pebbles of the liver coloured quartzite disappear from the Budleigh Salterton Pebble Beds Formation, their place being taken by cobbles and pebbles of locally derived limestone and grit with red or red-brown coarse sand. With the appearance of more calcareous material, an important change in aquifer potential of the formation occurs. South of Uffculme the pebble beds are unconsolidated and uncemented. Between Uffculme and Wellington the dominant cement is iron oxide. North of Uffculme the beds become progressively more cemented with strongly calcareous cement appearing in the Wellington area. The degree of cementation continues to increaseto the north, the pebble bed becoming a massive and very tough conglomerate in the Halse aquifer block in Somerset. The conglomerate shows a general increase in size of the fragments, especially in the lower beds, and a large increase in the number of limestone and grit pebbles often of considerable size. Breccio-conglomerates, interbedded sandstones and pebbly sandstones occur locally within the Taunton area. They are usually soft, weathered and gravelly but strong calcareous and ferruginous cementation occurs in places.

The overlying Otter Sandstone Formation is typically about 120 m thick (up to 170 m on the southern coastal outcrop) but thins to as little as 30 m northwards. It consists of reddish brown, cross-bedded quartz rich sandstone with beds of calcite-cemented conglomerate and scattered mudstone lenses. Like the underlying pebble beds, it is thought to have been deposited in a fluvial environment, with braided river channels gradually giving way to a meandering channel complex as deposition of the formation progressed.

Horizons of tough, iron-cemented sandstone occur to the south of Wellington which give way to a calcareous-cemented sandstone north of Wellington (King, 1972). This in turn becomes a very resistant calcareous sandstone northwards towards Bishop's Lydeard. The transformation to a hard sandstone allows slightly more frequent and open jointing to occur.

In the Taunton area the Otter Sandstone Formation is 30 to 60 m thick, composed of red, yellow and buff mottled, fine- to medium-grained sandstones. They vary from calcareous to soft and friable. Deposition from the south and west is suggested by scattered current bedding. Towards the base of the formation the sandstone is more pebbly, and sandy conglomerates and breccias are common. The top of the formation is at the junction with the sandstones and mudstones of the Mercia Mudstone Group. Calcite cements are locally present within the sandstone, giving rise to variation in strength from hard and calcareous to soft and friable. It is probable that most of the calcite cement was chemically derived from the waters of deposition, and zones of iron oxide within the calcite indicate several phases of cement precipitation.

Mercia Mudstone Group

The Mercia Mudstone Group is around 360 m thick, and consists mainly of red silty mudstone with subordinate beds of sandstone, gypsum and halite. It overlies the Sherwood Sandstone Group and confines it to the east in the Wessex basin.

General hydrogeology

The Exeter Group

The Permian strata act as local minor aquifers, and their aquifer properties greatly depend on the local lithology intersected by boreholes and the presence of fractures. Within the Permian strata sandstones, breccias and mudstones are interleaved resulting in very variable aquifer properties regionally. However the aquifer properties of each lithology are more constrained: higher permeability is found in sandstones than breccias, which in turn are more permeable than mudstones.

There is some faulting, which in places offsets the aquifer layers and complicates the response of the aquifers to pumping. Faults within the Crediton Breccia Formation often give rise to spring lines. The combination of complex interbedded lithology, facies changes, and disturbance by faulting, means that the strata penetrated by any one borehole can be very varied and differ markedly between adjacent boreholes.

Generally the Permian sediments are less well developed as aquifers than the Triassic Sherwood Sandstone Group. Although there are many boreholes providing limited amounts of water (typical borehole yields are shown in Table 7.9.2) there are few large public water supplies and few pumping test data. Such data as do exist are specific to the lithology of the borehole in question and cannot be extrapolated to the neighbouring areas with different sediments. There are no packer test data and little information from logging.

The sandstone horizons are interlayered with frequent silt and clay layers which reduce the overall permeability of the aquifers. The depth of the aquifer is the main control on the transmissivity, with aquifers thickening down dip. The depth of boreholes is generally a good guide to the effective aquifer thickness.

Breccias occurring stratigraphically above and below the Dawlish sandstones act as semi-permeable boundaries.

Table 7.9.2 Typical borehole yields in the Permian sandstones and breccias, south-west England.

Regional location	Formation	Typical well yield (l/s)
South Devon	Dawlish Sandstone	3–5
	Exmouth Sandstone and Mudstone	<5
Central Devon	Permian Breccias	<5
	Dawlish (Clyst) Sandstone	3–5
West Somerset	Exeter Group sandstones and breccias	0.5–5

The breccias at outcrop appear to have very low primary porosity, but secondary fracturing and sandstone bands contribute some permeability. Breccia layers within the sands divide the aquifer into a number of partly confined units. The position and extent of these intermediate layers is critical in determining the aquifer response and aquifer properties in any particular locality. Boreholes may show a confined, unconfined or semi-confined response to pumping, depending on the degree of penetration of these layers

In south Devon, near Dawlish, about 60 m of Dawlish Sandstone Formation are intercalated with Permian breccias that produce small yields of 3 to 5 l/sec. The Dawlish Sandstone Formation, within which both intergranular and fracture flow are important, is partly confined by the Aylesbeare Mudstone Group.

The Dawlish Sandstone Formation forms the main aquifer east of the Crediton Trough. There is thought to be contact between the aquifer and the River Exe, though this has not been tested. Boreholes in the Dawlish Sandstone Formation generally show a confined response, due to the frequent presence of mudstone bands. Comparison of field and laboratory data suggests that up to 40% of the transmissivity of the sandstone can be attributed to intergranular permeability, compared with less than 20% in the Bow Breccia Formation.

In the north-west of the region the Exeter Group sandstones are used for river augmentation to the Tone catchment (Wessex Water Authority, 1976). This aquifer outcrops to the west of Taunton in a narrow area running north–south with an area of about 21 km^2 and dips gently eastward under the Aylesbeare Mudstone Group and the Sherwood Sandstone Group. There are two sets of normal faults dissecting and offsetting the aquifer outcrop. It is estimated that resources of about 17 500 m^3/d are available from the aquifers in the Tone catchment, most of which currently supports environmental flows.

In the Tiverton and Crediton troughs, groundwater movement within the aquifers is mainly by fracture flow, although fractures may dewater on pumping. Boreholes generally perform better after development by pumping. It is estimated that 2% of the flow is intergranular and that the total porosity is approximately 6%, though this is higher in some localities. Aquifer thickness will effectively correspond to borehole depth, due to the interlayered nature of the sediments and low intergranular permeability which is likely to inhibit vertical flow from beneath the borehole. In general yields from the Permian breccias of this area increase with borehole depth.

The Knowle Sandstone Formation is located in the Crediton Trough where it is considered locally to be the major aquifer. The overlying Crediton conglomerates and the underlying Bow conglomerates are less productive and more indurated in nature, with a lower storage coefficient. The total outcrop of the Knowle Sandstone Formation is believed to be about 9 km^2 but the catchment of the main Knowle borehole [SS 777 014] is thought to be only 1.24 km^2, as it is limited by volcanic strata and faulting. The borehole penetrates 98 m of sandstone with 12 m of deeper conglomerates. Streams down stream from the borehole are effected by the pumping (Streetly, 1987). Borehole yields and specific capacities in this area depend mainly on the intersection of fractures and, to some extent, the presence of sandy permeable horizons.

Aylesbeare Mudstone Group

The Aylesbeare Mudstone Group constitutes an aquitard overlying and confining the Dawlish Sandstone Formation and corresponds to the Permian marls separating the Triassic and Permian sandstones which are found elsewhere in Britain. It has a mainly mud and silt lithology and is relatively impermeable, functioning as an aquitard, though locally small amounts of water may be obtained from it. This includes the Exmouth Mudstone and Sandstone aquifer that locally produces yields of the order of 5 l/sec. The group confines the Exeter Group sandstones and breccias and underlies the Budleigh Salterton Pebble Beds Formation, thereby separating the two main aquifers of the area. The sandstones of the Aylesbeare Mudstone Group do however supply some groundwater. The Exmouth Mudstone and Sandstone Formation is 225 m thick and comprises 60% sandstone within which fracture flow predominates.

The Sherwood Sandstone Group

Most development of groundwater is in the Triassic aquifers to the east of the region which outcrop along the western margin of the Wessex Basin. Here the Sherwood Sandstone is represented by the Otter Sandstone and Budleigh Salterton Pebble Beds formations in the Otter Valley and the Tone Catchment where together they form a major aquifer. The Triassic pebble beds and sandstones of the Otter Valley represent the most utilised groundwater resource of the region, especially in the south between Ottery St Mary and Budleigh Salterton. Abstraction from the Triassic sandstone of south-east Devon is around 25 000 m^3/d, estimated to be about half the recharge resources in the Otter Valley outcrop, excluding the effects of river recharge (Tubb, C, personal communication).

The Mercia Mudstone Group is used locally for very limited water supplies but is an effective aquitard above the Sherwood Sandstone Group. Beneath the Sherwood Sandstone Group the Aylesbeare Mudstone Group (Littleham Mudstone and Exmouth Mudstone and Sandstone formations) acts as a basal aquitard, though again local sandy horizons may supply limited quantities of water. The eastern limit of the Sherwood Sandstone aquifer is approximately 5 km east down dip beneath the overlying Mercia Mudstone Group, delimited by high total dissolved solids which render the water non-potable. The southern extent of the effective aquifer is defined by a saline water interface under the coast. This area has been the subject of borehole investigations and modelling (Water Management Consultants, 1993). Geophysical logging and water sample conductivities indicate a decrease in conductivity with depth, suggesting that limited saline contamination is occurring from the surface rather than from deep beneath the coast.

In the west of the Otter Valley area, the sandstones and the pebble beds can be taken as one aquifer and share a common water table. Towards the east, a less permeable iron pan reduces vertical movement between the aquifers (Sherrell, 1970). In many places a mud-ironstone layer up to 5 m thick occurs at the Otter Sandstone–Budleigh Salterton Pebble Bed boundary with secondary iron precipitates present where the mud layer is absent. The aquifer has some carbonate cement which increases north of the main Otter Valley (north of Wellington), resulting in a reduction in permeability and porosity.

In the Otter Valley the River Otter is in partial hydraulic continuity with the aquifer and there appears to be local flow from the river to certain boreholes (located close to the river). Quantification of river–aquifer interaction is difficult. Boreholes near the River Otter have higher specific capacity values, because of induced river recharge on pumping. Attempts to determine the river contribution to pumped waters indicated about one third to one half river water contribution, possibly greater at some sites. Water temperatures in some boreholes near to the river show similar changes to that in the river; the river temperature data shows more scatter than the borehole temperatures which seems to be a smoothed and delayed replica of the river temperature. This appears to reflect local river-aquifer contact. One tracer test near the River Otter indicated connection of the river with the borehole. Studies also suggested that the radius of influence of a typical major production borehole is up to 1200 m.

The Otter Valley has been highly developed for public water supply and there are many boreholes penetrating both the Otter Sandstone and the Budleigh Salterton Pebble Beds formations. Typical borehole depths in the Otter Valley are 50–140 m deep, with the deeper holes in the east. The effective aquifer thickness is thought to be all the Sherwood Sandstone Group, even if only the top part is penetrated. If a borehole only penetrates the Otter Sandstone Formation all the aquifer, including the Budleigh Salterton Pebble Beds Formation, eventually contributes to the yield, as water leaks up from beneath the base of the borehole.

Groundwater flow comprises both matrix and fracture flow, with fractures important in increasing the overall bulk permeability encountered by the borehole. Fractures are often sub vertical and so are rarely seen in drilling, although one sub-vertical fracture was intersected in a Harpford pilot borehole [SY 091 908] (Tubb, C, personal communication). Logs in the Otter Sandstone Formation near the coast indicate the presence of fractures which yield water (Water Management Consultants, 1993a). No packer test data are available.

Boreholes deep in the Otter Sandstone Formation penetrating the Budleigh Salterton Pebble Beds Formation have higher water levels (about 2 to 3 m AOD) compared to water levels in shallower boreholes in the sandstone (which are commonly just below OD). This indicates that there is an upward vertical hydraulic gradient within the Triassic strata. There is however no consistent pattern of up-flow from the Budleigh Salterton Pebble Beds Formation to the Otter Sandstone Formation. Vertical permeability is locally very variable and there are locally marl bands and occasional dolomite horizons. Frequently a band of running sands is found just above the pebble beds. In the upper levels of the Otter Sandstone sequence, east of Ottery St Mary, there are perched water levels, some due to marl bands.

North of Ottery St Mary the Otter Sandstone and the Budleigh Salterton Pebble Beds formations form a local water resource where they outcrop, but do not constitute such a good aquifer as in the Otter Valley. The pebble beds and the Otter Sandstone Formation are in hydraulic continuity forming an aquifer up to 150 m thick. Borehole yields in the unconfined aquifer vary greatly reflecting the local degree of cementation and interception of fractures.

North of the Otter Valley, in the west of Somerset, the aquifer is divided into compartments, (Wellington, Halse, and Bishop Lydeard), providing less potential for development. Here where there is little water development and few data, the aquifers are fragmented by faults, which act as low permeability boundaries and reduce well yields (compared with those in the main aquifer of the Otter Valley). The faults act as semi-permeable barriers by juxtaposing less permeable beds against permeable horizons, and are in some cases cemented. Faulting has altered the dip of the strata, rotating the aquifer blocks, so that the aquifer dip changes across faults. Yields from boreholes decrease in this northern area to less than 600 m^3/d. However clear boundary effects are not usually seen in pumping tests in the Otter Sandstone Formation. One exception is at Kersbrook where a fault with a significant displacement, (proved by drilling either side of the fault), was within a few tens of metres of the pumped source, and proved to be a significant hydraulic boundary (Tubb, C, personal communication).

Borehole problems

Sand ingress and borehole clogging are problems in the Otter Valley the origins of which are thought to lie in varying water chemistry. Waters in the Otter Sandstone Formation and the Budleigh Salterton Pebble Beds formations have a very different chemistry: the sandstones have a hard, highly mineralised carbonate rich water, whilst the pebble beds have a soft reducing acidic water. This becomes a problem in 'down dip' areas along the line of the Otter Valley where the water in the pebble beds is artesian, and where local faulting provides a higher permeability path, allowing more rapid upward leakage into the overlying sandstones. In the Otter Valley all boreholes with very high iron in the water occur near the central line fault. Oxygenation of water close to the borehole causes the soluble iron and magnesium to precipitate, which, combined with bacteria associated with these ions causes borehole clogging. Boreholes penetrating both aquifers also experience clogging problems. In addition running sands near the junction of the two aquifers can be a problem; these may have been caused by the dissolution of the carbonate cement in the zone of water mixing. Chemical problems can be avoided by casing-out the junction of the pebble beds and the Otter Sandstone where the Pebble Beds are anoxic, as this area is the likely source of iron where the pebble beds are anoxic (Walton, 1982). Drilling only partially penetrating boreholes which do not penetrate the iron pan at distances greater than 2 km from the outcrop reduces the amount of chemical mixing.

Aquifer thickness

Throughout the Permian strata the effective aquifer thickness equates to the borehole depth, and this is also considered to hold true for most of the Triassic sandstone aquifers. In the Otter Valley however the whole of the aquifer responds slowly over a long time: vertical leakage is a significant process. This means that over a number of years water is taken from the whole aquifer (the Otter Sandstone and the Budleigh Salterton Pebble Beds formations) even if the borehole only penetrates the Otter Sandstone Formation. This is different from much of the other Permo-Triassic sandstone aquifers in England and Wales where generally the effective aquifer thickness equals only the borehole depth.

Previous hydrogeological investigations

There have been a considerable number of studies of the hydrogeology of the Permo-Triassic aquifer in the south-west. Jones (1967) carried out a general hydrogeological survey of the Triassic sandstones whilst Walton (1978 and 1982) investigated the hydrogeochemistry. A hydrogeological map of the Permo-Triassic aquifers of south-west England is also available (Institute of Geological Sciences and South West Water Authority, 1982).

In general, most work has been carried out in the Otter Valley on the Otter Sandstone Formation which is the most productive aquifer. Substantial work has been carried out along the coast by Water Management Consultants (1993), and earlier work was carried out by the Water Authority in the centre of the valley. The Triassic aquifer in the Otter Valley has been modelled by MRM Partnership (1989). Other workers in the area include Henson (1970) and Sherrel (1970, 1973) and a number of groundwater consultants (Leonard Threadgold, 1990; Water Management Consultants (1993b); Yeandle Whittaker Partnership (1994). Student projects have investigated hydrogeology (Hayter, 1974), the chemistry (Pannet, 1987) and the geophysics (Bugg, 1976) of the Triassic sandstones.

In contrast there has been little work in the Tone catchment to the north of the Otter Valley and, apart from two MSc projects (King, 1972 and Grey, 1977), the Tone groundwater study (Wessex Water Authority, 1976) provides most of the information about this area.

Limited localised investigations into the Permian deposits have indicated their varied nature (Davy, 1981) but the complex nature of the Permian deposits means that localised knowledge is not easily transferred to other areas. There are no packer test data and little logging information. Flow logging data in particular is generally absent.

7.9.2 Hydraulic conductivity and transmissivity

Core data

Permo-Triassic data

Laboratory permeability measurements (total of 292 samples) have been made on the Sherwood Sandstone Group of the Otter Valley, the Dawlish Sandstone Formation and other Permian sandstones. The Permian samples are very biased towards the consolidated Permian sandstones, as analysis of breccias (with a large clast size) in the laboratory is not possible, and unconsolidated sediments cannot readily be analysed. Laboratory permeability results are very variable, with values ranging over seven orders of magnitude, from 1.9×10^{-6} to 5.8 m/d (water) hydraulic conductivity (Table 7.9.3, Figure 7.9.3a). The Triassic sandstones generally show a greater permeability variation than the Permian sandstones. Permeabilities in the Permian sandstones are generally higher than those in the Sherwood Sandstone Group. This is due to the values obtained from some clean, aeolian Permian sandstones, which are less well cemented than the Triassic Otter Sandstone Formation. Generally the horizontal core permeability is greater than the vertical permeability (Figure 7.9.3d) (Table 7.9.3). In both aquifers K_h/ K_v is usually less than ten. However between core samples within the same borehole there is a large variation in both vertical and horizontal permeability. This causes very significant anisotropy on a scale of centimetres to metres, and is seen as interlayering in boreholes. Over the length of a borehole sedimentary interlayers cause significant anisotropy on a scale of many metres. The combination of anisotropy on a number of scales means that the aquifers as a whole are highly anisotropic.

Sherwood Sandstone Group data

A total of 228 core samples (BGS data) of the Sherwood Sandstone Group predominantly from the Otter Valley area and mainly of plugs taken from outcrop samples, have a fairly uniform scatter of hydraulic conductivities, ranging between 10^{-6} to 6 m/d (Figure 7.9.3b, Table 7.9.3). The data do not appear to conform to a normal distribution, and the distribution is truncated at the lower end by the measurement limits of the experimental equipment. The median measured hydraulic conductivities is 0.024 m/d, with an interquartile range of 3.9×10^{-4} to 0.31 (Table 7.9.3). The distribution of hydraulic conductivities from horizontal and vertical samples is shown in Figure 7.9.3e, with statistics given in Table 7.9.4. The data suggest that horizontal hydraulic conductivities tend to be larger than vertical values, with a general K_h/K_v ratio of around 3:1. Otter Valley laboratory core hydraulic conductivities appear to be generally lower than the field bulk hydraulic conductivity values calculated from pumping test data, though there is some overlap of values. Intergranular permeabilities average 1 to 3 m/d in the south but are generally one to two orders of magnitude lower in the north, due in part to the increased cementation of the aquifer there. It has been shown (Lovelock, 1977; Sherrel, 1970) that the Budleigh Salterton Pebble Beds Formation has a much greater permeability than the Otter Sandstone Formation.

The wide variation in permeability (and porosity) may be a result of variable cementation of the sandstone in the Otter Valley. In the Otter Valley, permeability does not

Table 7.9.3 Permo-Triassic sandstone core hydraulic conductivity data for south-west England.

Group or Formation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Permo-Triassic sandstones (all data)	1.9×10^{-6}–5.8	5.9×10^{-4}–0.66	0.034	0.017
Sherwood Sandstone Group	2.1×10^{-6}–5.8	3.9×10^{-4}–0.31	0.024	0.011
Permian sandstones	4.77×10^{-5}–4.3	0.028–2.1	0.35	0.14

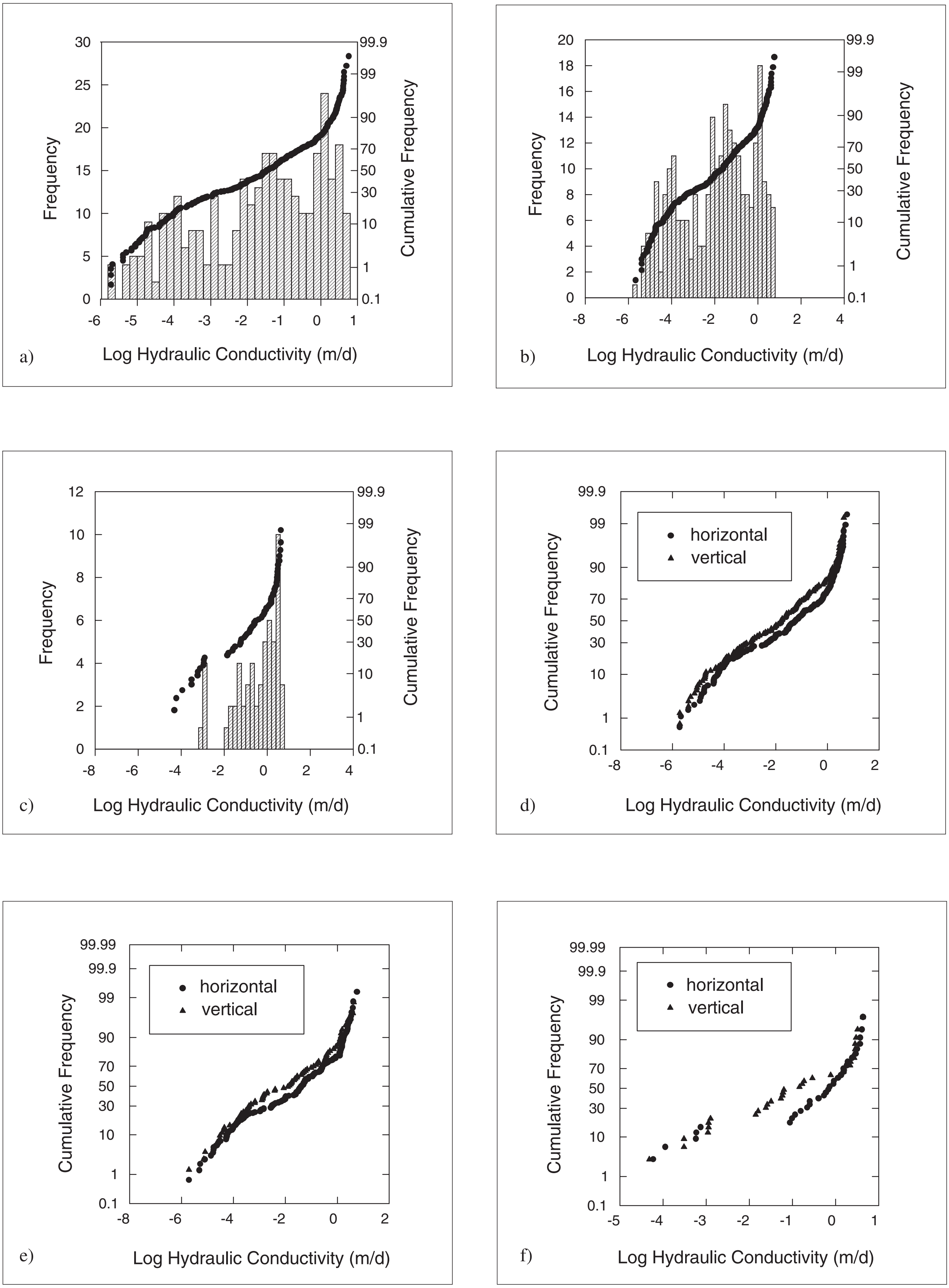


Figure 7.9.3 Distribution of hydraulic conductivity data for Permo-Triassic sandstone samples from south-west England, a) all data, b) Sherwood Sandstone Group data, c) Clyst Sandstone data, d) horizontal and vertical samples — all data, e) horizontal and vertical samples — Sherwood Sandstone Group, f) horizontal and vertical samples — Clyst Sandstone.

appear to vary systematically with depth. The idea that increased weathering at the surface would increase the permeability of the aquifer near the surface is not substantiated by the data available. Weathering appears to have occurred over the whole of the effective aquifer down to over 100 m deep in the zone of freshwater movement: permeability and porosity are greater here than deep in the Wessex Basin where water circulation is less (Allen and Holloway, 1984).

Permian sandstone data

The distribution of hydraulic conductivity data for the Permian sandstones is shown in Figure 7.9.3c. Statistics are presented in Table 7.9.3. The data vary over five orders of magnitude with a median value of 0.4 m/d and have a negative skew. Horizontal values tend to be higher than vertical values (Figure 7.9.3f, Table 7.9.4) with a K_h/K_v of 3 (geometric mean values) or 7 (median values).

Given the significant dependence of permeability on lithology in the area, ranges of transmissivity can be broadly estimated on the basis of lithology penetrated by a borehole. These are shown below (Table 7.9.5).

Empirical estimates of the intergranular hydraulic conductivity of the Dawlish Sandstone Formation from the general particle distribution of exposed surface samples (Table 7.9.6) were made by Davy (1981).

These particle size permeabilities may be used to estimate the transmissivity of a well, but tend to provide lower results than the basic lithology method (Table 7.9.5) (Davy, 1981).

Davy took the approach further at a specific site in the Dawlish Sandstone Formation (Starved Oak Cross [SX 913 988]) where he allocated values of hydraulic conductivity to specific lithologies (Table 7.9.7).

Pumping test transmissivity and hydraulic conductivity

Lithological control on aquifer properties

At the scale sampled by pumping tests the aquifer properties of the Permo-Triassic sandstones are largely determined by lithology. Thus a high marl content gives rise to a low transmissivity of usually less than 100 m^2/d, sand and pebble strata have a medium to very high transmissivity of up to around 1000 m^2/d and the highest values are found where fractures and a relatively uncemented clean sandstone matrix are present. However these generalities do not always hold and fractures account for the very large values of transmissivity obtained from some boreholes (Davy, 1981).

The hydraulic conductivity of the aquifer, as a whole, is the summation of the hydraulic conductivity of the different layers and is affected by the highly interlayered nature of the Permian and Triassic deposits. The overall horizontal hydraulic conductivity of the aquifers is dominated by the high permeability of the sandy layers (the extent and persistence of which is not clearly known, though they are likely to be locally significant in transporting water to a borehole). On the other hand the effective vertical permeability of a series of lithologies, (as is found in most of the boreholes in this area), is biased towards the low permeability members of the sequence (as calculated

Table 7.9.4 Horizontal and vertical core hydraulic conductivity data for the Permo-Triassic sandstones of south-west England.

Group or Formation	Orientation	Range (m/d)	Interquartile range (m/d)	Median (m/d)	Geometric mean (m/d)
Permo-Triassic sandstones (all data)	Horizontal	1.9×10^{-6}–5.8	1.3×10^{-4}–0.4	0.01	7.1×10^{-3}
	Vertical	1.9×10^{-6}–4.3	9.8×10^{-5}–0.1	5.9×10^{-3}	3.5×10^{-3}
Sherwood Sandstone Group	Horizontal	1.9×10^{-6}–1.19	1.3×10^{-4}–0.27	8.9×10^{-3}	5.6×10^{-3}
	Vertical	1.9×10^{-6}–4.3	7.5×10^{-5}–0.69	2.4×10^{-3}	2.2×10^{-3}
Permian sandstones	Horizontal	5.9×10^{-5}–4.3	0.12–1.9	0.71	0.24
	Vertical	4.8×10^{-5}–4.3	0.01–2.2	0.1	0.08

Table 7.9.5 Lithological control on Permian breccia aquifer properties, south-west England (after Davy, 1981).

Transmissivity	Lithology
0–10 m^2/d	Tight breccias in which the well penetrates few major fracture zones. Strata adjacent to the Culm Measures, either at outcrop or subcrop. Probably the Culm Measures themselves.
10–50 m^2/d	Breccias with some sandy horizons or considerable fracture zones penetrated.
50–100 m^2/d	Breccias with appreciable thicknesses of sandstone units, the better-cemented sandstones.
100–300 m^2/d	Less well-cemented sandstones where both intergranular and fracture flow are of importance. May be some induced recharge via leakage.
10–100 m^2/d	Breccia and sand with fractures.
>100 m^2/d	Sandstone, intergranular and fracture flow.
> 300 m^2/d	These values are only likely to be attained where recharge is induced e.g. from a river.

Table 7.9.6 Dependence of hydraulic conductivity on sandstone grain size in the Dawlish Sandstone Formation (after Davy, 1981).

Particle size	K (m/day)
Coarse–very coarse	0.38
Medium–coarse	0.3
Medium	0.16
Fine–medium	0.01
Fine	0.009
Fine with silt	0.0008

Table 7.9.7 Permeability dependence on lithology at Starved Cross Oak (after Davy, 1981).

Lithology	K (estimated) (m/d)
Sandstone, medium–coarse grained, mod. well cemented	1.3
Sandstone, med. grained, mod. well cemented	0.8
Sandstone, fine–med. grained, mod. well cemented	0.01
Sandstone, fine grained, silty, well cemented	0.0003
Siltstone well cemented	0.00005

by a harmonic mean of the individual vertical hydraulic conductivities for different layers). The available core data are from relatively high permeability sandstones and so do not represent the overall vertical permeability of the aquifers, which will be much lower, nearer the permeability of the interlayered silts.

The layered anisotropy of the aquifers affects their response to pumping. An initial confined response is seen, followed by a period of little increase in drawdown. Vertical head gradients set up between the pumping depth and the water table across the interlayered strata result in a slow drainage from the water table. This eventually leads to a water table, unconfined response, and an increase in drawdown rate. A type curve solution involving Boulton type curves with a spacing of between 1 and 2 cycles often fits pumping test data (Tubb, personal communication) (Section 7.1.4).

Such delayed yield effects are common in longer pumping tests, as the interlayering decreases vertical permeability and reduces vertical flows. Vertical head gradients are set up between layers and maintained by the low permeability silt and mud interlayers. The anisotropy of the aquifer means that the groundwater system can take a long time to reach equilibrium after a change in the pumping regime.

Another result of the permeability anisotropy caused by interbedding is the significant increase in head with depth observed in discharge areas. The level of water struck when drilling may rise as drilling progresses beneath the water table. The maintenance of such vertical head gradients within aquifers is an indication of the low vertical permeability of the aquifer.

The general effects of lithology on aquifer properties for the various Permo-Triassic aquifers of the region are summarised in Table 7.9.8.

Stratigraphic and regional variations in transmissivity

There is a wide range of transmissivity values and other Permo-Triassic aquifer properties in this region (Figure 7.9.4). Histograms of pumping test transmissivity values indicate that there are many boreholes with relatively low transmissivities, less than 200 m^2/d, and a few boreholes with higher values, with maxima over 1000 m^2/d (Figure 7.9.5, Table 7.9.9). The transmissivity distribution for the southwest region has an approximately log-normal distribution, with a geometric mean of 95 m^2/d, and an interquartile range of 30 to 300 m^2/d.

Calculation of the effective bulk hydraulic conductivity of a borehole from the transmissivity and the effective

Table 7.9.8 Lithological dependence of aquifer properties in the Permo-Triassic aquifers of south-west England (Tubb, C, personal communication).

Formation	Lithological character	Likely aquifer property
Permian Exeter Group		
Crediton Trough Breccias (excluding Knowle Sandstone	Pores indurated with finer-grained material, but some fracture permeability and storage	Low/very low bulk matrix K, higher pumping test K dependant on fractures; late pumping test S low (10^{-3} common).
Dawlish Sandstone Formation	Mainly clean, aeolian sandstone with some intermittent breccia horizons	High bulk matrix K, pumping tests, initial confined storage S, late time higher Sy.
Dawlish Sandstone Formation (east of Exeter)	Mainly clean aeolian sands	High bulk matrix K, pumping test, late time Sy obtained.
Triassic Sherwood Sandstone Group		
Budleigh Salterton Pebble Beds Formation	Poorly cemented cobbles with variable matrix fill and some mudstone/sand lenses	Locally high bulk matrix K, pumping test, late time Sy obtained in west, becomes confined (Ss) eastward under the Otter Sandstone Formation.
Otter Sandstone Formation (South: Otter Valley)	Cyclically bedded sandstone with some finer sand layer with laminar bedded mica	Bulk aquifer K_h in 'normal range', lower overall K_v, initial confined pumping test storage Ss, higher late time S.
Otter Sandstone Formation (North: Somerset outcrop)	Sandstone heavily indurated aquifer properties reliant on fractures	Very low bulk matrix K, low/variable pumping test K, low pumping test storage.

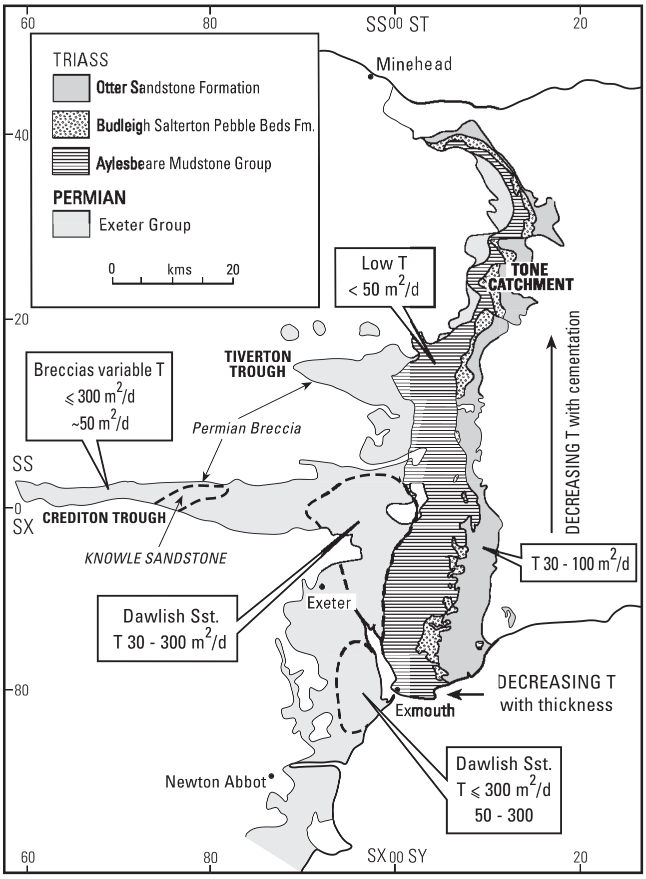


Figure 7.9.4 Regional transmissivity variations in the Permo-Triassic sandstones of south-west England.

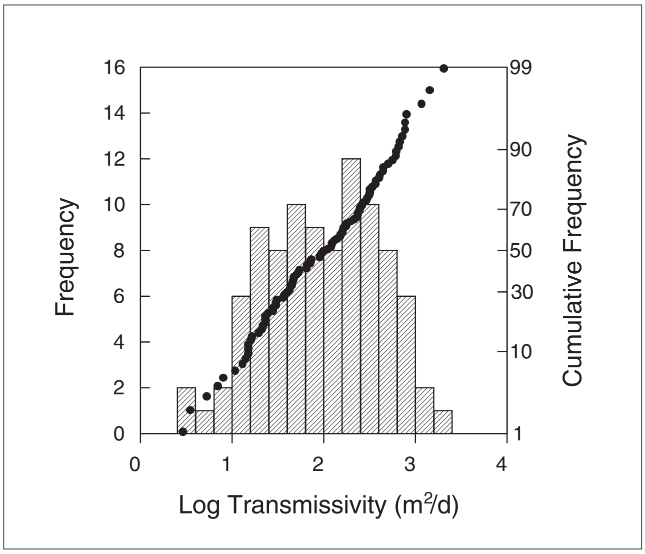


Figure 7.9.5 Distribution of transmissivity data from pumping tests in the Permo-Triassic sandstones of south-west England.

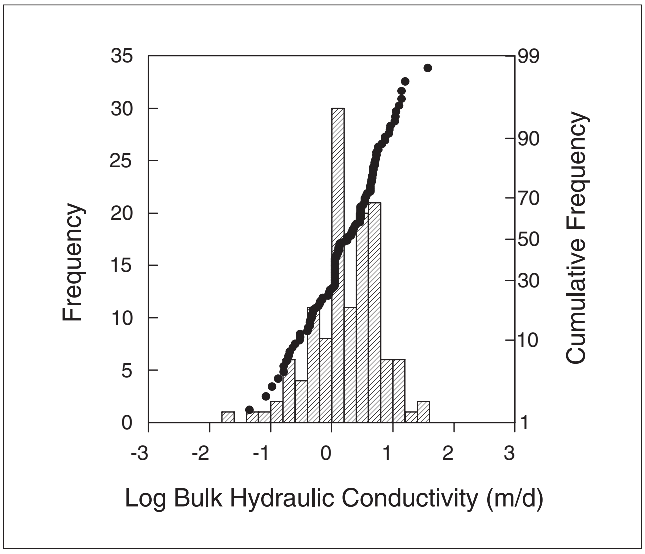


Figure 7.9.6 Distribution of bulk hydraulic conductivity data from pumping tests in the Permo-Triassic sandstones of south-west England.

aquifer thickness gives a similar distribution as transmissivity, with values averaging 2 m/d (Figure 7.9.6).

EXETER GROUP

The Permian sandstones underlying the Aylesbeare Mudstone Group have transmissivities generally in the range tens to 300 m^2/d, often around 100 m^2/d. This reflects the local extent of the sandstones and the interlayering of less permeable horizons within the sandstones.

Pumping tests give a range in transmissivity of 65 to 300 m^2/d for the Dawlish Sandstone Formation. This corresponds to a range in specific capacity of 61 to 342 m^3/d/m, but the exact relation of the two has not been fully investigated or verified. In such a layered aquifer as the Dawlish Sandstone Formation the significance of observation borehole data depends on the depth of penetration relative to that of the pumping borehole. Shallow observation boreholes may only indicate the water table response to pumping, but not the aquifer response at depth where heads may be higher, due to the anisotropic interlayered nature of the aquifer.

Exploratory borehole No 2 [SX 9128 9880] penetrates only the Dawlish Sandstone Formation, passing through

Table 7.9.9 Summary of aquifer properties data for the Permo-Triassic aquifers in south-west England from pumping tests.

Permo-Triassic sandstones (all data)	Range	Interquartile range	Median	Geometric mean
Transmissivity (m^2/d)	2.9–2033	30–303	105	95
Bulk hydraulic conductivity (m/d)	0.023–38	0.92–4.3	1.9	1.7
Storage coefficient	1.3×10^{-4}–0.15	2.6×10^{-4}–0.004	9×10^{-4}	0.0013
Specific capacity (m^3/d/m)	1–1713	51–126	101	79

layered sandstones, mudstones and occasional breccias. Extensive pumping tests were carried out with many observation boreholes. These indicated a mean transmissivity of 74 m^2/d for the pumped well, with 62 m^2/d for the deep observation well, and 42–140 m^2/d for various shallow observation boreholes. The lower values from the observation boreholes are possibly due to their penetrating only part of the aquifer and the aquifer responding as a series of layers. Distance drawdown analysis using observation borehole data also indicated a lower value of about 40 m^2/d. The observation boreholes along strike show similar transmissivity values to the average whereas those on a line of dip have a 10% decrease in transmissivity. This variation in transmissivity between different observation wells is interesting as it demonstrates the variable heterogenous nature of the sediments (Davy, 1981).

By allocating appropriate values of hydraulic conductivity to the various lithologies encountered by the borehole (Table 7.9.7) the intergranular transmissivity of the aquifer penetrated by the borehole can be estimated. This suggested that 26 m^2/d is accounted for in the intergranular permeability, indicating that most of the transmissivity is from fractures (Davy, 1981).

The Permian breccias have very variable transmissivities, generally less than 300 m^2/d and often of the order of 50 m^2/d, depending on borehole fracture intersection. At Colebrooke [SS 7570 0160], the mean intergranular hydraulic conductivity was 8×10^{-4} m/d compared to a field hydraulic conductivity of around 0.3 m/d, again indicating predominantly fracture flow. Fractures were also indicated at Burrow Farm production borehole [SX 941 995], where a step-test was carried out, during which water levels fell unexpectedly within constant rate steps. Water levels began to stabilise over a few hundred minutes before dropping again suddenly, probably due to the dewatering of discrete sets of fractures. The ratio of intergranular to fracture flow is very variable. There is a high component of fracture flow in all areas but this varies from around 30% to the total yield at a well.

The Aylesbeare Mudstone Group

The Aylesbeare Mudstone Group has low transmissivity values, generally less than 50 m^2/d, though some values are higher in the north of the area.

Sherwood Sandstone Group

The Otter Sandstone aquifer has a generally high transmissivity with values of the order of hundreds of square metres per day, ranging from tens to over 1000 m^2/d. A decrease in transmissivity of the Sherwood Sandstone Group is seen in the north of the Otter Valley.

Pumping test transmissivities are variable across the Otter Valley. At individual sites the transmissivity variation can broadly be explained in terms of aquifer thickness and borehole penetration. The transmissivity generally increases to the east and south as the aquifer thickens, and is generally greater for deeper boreholes. Boreholes penetrating beneath the Otter Sandstone Formation have enhanced transmissivities as the underlying Budleigh Salterton Pebble Beds Formation has a high permeability. These factors combined with the precise lithology of material penetrated by the borehole can be used to explain the aquifer response characteristics of most boreholes.

An increase in drawdown is seen towards the end of longer tests, and there is an apparent decrease in transmissivity with time. The increase in drawdown suggests an initially confined response turning into an unconfined response or possibly the effect of boundaries and non-interconnected fractures becoming apparent (Section 7.1.4). The apparent decrease in transmissivity indicates local high permeability with less connection of fractures throughout the whole aquifer. There is significant local lithological variation and interlayering which results in a high variability of borehole responses.

Investigations of boreholes near the coast around Otterton indicated that the transmissivity was in the region of 400 m^2/d, with test results ranging from 150 m^2/d to over 1000 m^2/d. Recovery tests usually had extremely high transmissivities of thousands of metres squared per day (which were not consistent with the pumping test results) and lower values of storage coefficient. The aquifer thickness decreases to the north and to the western feather edge, and pumping test transmissivities correspondingly decrease from around 560 m^2/d in the south to 6 m^2/d in the north whilst bulk borehole hydraulic conductivities, remain approximately constant (K_h 5 to 10 m/d BGS database).

Comparing the bulk borehole hydraulic conductivities, of 5 to 10 m/d, with core hydraulic conductivity which range from 2×10^{-6} to 5.8, shows the borehole conductivities to be generally greater than those of the core. Potentially this is because the higher permeability Budleigh Salterton Pebble Beds Formation are dominates the flow to boreholes, however not all the boreholes penetrate the pebble beds. Fractures, which are commonly important in groundwater flow to boreholes in the Triassic sandstones, are likely to be important in increasing the borehole bulk hydraulic conductivity above that of the matrix. The relatively constant bulk hydraulic conductivity northwards through the Otter Valley, as the aquifer thickness decreases, could be attributed to a fairly uniform fracture distribution: so that less fractures are intersected when there is less aquifer thickness.

The aquifer to the north of the Otter Valley area, although mainly composed of sandstone, has a very variable detailed lithology. Intercalations of marl with some very soft sandstones and sands occur, as well as coarser horizons. Very limited pumping test data exist for this area, though it is generally accepted that the permeabilities and transmissivities are on the whole lower than in the Otter Valley. The productive aquifer layers in the Tone catchment are generally less extensive and more dissected by faults than in the Otter Valley. The variations in lithology and the dissected nature of the aquifer are likely to result in equally variable aquifer properties, though there are insufficient data to see any trends. There is a general problem of pumping fine sediment, which causes clogging whilst borehole yield is limited by the thickness of sandstone penetrated. The number of the marl layers is a significant factor in the design and siting of a borehole. A low transmissivity of 8.1 m^2/d, (no storage values measured), was obtained from a pumping test at Milverton [ST 125 255].

Specific capacity and borehole yields

The majority of boreholes in the area have specific capacities less than 200 m^3/d/m, though some high-yielding boreholes have specific capacities ranging up to 1700 m^3/d/m (Figure 7.9.7). These high-yielding boreholes are indicative of fracture flow and possibly local effects such as river recharge. The latter are found mainly in the Triassic Sherwood Sandstone Group of the Otter Valley, with only a few high yielding boreholes in the sandy Permian deposits. There is a general relationship between transmissivity and specific capacity (Figure 7.9.8), but the correlation is not sufficiently good to be used for predicting transmissivity from specific capacity.

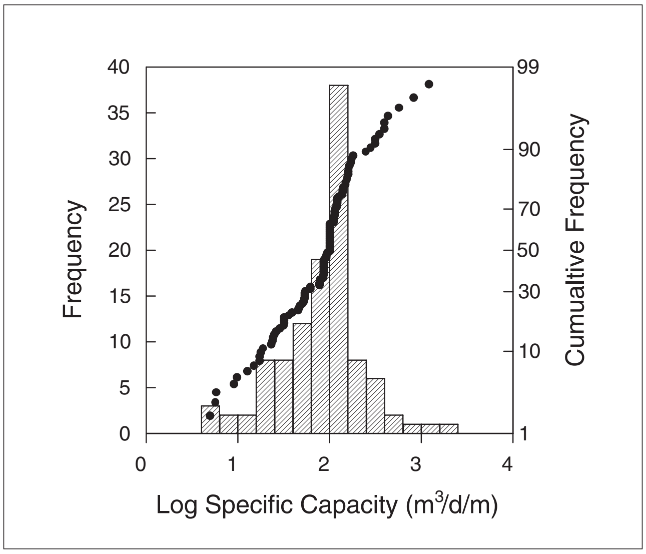


Figure 7.9.7 Distribution of specific capacity data for the Permo-Triassic sandstones of south-west England.

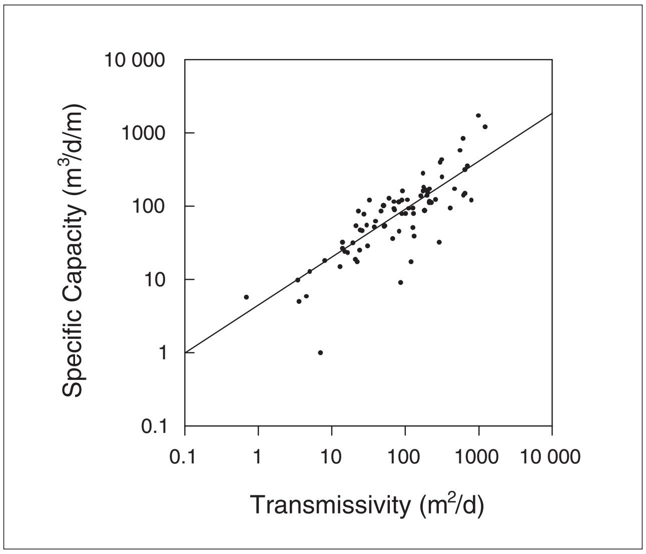


Figure 7.9.8 Plot of specific capacity (uncorrected) against transmissivity for the Permo-Triassic sandstones of south-west England.

On the basis of specific capacity the area divides up into general broad lithological zones, similar to transmissivity (Figure 7.9.9). Generally in the Permian Breccias the specific capacity is less than 50 m^3/d/m, and generally less than 100 m^3/d/m in the Permian sandstones, with many boreholes having a capacity greater than 100 m^3/d/m in the Triassic Sandstones of the Otter Valley area. These zones broadly indicate the typical yield that can be expected from each aquifer area. The well-sorted sandstones of the Otter Valley provide the most reliable yield, and the tight breccias in the west generally yield the least water.

Fracture flow

Fractures are present to some degree in all the Permo-Triassic sandstones of this area. They are especially important in the Permian breccias, which have low matrix permeability as they are poorly sorted sediments. Here fracture flow is vital to give a useful flow at boreholes. Fractures are likely

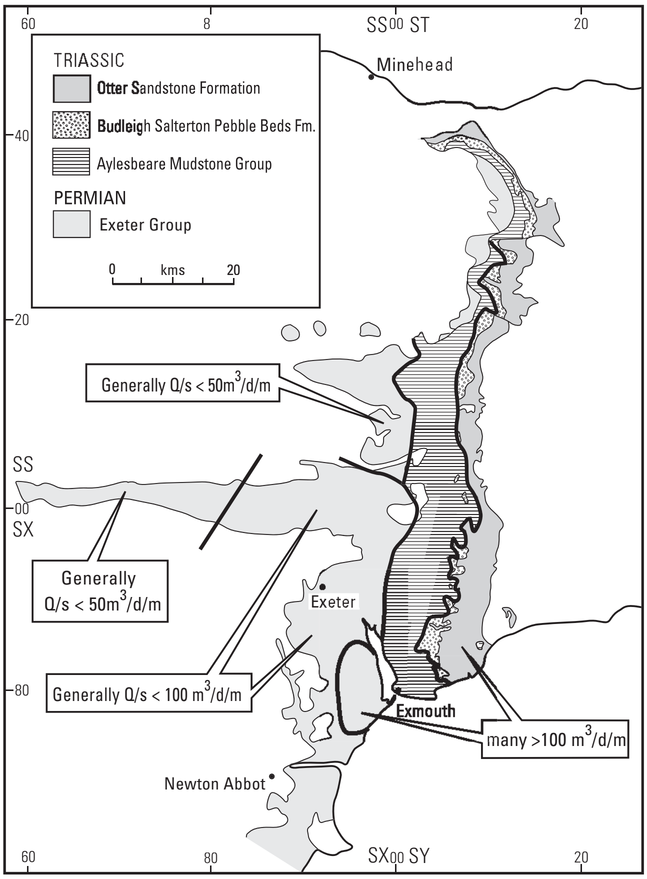


Figure 7.9.9 Regional specific capacity variations in the Permo-Triassic sandstones of south-west England.

to close with depth in the deep troughs, though this has not been demonstrated quantitatively. In practice however there is an optimum depth to drill, deeper than which the likely increase in yield will be small. In the sandstones fractures are important and cause much of the large variation in transmissivity found in pumping tests, high values greater than 300 m^2/d are thought due to fractures near the well.

Comparing the bulk well hydraulic conductivity and core hydraulic conductivities, the laboratory values are significantly lower than the average hydraulic conductivity determined from pumping test transmissivities. The highest intergranular (laboratory) hydraulic conductivities correspond to the lowest pumping test hydraulic conductivities. This supports the view that fractures are important in local flow to boreholes, contributing a high proportion of local flow in pumping tests above that which can be provided by purely matrix flow.

The Permian breccias are made up of many different lithological formations, and have only approximately 2% intergranular flow. Fractures provide most of the permeability, though they tend to dewater on pumping, indicating the generally low permeability of these sediments, the local nature of the fracturing, and low storage coefficient.

Packer test transmissivity and hydraulic conductivity: multi-layer aquifer modelling

The Sherwood Sandstone aquifer can be modelled as a series of horizontal layers (MRM Partnership, 1989), to allow variations in transmissivity with depth and vertical leakage between layers and so to simulate the confined and delayed yield response. Pumping tests were carried out at Tidwell [SY 061 829] on the Budleigh Salterton

Pebble Beds Formation isolated by a packer, the Budleigh Salterton Pebble Beds plus the Otter Sandstone Formation, and the Otter Sandstone Formation only, after backfilling the pebble beds. The response of the Tidwell borehole was modelled using a number of layers in the Otter Sandstone Formation and the Budleigh Salterton Pebble Beds Formation (Table 7.9.10). The model allowed each aquifer layer to contribute water, with the amount of water from each layer depending on the depth of the borehole and where it was opened for pumping. The results indicated that water is always drawn from the Budleigh Salterton Pebble Beds Formation, whether or not they are open to the borehole. If the Otter Sandstone Formation is open, water is also drawn from them. The higher permeability of the pebble beds means that they draw water from a wider area than the sandstones and so have a wider drawdown cone thus maintaining a higher head near the well. This means that the pebble beds can contribute water by vertical leakage from beneath the borehole; in turn, further away, they may induce downward leakage into the pebble beds from the overlying Otter Sandstone Formation.

The proportion of water from each layer in different modelled pumping regimes is determined by the relative transmissivities of each of the layers, their vertical hydraulic conductivity, and thicknesses of the layers. Model parameters were determined by trying to match the observed drawdowns to those expected. The results were then compared with the chemistry of the discharge water which is a mixture of Otter Sandstone Formation and Budleigh Salterton Pebble Beds Formation water. The chemical and the hydraulic methods had good agreement.

These simulations indicate that the Otter Sandstone Formation has a transmissivity of 40 to 80 m^2/d and the Budleigh Salterton Pebble Beds have a transmissivity of 120 to 140 m^2/d. These are consistent with values quoted by Sherrell (1970). A permeability anisotropy of a horizontal permeability ten times the vertical was used. (Note however that locally the base of the sandstone is more marly and so is likely to have a lower vertical permeability than the rest of the sandstone unit). The proportion of water coming from the Pebble Beds from the above results is 73% in the test on the pebble beds only, and 52% when all the layers are open. The model assumes that no water is pumped from the Pebble Beds when only the Otter Sandstone Formation is open. The results indicate that the Pebble Beds provide around 75% of the transmissivity to a borehole only open to the pebble beds and half the transmissivity when a borehole is open to all the layers. This high contribution of water from the pebble beds is a result of their greater permeability. The model proved very sensitive to the vertical permeability but less so to the storage Sy value used. This vertical model can be compared with chemical mixing modelling (Walton, 1978). Walton (1978) used bicarbonate as an indicator in mixing diagrams to identify the relative proportions of water coming from the Budleigh Salterton Pebble Beds Formation and the Otter Sandstone Formation. Flow from the sandstone is proportional to bicarbonate and therefore to conductivity.

The chemical mixing model gives good correlation with the vertical hydraulic model for the pebble beds and complete hole tests (Table 7.9.11). The chemical model also suggests that the pebble beds will contribute water by upward leakage up even when they are not directly open to the well. In addition the chemical model suggests that the proportion of the pebble beds water will increase with time. This upward leakage needs to be managed if water quality problems are to be avoided, due to the different chemistry

Table 7.9.10 Four-layer model results for the Tidwell borehole (after MRM Partnership, 1989).

Layer	T (m^2/d)	Thickness (m)	S	K_v (m/d)	Q (m^3/d)
1 PB	130	30	8×10^{-4}	0.1	—
2 OS	25	68	4×10^{-4}	0.075	520
3 OS	50	48	2×10^{-4}	0.015	400
4 Cased OS	5	14.6	2×10^{-4}	0.1	—

Otter Sandstone Formation test, actual abstraction 920 m^3/d, modelled as four layers.

Layer	T (m^2/d)	Thickness (m)	S	K_v (m/d)	Q (m^3/d)
1 PB	120	30	3×10^{-4}	0.4	605
2 OS	15	20	2×10^{-4}	0.1	125
3 OS	20	48	7.5×10^{-5}	0.05	100
4 Cased OS	5	14.6	7.5×10^{-5}	0.075	—

Budleigh Salterton Pebble Beds Formation test, actual abstraction 820 m^3/d, modelled as four layers.

Layer	T (m^2/d)	Thickness (m)	S	K_v (m/d)	Q (m^3/d)
1 PB	130	30	6×10^{-4}	0.5	600
2 OS	15	20	4×10^{-4}	0.85	200
3 OS	35	48	1.5×10^{-4}	0.15	270
4 Cased OS	5	14.6	1.5×10^{-4}	0.1	—

Whole borehole test, actual abstraction 1000 m^3/d, modelled as four layers.

Key OS = Otter Sandstone Formation; PB = Budleigh Salterton Pebble Beds Formation
T = Transmissivity; K_v = vertical hydraulic conductivity
S = Storage coefficient; Q = Modelled discharge from each layer

Table 7.9.11 Tidwell borehole tests — chemical mixing data using bicarbonate as an indicator of mixing (after MRM Partnership, 1989).

Test	Conductivity (μS/cm)	Proportion of Otter Sandstone water from mixing diagram (%)	Groundwater model proportion of Otter Sandstone water (%)
Pebble Beds	292	28	27
Complete hole	360	50	48.5
Sandstone 3 day test	320	35	—
Sandstone 6 day test	310	33	—

of the Pebble Beds water, which is soft and acidic and therefore has the potential to dissolve iron and manganese. In practice it is observed that boreholes have increasing iron problems when they are open near to the Budleigh Salterton Pebble Beds Formation indicating leakage of reducing waters from beneath the borehole up into the Otter Sandstone Formation, after pumping for some time.

Model hydraulic conductivity

A 2-D regional finite difference (steady state and transient) model of the Otter Valley Triassic aquifer has been constructed (MRM Partnership, 1989). The aquifer was assumed to be both homogeneous and isotropic. Both Sherwood Sandstone Group formations were modelled together due to lack of differential head data. The model was calibrated by varying the hydraulic conductivity around those values estimated from pumping tests. Final model hydraulic conductivities, based on the best fit of water level data for two years, were $K_h = K_v = 1.75$ m/d. This is within the upper range of the core permeabilities and at the lower end of the average borehole hydraulic conductivities, indicating that on the regional scale fractures are not very important for transmitting water, and flow through the matrix is important.

7.9.3 Porosity and storage

Core data

Sherwood Sandstone Group

The core porosity measurements (BGS data) have a skewed distribution (Figure 7.9.10a, Table 7.9.12), with 50% of samples having a porosity between 9.9 and 19.5% and with a median porosity of 14.8% (Table 7.9.12). This compares with ranges of porosity of 16–33% for outcrop samples (Morgan-Jones, 1975). Generally a decrease in porosity is seen northwards from over 33% in the southern outcrop of the Otter Sandstone to generally less than 20% in the north of the region (Figure 7.9.11). The wide variation in porosity (and permeability) may be a result of variable cementation of the sandstone in the Otter Valley; specifically the general decrease in porosity northward is thought to be due to the increase in sandstone cementation.

Exeter Group

Figure 7.9.10b shows the distribution of porosity data for samples from the Permian sandstones; statistics are given in Table 7.9.12. Values vary from 6.5% to 32.5% with a median of 22.4%.

In general the sandstone units provide the highest porosity within the aquifer with some component from the breccia bands. The actual local matrix porosity is likely to be very variable depending on the local sedimentology (Section 7.9.1).

The Dawlish Sandstone Formation shows an initial leaky or confined response, with pumping test storage coefficients of approximately 2×10^{-4}. Analysis of groundwater level responses to seasonal recharge suggest specific yield values in the range 0.1–0.2 consistent with expectations based on laboratory porosity measurements.

Summary

Porosities in the Permian sandstones, averaging 22% are significantly higher than those in the Sherwood Sandstone

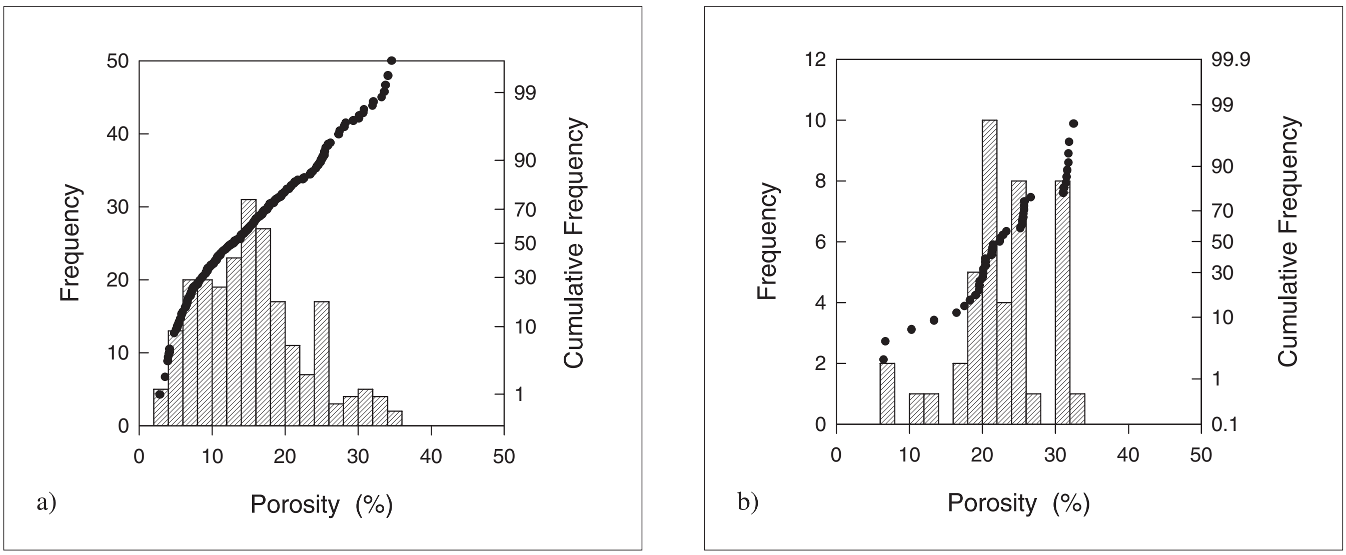


Figure 7.9.10 Distribution of porosity data for Permo-Triassic sandstone samples from south-west England, a) Sherwood Sandstone Group samples, b) Clyst Sandstone samples.

Table 7.9.12 Core porosity data for the Permo-Triassic sandstones of south-west England

Group or Formation	Range (%)	Interquartile range (%)	Median (%)	Arithmetic mean (%)
Sherwood Sandstone	2.2–34.6	9.9–19.5	14.8	15.5
Permian sandstones	6.5–32.5	19.7–25.8	22.4	22.8

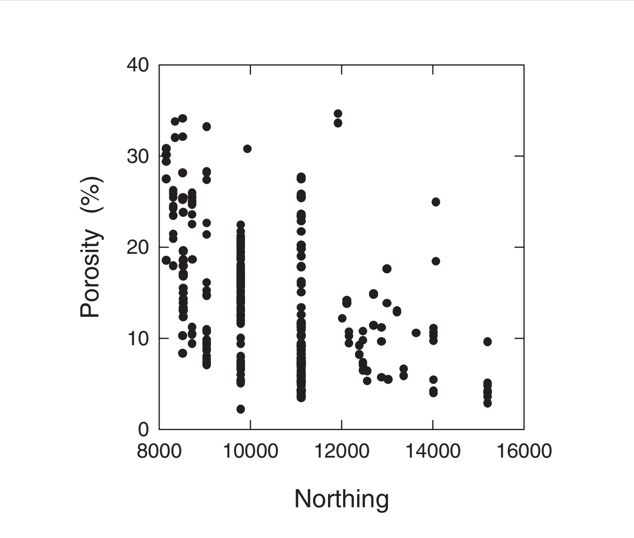


Figure 7.9.11 Variation of core porosity data for Sherwood Sandstone Group samples from south-west England with northing.

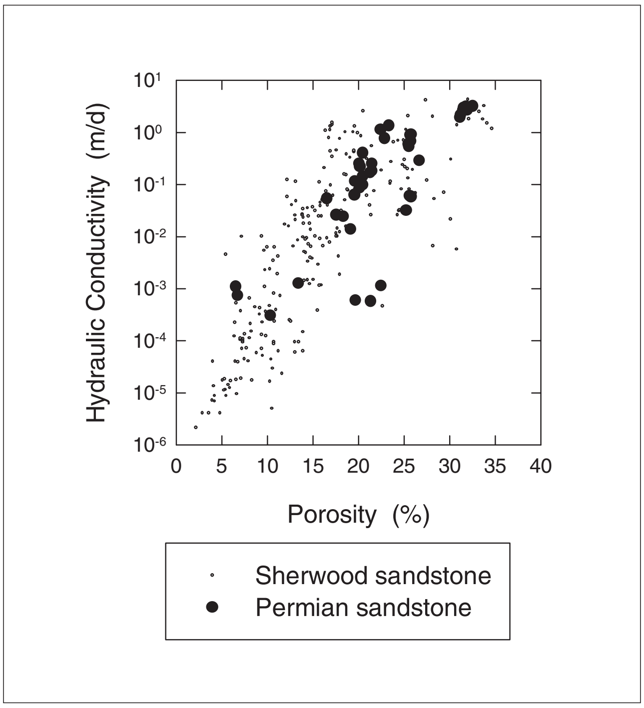


Figure 7.9.12 Plot of hydraulic conductivity against porosity for Permo-Triassic sandstone samples from south-west England.

Group which are more highly cemented, having an average porosity of only 15.5%. Permian breccias have a low porosity of around 6%.

These figures indicate that the cleaner sandstones have a high porosity, which should equate with a high specific yield, even though high storage values are not usually seen in pump-tests of normal duration. There is no correlation locally of laboratory permeability or porosity with depth in the freshwater aquifers; though generally in the Wessex Basin a decrease in porosity is seen with depth. Correlation of permeability and porosity, (Figure 7.9.12), shows a general trend of increasing permeability with increasing porosity in both the Permian and Triassic sandstones. The more well-sorted, open sandstones are more permeable than poorly sorted well-cemented sediments.

Pumping test storage coefficients

In the Permo-Triassic sandstones of south-west England many pumping tests are performed without observation boreholes and therefore storage coefficient data are limited. In general there is little drift cover and the sandstone aquifers appear essentially unconfined at outcrop.

Despite the unconfined nature of the aquifers the storage coefficient values that are calculated from pumping tests nearly all indicate semi-confined conditions (Figure 7.9.13). Most values are of the order of 10^{-4} to 10^{-3} (i.e. confined storage to semi-confined storage) and very few tests show analyzable unconfined specific yield values. The geometric mean of storage coefficient data is 0.0013 (Table 7.9.9). In this region the critical factor in determining the Permo-Triassic aquifers' confined or unconfined response to pumping is the ratio of the horizontal to vertical permeability. High ratios (that is relatively low vertical permeabilities) lead to a confined or semi-confined response on pumping even if the aquifer does not appear to be confined at the surface (Cookey et al., 1987). The slow vertical movement of water means that the water table does not immediately respond to a head decrease at depth caused

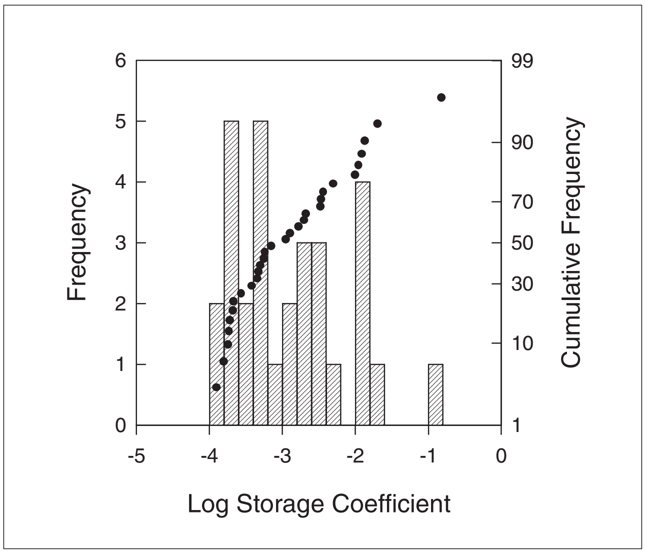


Figure 7.9.13 Distribution of storage coefficient data from pumping tests in the Permo-Triassic sandstones of south-west England.

by pumping a well. The few tests that have larger storage values tend to be the longer tests and to be in the more well sorted sandstones rather than the breccias.

The storage coefficient values increase with the length of the test, suggesting that pumping boreholes respond in a semi-confined to confined way (at least over the period of weeks or less of most tests), and most tests are not continued for a sufficient length of time to positively identify the final unconfined storage value (Tubb, C, personal communication).

The variable effect of delayed yield and vertical flow in pumping tests means that values of storage coefficient other than those obtained from the initial confined response to pumping are difficult to determine from pumping tests. Specific yield values suitable for aquifer modelling and management are not obtained from short pumping tests (Tubb, C, personal communication). Modelling of pumping tests using a vertical flow model with interlayering of sediments of different permeabilities has been found to be successful near boreholes in simulating the response of a pumped well with time, where more traditional type curve matching has not produced a consistent result.

The storage coefficient values in the Sherwood Sandstone Group in the Otter Valley are generally in the confined to semi-confined range. Confined conditions were found near to the coast in the Otter Sandstone Formation even in shallow boreholes screened only a few metres below the water table. This is the result of the interbedding of finer sediment, rather than an obvious confining layer. New boreholes near the coast show clay material near the surface made up of weathering products, with another clay layer above the Budleigh Salterton Pebble Beds Formation, which could be responsible for the confined multi-layer response of the aquifer. Along the coast in the south specific storage values are confined (around 10^{-4}) to unconfined (of the order of 10^{-2} to 10^{-1}), the higher values being seen in longer, higher pumping rate tests. Recovery tests usually had anomalously higher transmissivity values and lower storativity values. In general the preferred confined/semi-confined storage value of 0.001 was taken as representative of this area in the south of the Otter Valley (Water Management Consultants, 1993). Observation boreholes to the west of Otterton showed a semi-confined response. The specific yield of the aquifer in the unconfined zone is thought to be 0.1–0.2.

In the Permian sandstones the complex interlayering of sediments is seen in well and borehole responses to pumping. Unconfined conditions are encountered locally in shallow boreholes within surficial deposits e.g. shallow brick wells. Locally confined conditions are caused by surface clay deposits, such as are seen in the Duckaller area [SX 95 80]. However very long tests may show unconfined conditions depending on the extent of the cone of depression. Vertical layering gives rise to increasingly confined conditions with depth, so that upward vertical head gradients may be encountered in boreholes. On drilling a borehole the water level frequently rises with depth drilled, and may, in some cases, become artesian and overflowing. Changes in head frequently coincide with the penetration of a deeper breccia layer.

Pumping tests conducted in boreholes penetrating Permian breccias indicate a confined coefficient of storage of the order of 4×10^{-4}, with little apparent variation. This emphasises the influence of fractures and interlayering of sediments on the response to pumping.

Aquifer response times, tidal and barometric efficiency

The Otter Sandstone Formation outcrops down the Otter Valley to the coast and boreholes along the coast exhibit a high degree of tidal and barometric efficiency. Tidal efficiency increases towards the coast and towards the top of the aquifer (for example near to the coast a saline monitoring well exhibited a tidal range of 1.3 m, strong enough to mask the effects of pumping inland). The tidal influence extends up to 1 km inland. Boreholes with confined responses to pumping show greater tidal and barometric influences whereas boreholes with unconfined responses better reflect seasonal recharge events. Boreholes screened at depth show less tidal efficiency; this is probably because the low vertical permeabilities attenuate tidal effects at depth. The borehole response to tidal fluctuations decreases from around 2 m water level fluctuation in shallow boreholes to 0.2 m in deeper boreholes penetrating the Budleigh Salterton Pebble Beds Formation.

In the Otter Valley model the aquifer response time was investigated. Aquifer response time is a measure of the response time of river base flow to infiltration or abstraction remote from the river. (Aquifer Response Time = Transmissivity/Storage Coefficient $-L^2$, where L is the distance from the river to an impermeable boundary or groundwater divide parallel to the river, as defined by Oakes and Wilkinson, 1972). Transmissivity estimated from the amplitude and lag of tidal response from borehole hydrographs is 300 to 400 m^2/d with a semi-confined storage of 1×10^{-3}–1.5×10^{-3}.

Modelling the cessation of all pumping in the Otter Valley gave a less than 5% difference between original naturalised model flow and recovered model flows after a ten year simulation period. This suggests that the aquifer has a long response time of the order of tens of years to any changes in abstraction. This is a common feature in the Permo-Triassic sandstones which appear frequently to only ever reach a dynamic rather than a completely static equilibrium, as pumping rates rarely stay constant for tens of years.

Model storage coefficient values

The Otter Valley model was calibrated from the groundwater level response to recharge. An unconfined value of storage coefficient of 0.2 was determined by transient calibration to seasonal water-level changes and base flows (MRM Partnership, 1989). This appears to be realistic, despite early responses from pumping tests indicating lower values of storage coefficient. A good correlation was found between adjusted seasonal change in storage and natural recharge.

Long-term storage coefficients from water-level fluctuations

Analysis of annual hydrographs from recharge zones can be used to estimate long-term drainable storage. This is calculated from a match between the annual range of the water-level fluctuation and the equivalent depth of recharge (in metres). This is easiest for sites with long-term records over a number of years. Estimates of specific yield from this process agree with figures estimated from very long-term pumping tests (Tubb, C, personal communication).

7.9.4 Summary

Sherwood Sandstone Group

Modelling studies and pumping tests show that the Otter Sandstone and the Budleigh Salterton Pebble Beds for-

Table 7.9.13 Summary of the aquifer properties of the Sherwood Sandstone Group in the Otter Valley.

Parameter	Pump test	Lab	Recharge GWL response analysis	Model
T (m^2/d)	6–3000	—	—	< 250
K (m/d)	9 (1–10)	1–3	—	1.75
Sy, porosity	N/A	0.05–0.3	0.1–0.2	0.1–0.2
Storage coefficient	0.001	—	—	10^{-4}

GWL = groundwater level

mations respond as one aquifer, and that vertical leakage occurs between the different layers. Model permeabilities are similar though slightly lower than those obtained from pump testing and represent the regional matrix permeability without local high permeability zones and fractures. Values of storage coefficient used in steady state models are comparable to low core porosities and specific yields obtained from long pumping tests. On a short time scale the aquifer responds in a confined manner in short pumping tests and exhibits barometric efficiency. Table 7.9.13 gives a summary of data for the area.

Exeter Group

Data from both core and field tests suggest that intergranular permeability may account for up to 40% of flow in the Dawlish Sandstone Formation but less than 2% in the Knowle Sandstone Formation and Bow Conglomerate Formation (Davy, 1981). Estimates of hydraulic conductivity from pumping tests give values in the range 1.7 to 5.7 m/d (assuming that only the sands contribute to the flow). This compares with an interquartile range of 0.1 to 2 m/d (median 0.7 m/d) for horizontal core samples (Table 7.9.4).

The sandstone aquifers behave in an unconfined manner on a longer time scale but in a confined way over the period of a short pumping test. They exhibit both barometric and tidal efficiency.

In general the Permian breccia aquifers respond as fractured aquifers of relatively low storage and very variable permeability depending on the degree of fracture intersection and the local intergranular permeability of strata.

The breccias are only of limited local use for water supply. The more extensive sandstone areas have more potential for groundwater development. Little modelling has been carried out on the Permian sandstones and breccias and in consequence no regional models are available. The creation of realistic models is likely to prove very difficult due to the heterogeneous and fractured nature of the Permian sediments.

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8 The Magnesian Limestone

8.1 INTRODUCTION

The Magnesian Limestone aquifer occupies a narrow north–south outcrop from Sunderland to Nottingham (Figure 8.1.1). In Durham the Magnesian Limestone aquifer is divided into three; the Lower and Middle Magnesian limestones, which are locally separated from the Upper Limestone by marls and siltstones. Further south it is divided into two: the Upper and Lower Magnesian limestones, again separated by marls and siltstones. The limestones comprise compact fractured dolomite, which is brecciated and cavernous in some areas, for example east of Durham. There is some hydraulic continuity between the units and they are generally treated as one aquifer. In Durham the Middle Magnesian Limestone is more porous than the Upper and Lower Magnesian Limestones, however the permeability of the whole aquifer is extremely variable as a result of the fracturing. Surface and groundwater flow are interconnected where drift is thin or absent. This chapter concentrates on the Magnesian Limestone aquifer at outcrop, where it is most developed, and compares this with one site down dip.

8.2 GEOLOGY

8.2.1 Stratigraphy

The stratigraphy of the Permian is quite complex. The traditional nomenclature is used in this text as it is most widely used by hydrogeologists, but the correlation with the revised nomenclature is given in Table 8.1.1. The Middle Magnesian Limestone is only present in County Durham, but in Yorkshire two divisions of the Lower Magnesian Limestone are recognised. The summary table below (Table 8.1.2) indicates the basic stratigraphical divisions and their hydrogeological significance.

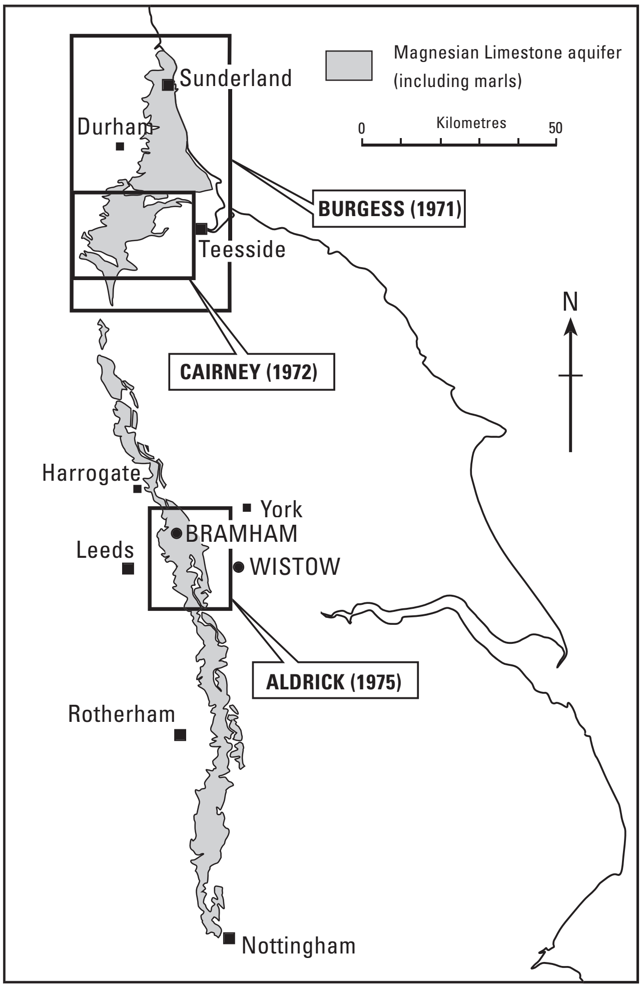


Figure 8.1.1 Distribution of the Magnesian Limestone at outcrop, showing areas of main hydrogeological investigations.

Table 8.1.2 Summary of stratigraphy for the Permian Magnesian limestones and their hydrogeological significance (Thicknesses taken from Smith, 1974; Smith et al., 1986; Cooper and Burgess, 1993; Powell, Cooper and Benfield, 1992, and Grant, 1994).

Stratigraphy				Hydrogeological significance
Durham		*Yorkshire*		
Upper Permian Marl	30–40 m	Upper Permian Marl	30 m	Aquitard
Upper Magnesian Limestone	21–28 m	Upper Magnesian Limestone	10–35 m	Aquifer
Middle Permian Marl	10–50 m	Middle Permian Marl	up to 60 m	Leaky aquitard
Middle Magnesian Limestone	up to 95 m	Lower Magnesian Limestone (including Lower Permian Marl and Hampole Beds where present)	up to 100 m	Aquifer (Lower Permian Marl–aquitard)
Lower Magnesian Limestone	20–50 m			
Marl Slate	few m	Marl Slate	1–9 m	
Basal Permian Sands (Yellow Sands)	0–60 m	Basal Permian Sands	0–15 m	Aquifer

Table 8.1.1 Stratigraphy of the Magnesian Limestone aquifer.

	DURHAM			YORKSHIRE					
	Traditional	Revised nomenclature (Smith, 1986)		Traditional		Revised nomenclature (Smith, 1986)			
		At Outcrop	*At Depth*			*At outcrop*		*At Depth*	
UPPER PERMIAN	Upper Permian Marl (and gypsum)	Roxby Formation	Roxby Formation	Upper Permian Marl		Roxby Formation		Roxby Formation	
			Sherburn Anhydrite					Sherburn Anhydrite Formation	
			Billingham Anhydrite					Billingham Anhydrite Formation	
	Upper Magnesian Limestone	Seaham Formation	Seaham Formation	Upper Magnesian Limestone		Brotherton Formation		Brotherton Formation	
		Seaham Residue	Fordon Evaporite Formation	Middle Permian Marl		Edlington Formation (and gypsum)		Fordon Evaporite Formation	
		Roker Dolomite Formation						Kirkham Abbey Formation	
		Concretionary Limestone						Edlington Formation	
	Middle Permian Marl (and gypsum)	Edlington Formation	Edlington Formation and Hartlepool Anhydrite					Hayton Anhydrite	
	Middle Magnesian Limestone	Ford Formation		Lower Magnesian Limestone	Upper Subdivision	Cadeby Formation	Sprotborough Member	Cadeby Formation	Sprotborough Member
					Hampole Beds		Hampole Beds		Hampole Beds
	Lower Magnesian Limestone	Raisby Formation			Lower Subdivision		Wetherby Member		Wetherby Member
	Marl Slate	Marl Slate Formation		Marl Slate		Marl Slate Formation			
LOWER	Basal Permian Sand	Yellow Sands Formation		Basal Breccia/ Basal Permian Sands		Basal Breccia/ Basal Permian Sands			

8.2.2 Lithology and geological history

The early Permian was characterised by extensive desertification and erosion in Britain. The Basal Permian Sands represent the desert strata in this area and are composed of dune sands of Lower Permian age. Conditions in the Upper Permian changed abruptly with the formation of the Zechstein Sea. The Upper Permian deposits are cyclic, reflecting alternate phases of transgression and regression, due to marine expansion and contraction. A number of sub-basins were formed divided by ridges, and one such 'high' separated the Durham Province to the north from the Yorkshire Province to the south. In general, the outcrop rocks in Durham were formed further offshore than those at outcrop in Yorkshire.

The Basal Permian Sands (known locally as the Yellow Sands in the Durham Province) are aeolian dune sands.

The first Upper Permian cycle begins with the Marl slate, the initial marine deposit composed of organic-rich siltstones and dolomite. The overlying Lower Magnesian Limestones generally thicken to the east. In the Yorkshire Province the Lower Permian Marl is present at some locations and is composed of calcareous and dolomitic siltstones. It is up to 55 m thick in the south and thins rapidly to the north where it passes into the dolomitic Lower Magnesian Limestones. In the Yorkshire Province south of Ripon the Lower Magnesian Limestone is divided into two subdivisions separated by the thin Hampole Beds, but to the north these are not easily distinguished. In the Durham Province the equivalent strata includes the Lower and Middle Magnesian Limestone.

The Middle Permian Marl comprises dolomitic mudstones and siltstones, containing nodular, layered and massive gypsum or anhydrite. In eastern Yorkshire and northern Lincolnshire the Lower Magnesian Limestone is overlain by the Hayton Anhydrite which can be up to 40 m thick; in the Durham Province the Lower and Middle Magnesian Limestones are overlain by the equivalent Hartlepool Anhydrite. These evaporites pass laterally into secondary gypsum deposits updip which are dissolved away at outcrop where they pass laterally into the Middle Permian Marl.

In the Yorkshire Province the Upper Magnesian Limestone is a uniform sequence of white to grey dolomitic carbonates, overlain by anhydrite and passing up into the Upper Marl, a sequence of mudstones and siltstones with thin lenses of gypsum or anhydrite. In the Durham Province the Upper Magnesian Limestone includes three calcareous formations. The Seaham Formation at the top consists of thin bedded, white to grey dolomitic limestone. Near the outcrop the foundering of this Magnesian limestone is common due to the dissolution of gypsum in the underlying horizons.

8.3 GENERAL HYDROGEOLOGY

8.3.1 Introduction

The hydrogeology of the Magnesian Limestone aquifer is controlled by lithology and structure. Variations in lithology result in changes in hydraulic conductivity and hence transmissivity and yield. However, the greatest control on the aquifer properties is the extent of the fracturing. As a consequence aquifer properties are extremely unpredictable.

The transmissivity of the Magnesian limestones is dependent on fracturing, although there is some intergranular storage. The Middle Permian Marl functions as a 'leaky' aquitard and thus generally maintains a slight head difference between the Upper and Middle and/or Lower Magnesian limestones. As a result of the presence of reef complexes, which are frequently permeable, the Middle Magnesian Limestone is generally thought to be the best prospect for groundwater development in the Durham area. However the Lower and Upper Magnesian limestones may have substantial transmissivities where the fracture frequency is high. In Yorkshire the best prospects are where the Upper and Lower Magnesian limestones are faulted increasing their hydraulic conductivity. Small dry caves are recorded in the Lower Magnesian Limestone of Yorkshire and at a few locations in Durham (Gibson et al., 1976; Anon, 1973, 1974). While some of these caves are rift fractures along valleys others are phreatic and development of such phreatic caves below the water table could locally influence the aquifer characteristics.

The aquifer is developed for public supply in Northumbria and Yorkshire. Further south towards Nottingham there is a lateral facies variation. The Upper Magnesian Limestone wedges out and the Middle and Lower Permian Marls become more sandy and pass up into the Permo-Triassic sandstones. Generally the importance of the Limestone as an aquifer decreases southwards, although there are some abstractions at Bolsover (Smith et al., 1967).

8.3.2 General aquifer properties

Laboratory core data

Core data representing the matrix properties of the aquifer are available for the Upper and Lower Magnesian limestones from a small number of sites in the Yorkshire Province. There are no data from any of the limestones in the Durham Province. The dataset is dominated by samples from the Wistow borehole (see Section 8.4.4) and there are no depth data for any of the other samples. A summary of all available data is given in Tables 8.3.1 and 8.3.2. The Lower Magnesian Limestone data are positively skewed (Figure 8.3.1) while the hydraulic conductivity data approximate to a lognormal distribution (Figure 8.3.2). There is some correlation between hydraulic conductivity and porosity (Figure 8.3.3). Porosity generally increases with increasing hydraulic conductivities, although there is significant scatter in the data. The Upper Magnesian Limestone shows a narrower range in porosity and the range of hydraulic conductivity is also more restricted than for the Lower Magnesian Limestone. The porosity and hydraulic conductivity data do not conform to a standard distribution (Figures 8.3.4 and 8.3.5). Again there is a

Table 8.3.1 Summary of core porosity data for the Magnesian Limestone.

Magnesian Limestone	Number of samples	Range	Arithmetic mean	Interquartile range	Median
Lower	107	1–30%	13.7%	8.5–18.7%	15.0%
Upper	28	6–30%	17.4%	9.9–22.4%	16.6%

Table 8.3.2 Summary of core hydraulic conductivity data for the Magnesian Limestone.

Magnesian Limestone	Number of samples	Range (m/d)	Geometric mean (m/d)	Interquartile range (m/d)	Median (m/d)
Lower	107	1.9×10^{-6}–0.85	1.8×10^{-3}	2.9×10^{-4}–0.015	1.4×10^{-3}
Upper	28	1.9×10^{-6}–0.14	8.3×10^{-4}	5.6×10^{-5}–0.017	5.5×10^{-4}

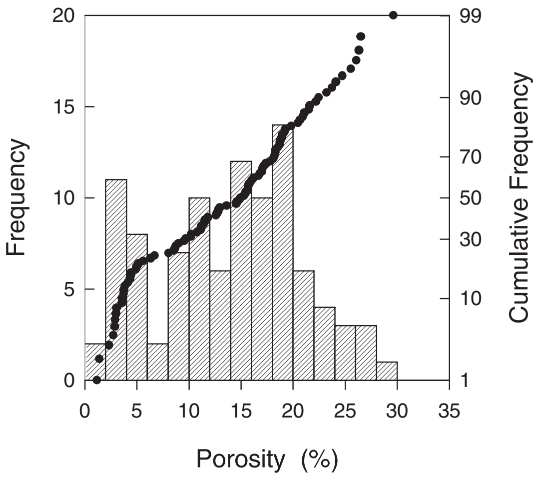


Figure 8.3.1 Distribution of porosity data for Lower Magnesian Limestone samples.

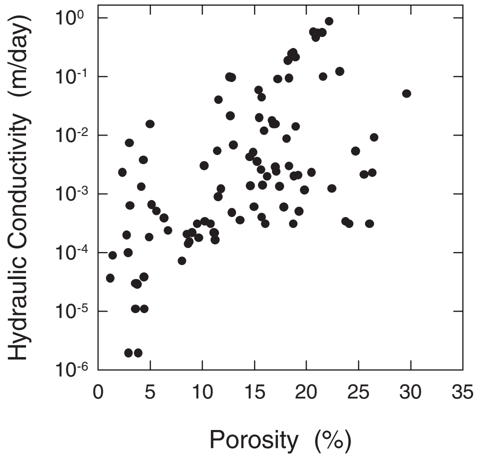


Figure 8.3.3 Plot of hydraulic conductivity against porosity for Lower Magnesian Limestone samples.

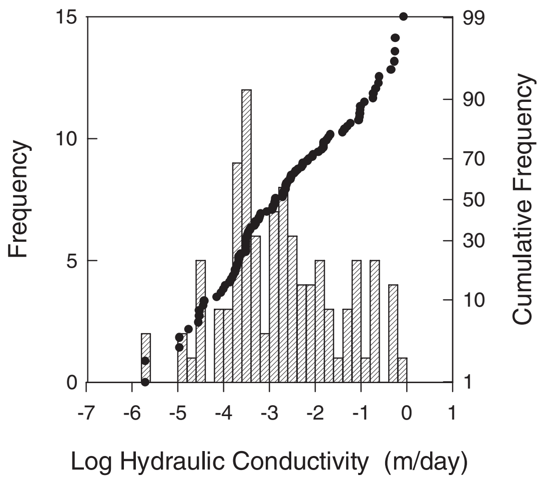


Figure 8.3.2 Distribution of hydraulic conductivity data for Lower Magnesian Limestone samples.

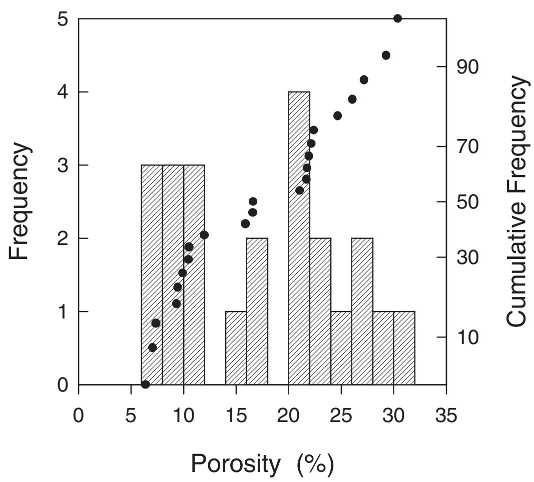


Figure 8.3.4 Distribution of porosity data for Upper Magnesian Limestone samples.

trend of increasing porosity with hydraulic conductivities (Figure 8.3.6).

Field data

The database data cover 105 tests from 80 localities in the Magnesian Limestone aquifer. At only five locality has more than one pump test been carried out. Locality transmissivities range over several orders of magnitude, from 6 to 4300 m^2/day with a geometric mean of 255 m^2/day, (Figure 8.3.7). The interquartile range is 131 to 763 m^2/day with a median of 229 m^2/day. There is little difference in distribution between the Durham and Yorkshire data (see Sections 8.4.2 and 8.4.3). The test transmissivity values generally correlate well with the specific capacity calculated for the corresponding test (Figure 8.3.8).

The transmissivity values show very little systematic spatial variation. The highest transmissivities are associated with the fault zones. Within the faulted blocks the transmissivities are generally lower but extremely variable, depending on the extent of fracturing in the aquifer.

Storage coefficients are recorded from 28 locations in the database. The values for the storage coefficient vary over

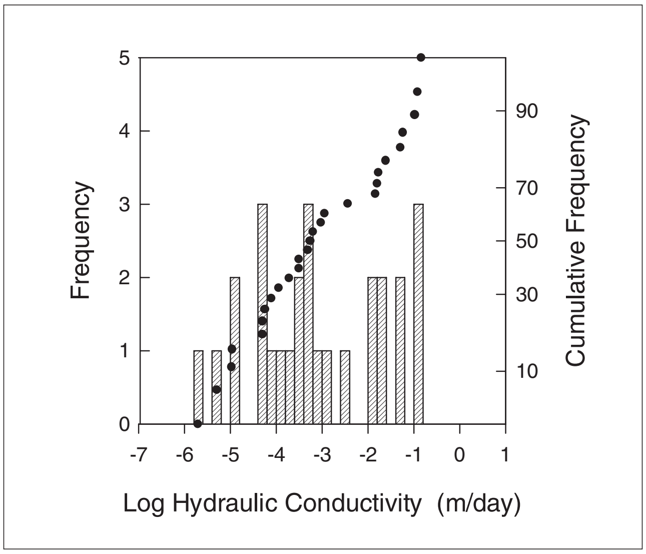


Figure 8.3.5 Distribution of hydraulic conductivity data for Upper Magnesian Limestone samples.

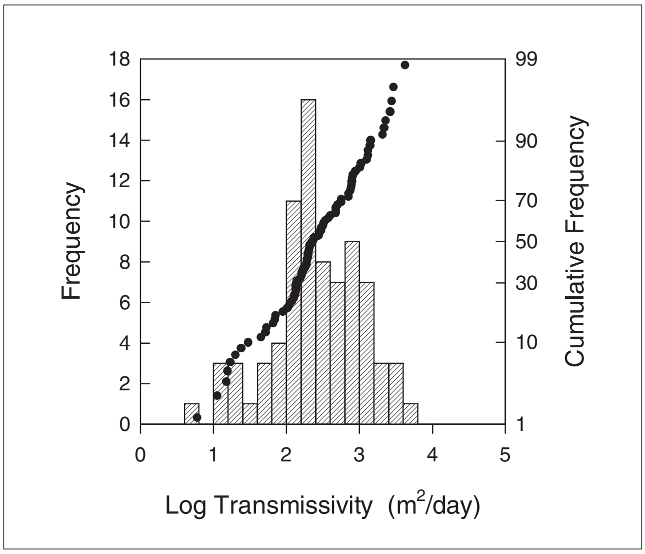


Figure 8.3.7 Distribution of transmissivity data from pumping tests in the Magnesian Limestone.

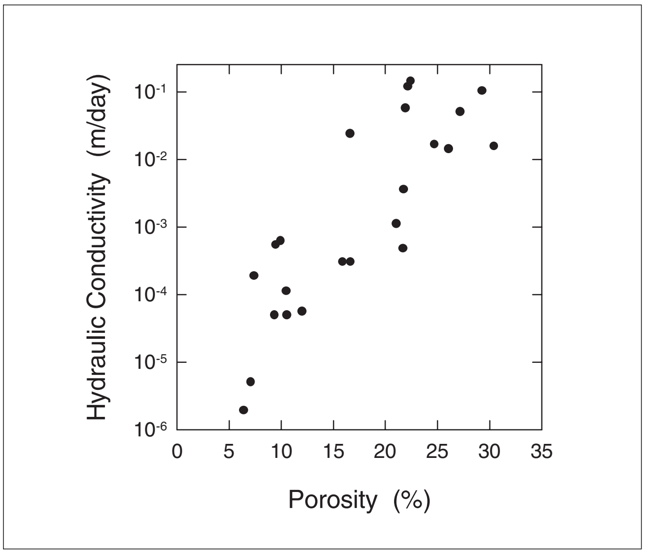


Figure 8.3.6 Plot of hydraulic conductivity against porosity for Upper Magnesian Limestone samples.

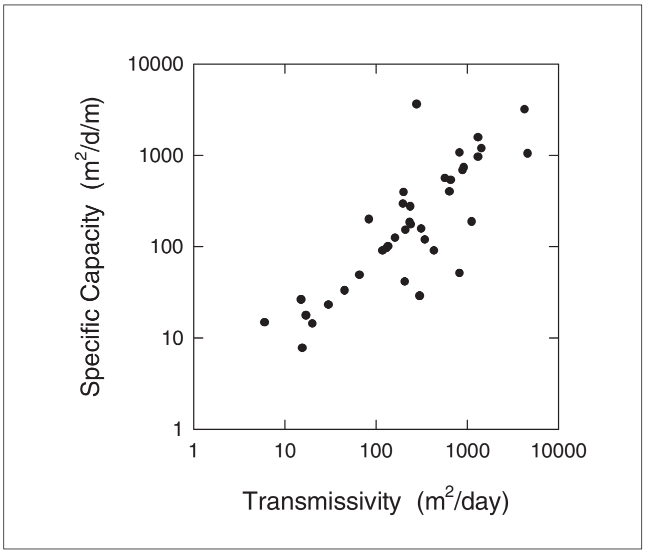


Figure 8.3.8 Plot of specific capacity against transmissivity for the Magnesian Limestones.

several orders of magnitude from 3.4×10^{-6} to 2.4×10^{-2} with an interquartile range of 1.3×10^{-4} to 8.0×10^{-4}. The storage coefficient data approximate to a lognormal distribution with an geometric mean of 2.9×10^{-4} and a median of 2.2×10^{-4} (Figure 8.3.9). There does not appear to be any systematic spatial variation in the values of storage coefficient.

8.4 REGIONAL AQUIFER PROPERTIES

8.4.1 Introduction

The properties of the Magnesian Limestone aquifer have only been extensively investigated in three regions. The area from the River Wharfe to the River Aire in Yorkshire, the area of County Durham, both on the outcrop and under the drift, and the area around Wistow below the Triassic cover (Figure 8.1.1).

8.4.2 County Durham

Geology and hydrogeology

County Durham has been the focus of a number of studies and reviews (Cairney, 1972; Burgess, 1971 and Younger, 1994)

The Magnesian Limestone aquifer lies unconformably over the Carboniferous and is overlain by glacial drift, commonly composed of stiff stony clays of low permeability, although these include beds of sand and are generally sandier and more permeable to the west. The glacial drift is at its thickest in the east where it reaches a maximum thickness of 84.5 m. In County Durham east of the River Skerne the glacial drift is always in excess of 30 m thick. West of the Skerne the thickness does not exceed 30 m and over considerable areas is less than 3 m thick.

North of the Hartlepool Fault system the aquifer is unconfined and the Lower Magnesian Limestone constitutes the major aquifer. South of the Hartlepool Fault

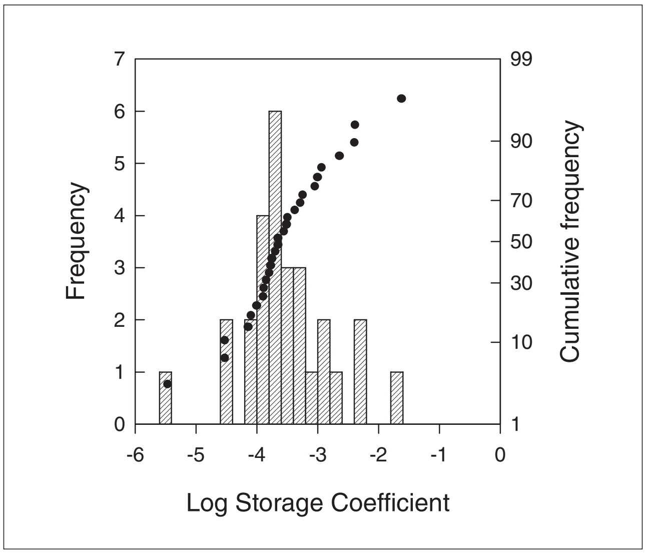


Figure 8.3.9 Distribution of storage coefficient data from pumping tests in the Magnesian Limestones.

system the major aquifer is the more permeable Middle Magnesian Limestone.

Recharge areas are located towards the western edge of the Permian outcrop, and strata dip gently eastwards or south-eastwards. The flow direction is towards the east, with discharge to the sea.

Recharge can occur through the drift from surface water sources. An investigation in the late 1970s (Hamil, 1980 and Cairney and Hamil, 1977, 1979) indicated that up to 37% of the flow of the River Skerne was being lost to groundwater as a result of the progressive development of the river as a recharge zone to the underlying aquifer. This had been induced as a result of groundwater abstraction.

There has been a general rise in water levels in the Durham area in the last 20 years (Figure 8.4.1, after Younger, 1994) due mainly to the reduction in abstraction along the coast. Cessation of dewatering in underlying coal workings may account for some of the rise in the south-western part of the area. This has implications for groundwater quality in the Magnesian Limestone if the water levels continue to rise.

The Lower Magnesian Limestone in the west of the region is water worn and eroded with fractures showing signs of leaching. In the centre of the area, where the Lower Magnesian Limestone lies under the Middle Magnesian Limestone the Lower Magnesian Limestone is massive and fresh showing no signs of water flow. Where the Middle Magnesian Limestone lies directly below the glacial drift it is disaggregated and highly permeable. Where the Middle Magnesian Limestone occurs below the Upper Magnesian Limestone it tends to be less permeable. The yield from the Upper Magnesian Limestone is unpredictable, varying with the degree of collapse brecciation. The Magnesian Limestones dip and thicken to the east and are openly folded and extensively faulted. The marls and clays generally act as aquicludes except where they are fractured by post-depositional foundering, slumping and faulting (Smith, 1972).

Data availability

The Aquifer Properties Database contains transmissivity values from 45 locations and storage coefficient values from 23 locations in the Magnesian Limestone in this

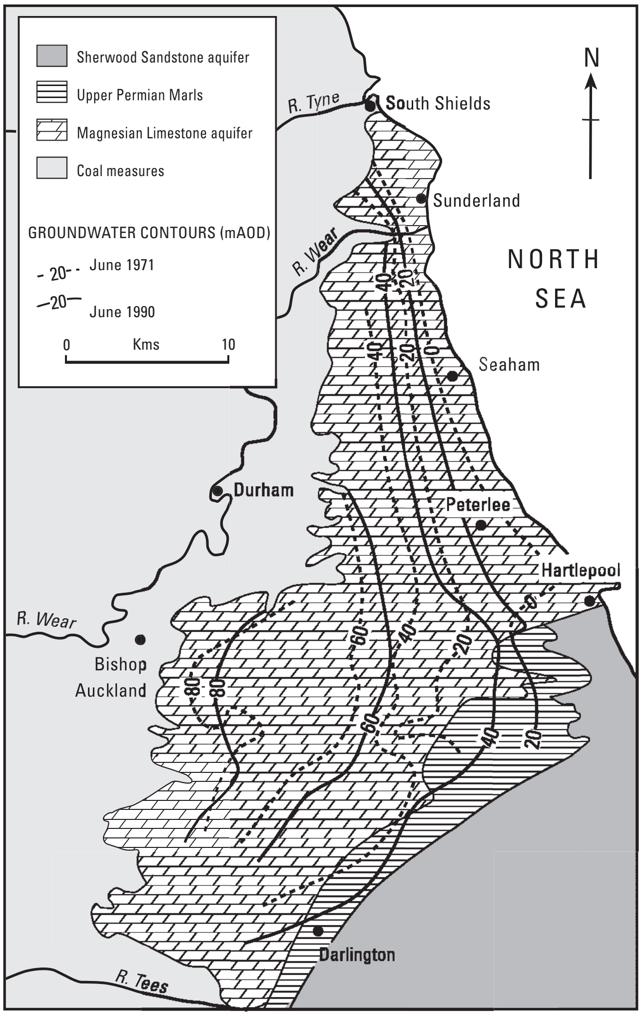


Figure 8.4.1 Water levels in the Durham area (after Younger, 1994).

area. Transmissivity and storage coefficient data are fairly evenly spread over the area. There are no porosity or hydraulic conductivity values from core data.

Porosity and storage

Burgess (1971) stated that the Middle Magnesian Limestone has greater porosity than the Upper or Lower Magnesian Limestones.

Storage coefficient values vary over several orders of magnitude from 3.0×10^{-5} to 2.4×10^{-2} with an interquartile range of 1.3×10^{-4} to 5.7×10^{-4}. The distribution of the storativity values approximates to a lognormal distribution with a geometric mean of 3.0×10^{-4} and a median of 2.2×10^{-4} (Figure 8.4.2).

Transmissivity and permeability

Transmissivity values in the database vary in the range 11 to 2200 m^2/day with an interquartile range of 139 to 564 m^2/day. The data distribution is positively skewed (Figure 8.4.3). The geometric mean of all the location values in the County Durham area is 263 m^2/day and the median value is lower at 205 m^2/day.

The Upper and Lower Magnesian limestones yield only appreciable volumes when fractured. The Middle Magnesian Limestone has greater porosity. The open texture of the Middle Magnesian Limestone and the brecciated Upper Magnesian Limestone result in higher

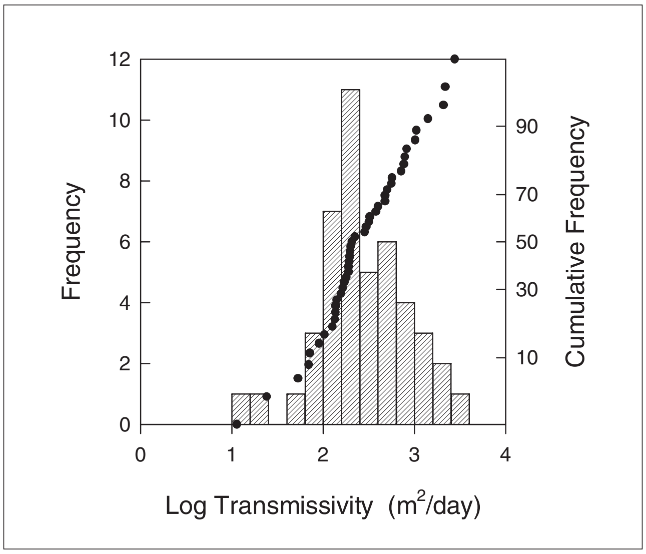


Figure 8.4.2 Distribution of transmissivity data from pumping tests in the Magnesian Limestones of the Durham area.

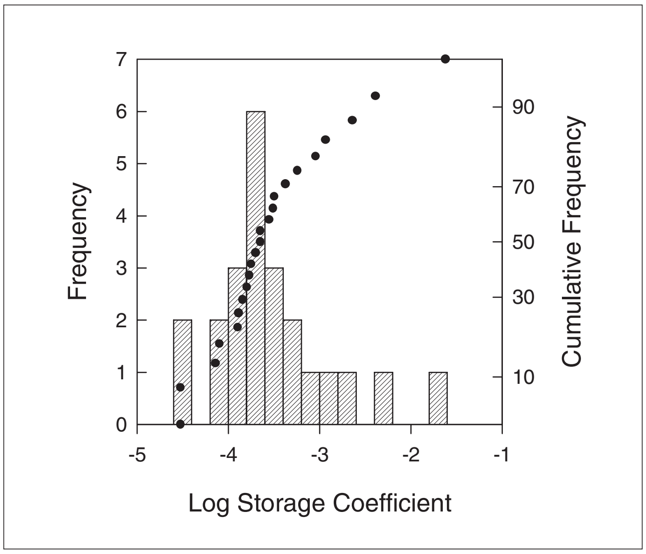


Figure 8.4.3 Distribution of storage coefficient data from pumping tests in the Magnesian Limestones of the Durham area.

hydraulic conductivities than in the more competent Lower Magnesian Limestone. Hydraulic conductivities of greater than 12 m/day are found where the Middle Magnesian Limestone or brecciated Upper Magnesian Limestone represents over half of the saturated aquifer thickness. Where the Lower Magnesian Limestone is the only aquifer the hydraulic conductivity is less than 5 m/day. The Lower Magnesian Limestone appears to show a variation in hydraulic conductivity with depth, possibly as a result of the presence of the more massive and sometimes calcitic beds which occur at the base of the formation (Burgess, 1971).

Test pumping in south-east Durham indicated that transmissivities in some boreholes in the Middle Magnesian Limestone were low due to the presence of sulphate cements which reduce the porosity (Northumbrian River Authority, 1969).

Borehole behaviour

The glacial drift generally has subhorizontal stratification and negligible vertical permeability. Pumping tests carried out at a number of boreholes in south-east Durham abstracting water from the Magnesian Limestone had no affect on the water levels in the drift. Therefore vertical leakage was assumed to be insignificant and the pump tests were analyzed as 'simple artesian aquifers' (Cairney, 1972). Analysis and extrapolation of results are difficult due to the presence of many hydrogeological barriers formed by faults and basement highs.

During test pumping of large diameter boreholes in south-east Durham yields varied from 2180 m^3/day to 8720 m^3/day depending on the amount of artesian head and local differences in transmissivity (Northumbrian River Authority, 1969). Jacob and Theis methods were used for analysis, but it was felt that the Jacob approximation was not valid in many cases in an aquifer with many groundwater barriers. The Theis values, although technically more correct, were felt to be of limited practical value in the extrapolation of pumping test effects to differing abstraction regimes due to the inhomogeneous nature of the aquifer.

8.4.3 Yorkshire and Nottinghamshire

Introduction

The Yorkshire Magnesian Limestone has only been extensively investigated in the area from the River Aire to the River Wharfe (Aldrick, 1978), but the database covers tests over the whole outcrop of the Yorkshire and Nottinghamshire Magnesian Limestone.

Geology

The Basal Permian Sands and the Lower Permian Marl are thin and may be absent. The upper and lower divisions of the Lower Magnesian Limestone are divided by less than 1 m thickness of the Hampole Beds. The Limestones are porous, micro-cellular dolomites with reef formations in places. They become more dense and micro-crystalline towards the top. The Middle Permian Marl is a sequence, about 10–25 m thick at outcrop, of mudstones and siltstones, with gypsum beds, thickening eastwards (downdip) to about 50 m where up to 40 m of gypsum or anhydrite are present. The Upper Magnesian Limestone is a dense dolomite or dolomitic limestone about 10–20 m thick and which thickens eastwards. There are many cavities in the upper beds of the Lower Magnesian Limestone, sometimes filled with secondary crystals. The Upper Permian Marl is similar to the Middle Permian Marl, but there is a 6–10 m thick gypsum horizon in the lower half. Collapse brecciation is common from Doncaster north through Ripon to Catterick due to the dissolution of gypsum in the marls (Cooper, 1986, 1995). This may be exacerbated by abstraction if greater water flow increases the rate of dissolution (Cooper, 1988).

In the Ripon, Bedale and Sherburn in Elmet areas there is evidence of breccia pipes in the Upper Magnesian Limestone containing stratigraphically younger material (Smith, 1972; Cooper, 1986, 1988, 1995). These pipes locally connect the drift to the Magnesian Limestone aquifer and there is some evidence that pumping in the Ripon and Darlington area affect the water levels in the drift deposits. Regional water levels are shown in Figure 8.4.4.

The sequence dips eastwards with some minor folding. As a result of reactivation of Carboniferous faults several major faults trend WSW to ENE, with a secondary set trending WNW to ESE. The Permian Limestone sequence is overlain in the east by the Triassic sandstones. Superficial deposits cover the Triassic and much of the Upper Permian Marl. Most of the Permian outcrop in South Yorkshire is not covered by superficial deposits, but in North Yorkshire north of Wetherby the drift is thick over most of the Permian.

Data availability

The database contains transmissivity values from 35 locations and storage coefficient values from 5 locations in the Magnesian Limestone in this area. Transmissivity and storage coefficient data are fairly evenly spread over the area.

The core database contains 24 Upper Magnesian Limestone and 104 Lower Magnesian Limestone porosity and 27 Upper Magnesian Limestone and 102 Lower Magnesian Limestone hydraulic conductivity values, but the majority of these are from the Wistow borehole (see Section 8.4.4). The porosity and hydraulic conductivity data are relatively sparsely distributed.

Porosity and hydraulic conductivity

Porosity and hydraulic conductivity data from the Lower Magnesian Limestone (excluding the Wistow borehole) are shown in Figures 8.4.5 and 8.4.6 respectively. The porosity data approximate to a normal distribution in the range 9 to 30% with an interquartile range of 15.6% to 21.6%. The arithmetic mean is 18.5% and the median slightly lower at 18.3%. The hydraulic conductivity data from core samples do not conform to a standard distribution but have a range of 3.1×10^{-4} to 0.85 m/day with an interquartile range of 2.1×10^{-3} to 0.13 m/day. The geometric mean is 0.013 m/day and the median slightly higher at 0.015 m/day. The porosity–hydraulic conductivity cross-plot (Figure 8.4.7) does not show any trend. There are not enough samples (excluding the Wistow borehole) from the Upper Magnesian Limestone for analysis.

Transmissivity and storage

Transmissivity values in the database vary in the range 6 to 4300 m^2/day with an interquartile range of 66 to 885 m^2/day. The data distribution is negatively skewed (Figure 8.4.8). The geometric mean of all the location

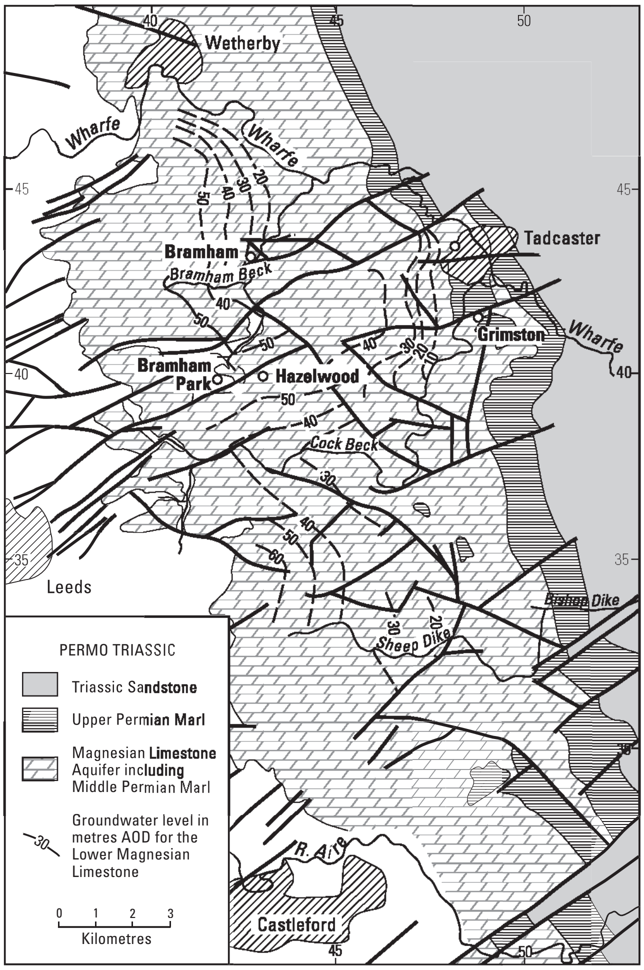


Figure 8.4.4 Regional water levels in the Yorkshire area (after Aldrick, 1978).

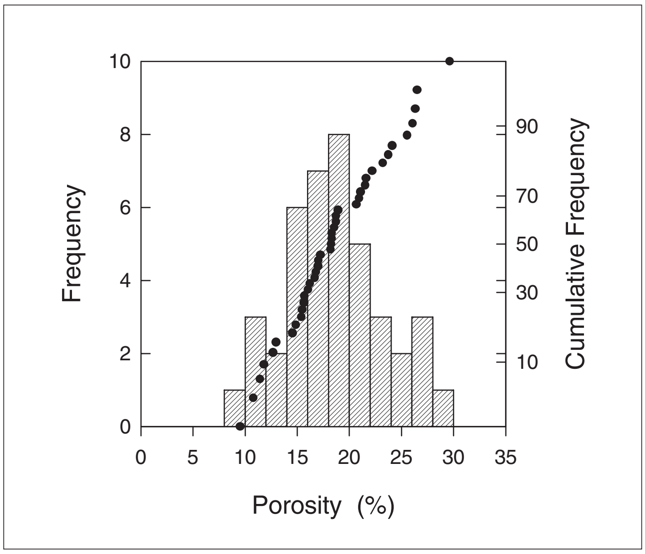


Figure 8.4.5 Distribution of porosity data for Lower Magnesian Limestone samples from the Yorkshire area.

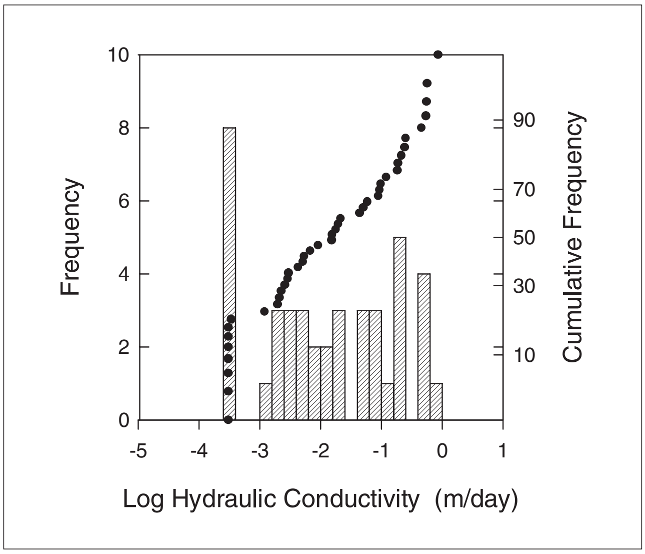


Figure 8.4.6 Distribution of hydraulic conductivity data for Lower Magnesian Limestone samples from the Yorkshire area.

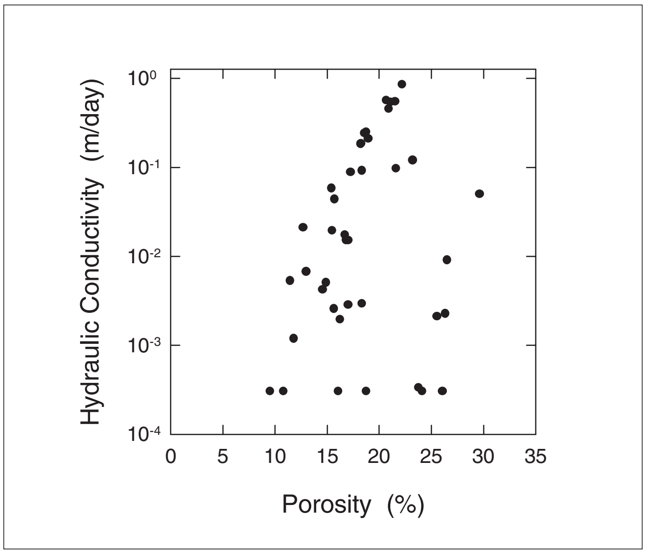


Figure 8.4.7 Plot of hydraulic conductivity against porosity for Lower Magnesian Limestone samples from the Yorkshire area.

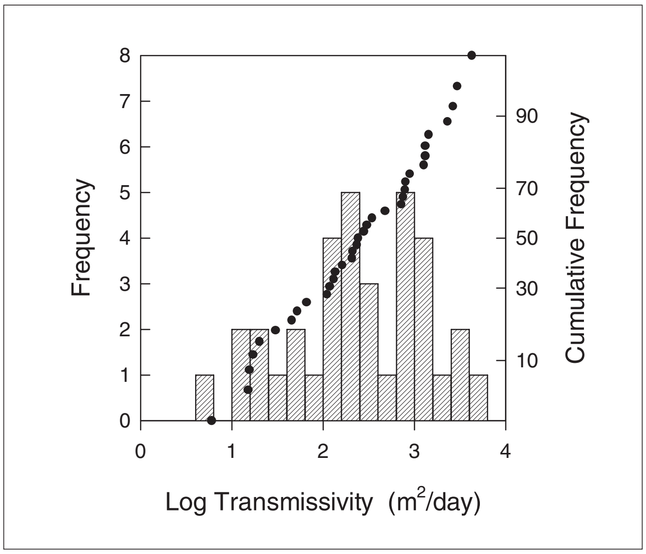


Figure 8.4.8 Distribution of transmissivity data from pumping tests in the Magnesian Limestones of the Yorkshire area.

values in the Yorkshire area is 233 m^2/day and a median of 240 m^2/day.

Storage coefficient values vary over several orders of magnitude from 3.4×10^{-6} to 4.0×10^{-3} with a median of 5.2×10^{-4}. There are not enough samples to allow comment on the distribution.

Some fractures allow the easy movement of groundwater along them and between the limestone horizons, other faults restrict groundwater movement and divide the aquifer into smaller units. There is restricted movement across the Bramham Park–Tadcaster and the Bramham–Hazelwood Faults. The groundwater movement is towards the main surface streams. Water levels in the confined Magnesian Limestone are frequently artesian by up to 2 m.

Borehole behaviour

Borehole yield is extremely variable. The majority of boreholes are small diameter for domestic and agricultural use, although there are some of 500 mm which can provide up to 290 m^3/h. Large boreholes for public supply, irrigation or industrial use tend to be acidised. Abstraction is more common from Harrogate northwards as the mains is not sufficient for all users.

The yield–drawdown characteristics of boreholes in the Magnesian Limestone fall into two main types: Low yield–high drawdown boreholes are situated away from fault zones, while high yield–low drawdown boreholes, such as those at Tadcaster, Grimston and Bramham (see Figure 8.4.4 for locations), lie on or adjacent to faults (Aldrick, 1975a). Further north at Norton and Sprotborough faulting of the limestones also increases the yields (YRA, 1973).

Pump tests carried out at Bramham indicated higher transmissivities at lower pump rates. Fracturing and dissolution have increased the permeability within the zone of water table fluctuation and as a result the top 4 m of the saturated aquifer is more weathered, and therefore more permeable. The yield–drawdown characteristics are due to the decrease in saturated thickness with increasing rates of abstraction and to the presence of a more permeable weathered zone at the top of the aquifer. The boreholes at Grimston show yield–drawdown characteristics similar to those of the Chalk, but the Bramham boreholes show a marked breakaway from these type curves, due to the presence of the weathered zone.

8.4.4 Wistow

Introduction

The Wistow borehole is constructed into the Magnesian Limestone sequence through over 100 m of drift and Triassic sandstone cover. Although not used for water supply this borehole gives an insight into the properties of this sequence of rocks at depth. It provides an interesting comparison with the aquifer at outcrop, illustrating the changes to the aquifer which occur downdip.

Geology

The geological succession at Wistow is as follows (Murphy 1986 after Aldrick 1975b):

	Thickness (m)	Depth (m)
Drift	22.12	22.12
Triassic sandstones	91.86	113.98
Upper Permian Marl	26.29	140.27
Upper Magnesian Limestone	24.63	164.90
Middle Permian Marl	34.10	199.00
Lower Magnesian Limestone	63.00	262.00
Basal Permian Sands	2.00	264.00
Coal Measures	4.50	268.50

Data availability

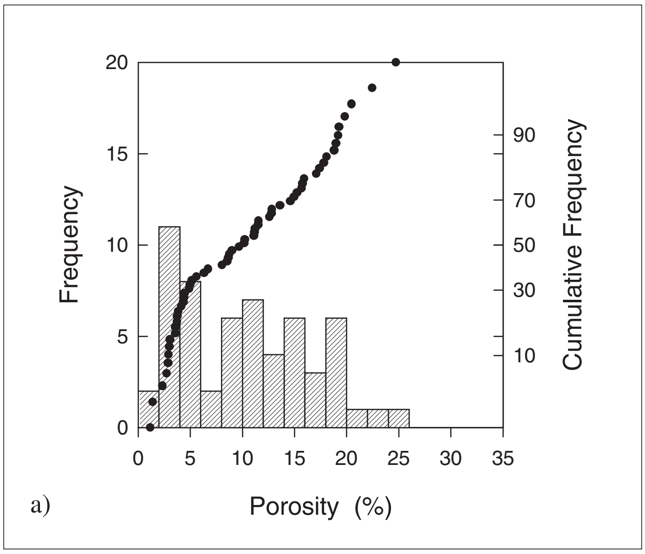
Porosity and Permeability results are available from 84 core samples from this borehole. The borehole was pump tested in 1975 and the results analysed by Aldrick (1975b) and Murphy (1986).

Porosity and permeability (laboratory)

Porosity data from core samples from the Wistow borehole (22 samples from the Upper Magnesian Limestone and 62 samples from the Lower Magnesian Limestone) show two distinct datasets. The range of porosity values is similar for each Limestone but the values are generally lower in the Lower Magnesian Limestone than in the Upper (Figure 8.4.9). The porosity in the Lower Magnesian Limestone range from 1 to 25% with an interquartile range of 4.3% to 15.7%, in the Upper Magnesian Limestone they range from 6 to 30% with an interquartile range of 9.4% to 16.0%. The porosity distributions show that the data from the Lower Magnesian Limestone is positively skewed while the Upper Magnesian Limestone appears to contain two suites of samples, there being no porosities in the range 13 to 21%. (Figure 8.4.10a and 8.4.10b) The arithmetic mean of the porosity for the Upper Magnesian Limestone is 16.7% and for the Lower Magnesian Limestone is 10.3%. The median value of porosity in the Upper Magnesian Limestone is 12.0% and for the Lower Magnesian Limestone is 9.9% In comparison the porosities in the Lower Magnesian Limestone at outcrop in Yorkshire are generally higher than those at depth.

The hydraulic conductivity values do not show any trends with depth (Figure 8.4.11), although there appears to be a restricted range of permeability at a depth of 200–220 m below ground level. Hydraulic conductivity values range from 1.9×10^{-6} to 0.10 m/day in both the Upper Magnesian Limestone and in the Lower Magnesian Limestone. The interquartile range in the Upper Magnesian Limestone is 4.9×10^{-5} to 7.2×10^{-3} m/day and for the Lower Magnesian Limestone is 1.4×10^{-4} to 2.2×10^{-3} m/day. The geometric mean of the hydraulic conductivity values for the Upper Magnesian Limestone is 3.9×10^{-4} m/day and for the Lower Magnesian Limestone is 4.8×10^{-4} m/day. The median value of the hydraulic conductivity values for both the Upper and Lower Magnesian limestones is 4.8×10^{-4} m/day. The hydraulic conductivity distributions approximate to lognormal distributions in both the Upper and Lower Magnesian limestones (Figures 8.4.12a and 8.4.12b). The range of hydraulic conductivities in the Lower Magnesian Limestone at outcrop are generally higher.

Figure 8.4.13 shows that there is a trend of increasing hydraulic conductivity with increasing porosity as seen at outcrop although the data are quite scattered.



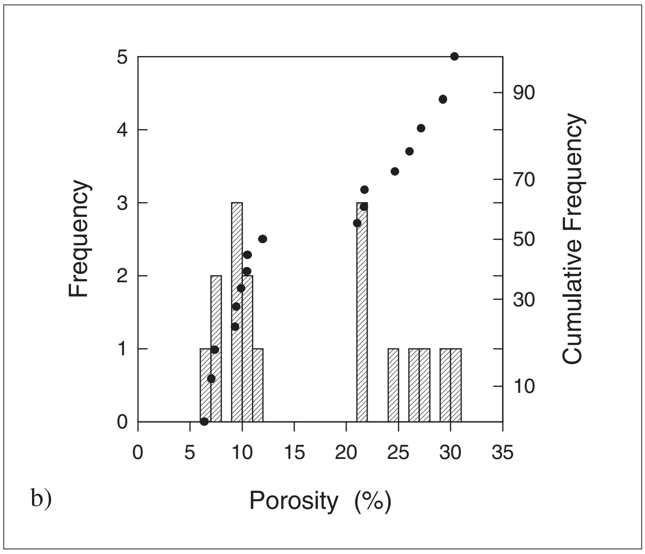


Figure 8.4.10 Distribution of porosity data for samples from the Wistow borehole, a) Lower Magnesian Limestone, b) Upper Magnesian Limestone.

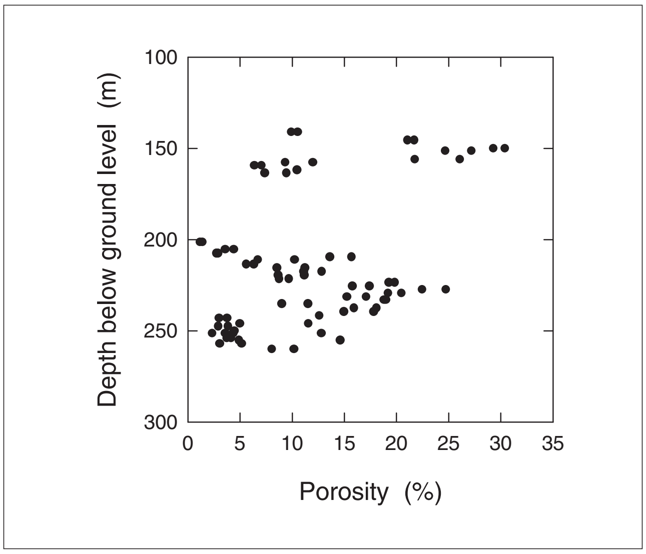


Figure 8.4.9 Variation in porosity with depth at the Wistow borehole.

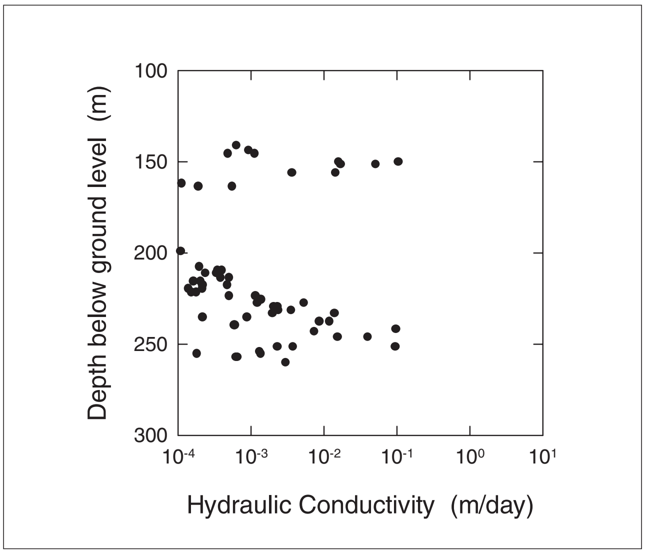


Figure 8.4.11 Variation in hydraulic conductivity with depth at the Wistow borehole.

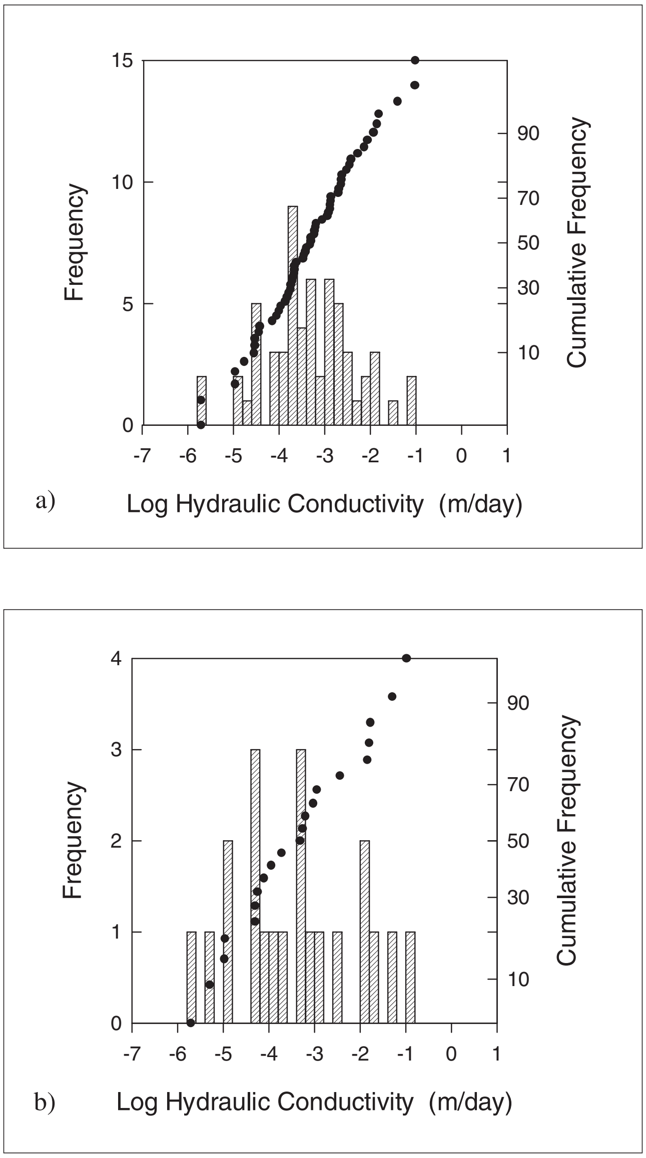


Figure 8.4.12 Distribution of hydraulic conductivity data for samples from the Wistow borehole, a) Lower Magnesian Limestone, b) Upper Magnesian Limestone.

Transmissivity and storage

The results of the test pumping of the Wistow Mine Borehole gave a transmissivity of 24.3 m^2/day and a confined storage coefficient of 1×10^{-5}. This is higher than other shafts nearby (Murphy, 1986):

Milford Hagg	T = 5 m^2/day	S = 7×10^{-6}
Stillingfleet	T = 0.4 m^2/day	S = 8×10^{-6}
Ricall	T = 1.3 m^2/day	S = 6×10^{-6}

Stillingfleet and Ricall showed a marked reduction in transmissivity in the lower 20 m of the Magnesian Limestone. The higher transmissivity at Wistow is thought to be due to the especially vuggy nature of the Magnesian Limestone in this area. The transmissivities at outcrop are generally much higher than the values here at depth.

The hydraulic connectivity of the aquifer is extensive. Water levels at the outcrop some 10 km distant were effected by an inrush to the Wistow mine from the Magnesian Limestone.

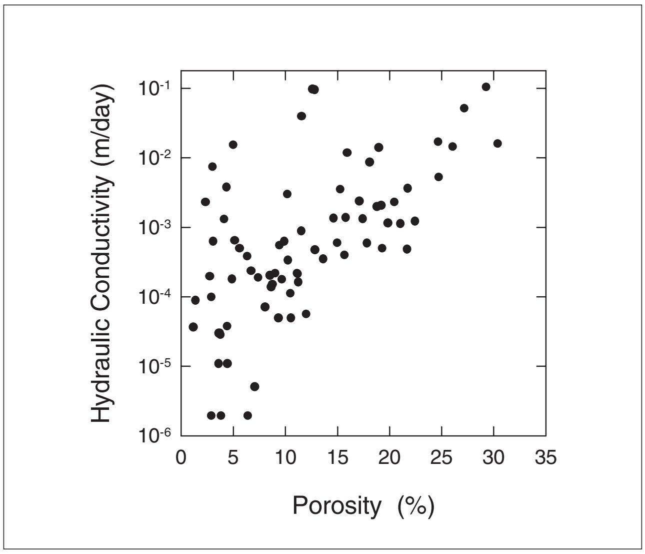


Figure 8.4.13 Plot of hydraulic conductivity against porosity for Magnesian Limestone samples from the Wistow borehole.

8.5 SUMMARY

The Magnesian Limestone aquifer is extremely unpredictable exhibiting large ranges of transmissivity values from 6 to 4300 m^2/day. The hydrogeology of the aquifer is controlled by the lithology and the structure, particularly the extent of fracturing. Transmissivities tend to be highest along major fault zones.

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9 The Carboniferous Limestone

9.1 GENERAL GEOLOGY AND HYDROGEOLOGY

9.1.1 General geology

The Carboniferous Limestone aquifer is of early Carboniferous (Dinantian) age. Dinantian outcrops cover approximately 12 per cent of the land area of England and Wales and involve a wide variety of rock types, including mudstones, siltstones and sandstones in addition to the limestones (Leeder, 1992). The massive, well-fractured limestones generally associated with the Carboniferous Limestone aquifer are well developed in the Peak District of Derbyshire, the Mendip Hills, North and South Wales, and north-west Yorkshire. In the Craven district of Yorkshire a predominantly shale sequence is found; further north, in Northumberland, the succession is more arenaceous but includes thin shales and thin limestones.

9.1.2 General hydrogeology

Where it is a major aquifer, the Carboniferous Limestone in England and Wales is commonly considered to exhibit 'karstic' hydrogeological behaviour. The term 'karst' is not precisely defined but is associated with terrain which has distinctive landforms and hydrology by virtue of a combination of high rock solubility and well-developed secondary (fracture) porosity. Typical karst features are sinking streams, caves, enclosed depressions, fluted rock outcrops and springs (sometimes with large flows), as exemplified by the Karst district on the border between Italy and the former Yugoslavia.

In hydrogeological terms the main attribute of karstic aquifers is that groundwater — recharged either from sinking streams or by diffuse infiltration — is to a significant extent concentrated in, and flows rapidly through, a network of fractures, conduits and caves which have been enlarged by solution. Flow tends to be directed to discrete discharge areas in the form of single springs, or spring groups. It is axiomatic that for such a karstic hydrogeological system to be developed there must be a rock which is sufficiently soluble, sufficient recharge occurring over a suitable time period for conduits to be produced, and sufficient topographic variation for adequate head gradients to be imposed on the aquifer. It also follows that karstic systems are dynamic, with solution (and reprecipitation) processes affected by a variety of controls such as head gradient, temperature, and water chemistry.

Controls on aquifer properties

The matrix of the Carboniferous Limestone has very low values of porosity and permeability. Drew (1968) obtained a porosity value of 0.18%, and Gunn (1992) suggested intergranular hydraulic conductivity values in the range 0.001–0.01 m/d. Recent work on Carboniferous Limestone core from north-east England indicates porosity values of 0.2% to 5.9% (median 1.2%) and a median hydraulic conductivity value of 3×10^{-6} m/d (Nirex, 1993). Such values are unlikely to contribute to the water-bearing properties of the aquifer.

The Carboniferous Limestone is therefore an aquifer almost entirely by virtue of the secondary network of solution-enlarged fractures (commonly termed conduits). These conduits often form complex branching systems ranging in scale from microfractures to extensive cave systems (the Carboniferous Limestone aquifer of England and Wales has over 500 km of accessible cave Passages (Hardwick and Gunn, 1989).

The general factors which influence the development of the conduits in Karst are discussed by Ford and Williams (1989). They state that the most extensive development of conduits occurs in fine-grained limestones with low primary porosity, and suggest that mineralogy is important, with clay contents of greater than 20 or 30% inhibiting conduit development. They also suggest that limestones that are interbedded with other, non-calcareous, sediments tend to have a restricted development of small, independent and poorly connected solution conduits. It is also thought that oxidation of pyrite may produce incipient conduits, which may be enlarged later by circulating groundwater (Gunn, 1992).

Ford (1968) studied the development of cave systems in the Mendips and noted that horizons exploited by solution almost always had some distinguishing feature, for example thin shale or mineral filling to account for their preferential selection. This is discussed further in Section 9.2 with regard to 'phreatic looping'.

Tectonic effects on the rock mass also strongly affect groundwater circulation, and hence dissolution and rock aquifer properties. As with other aquifers, tectonic fractures may act as high or low permeability zones. Joints are likely to enhance rock permeability as they simply pull apart. Where there is lateral displacement (i.e. faulting), the change in permeability is difficult to predict because the result depends on factors such as the presence, amount and permeability of fault gouge, and whether the fault provides a connection between groundwater bodies. It may be that tensional faults (e.g. normal faults) are on the whole more permeable than compressional features (e.g. reverse faults), but there is no direct evidence for this. Both joints, faults and incipient bedding plane partings may therefore provide a route for water flow and thus the basis for rock dissolution and further enlargement of the fracture.

It is likely that folding also influences groundwater flow and therefore conduit development in karst systems. The fold stresses cause the development of joints and faults which may be zones of enhanced permeability.

An important aspect of karst systems is that they are dynamic, with conduit networks continuously changing. Processes such as spring capture, linking of previously separate systems (with associated reorientation of head gradient), and abandonment of old conduits probably occur to varying degrees, and it has been suggested (Ewers, 1982) that the systems tend to evolve towards a simplified network of a few main routes. In general, karst systems will tend to evolve downwards. Karst that is thus abandoned by the development of lower conduit networks is termed relict karst and karst which is decoupled from active flow by burial is termed palaeokarst.

Flow in the Carboniferous Limestone

Where it is a major aquifer flow in the Carboniferous Limestone is almost entirely along solution-enlarged fractures, and the velocity of flow will depend on the prevailing hydraulic gradient and size of the fractures. Flow velocities in the saturated zone (and in conduits containing water in the unsaturated zone) can be very rapid, of the order of hundreds of metres per hour (as shown by tracer experiments), but this depends on the presence of large interconnected conduit systems, and in regions without such systems velocities will be much slower.

The direction of flow may also be difficult to predict in the Carboniferous Limestone aquifer. The generally anisotropic nature of the aquifer means that flow may not be perpendicular to lines of equipotential, and there is the added complication that such equipotentials may themselves be difficult or impossible to ascribe in the more karstic areas of the aquifer where conduit systems may appear to act independently.

Problems of aquifer properties characterisation in the Carboniferous Limestone

There are two main problems in characterising the aquifer properties of the Carboniferous Limestone aquifer; the aquifer is unpredictable at the scale of hydrogeological interest, and there is little hydrogeological information.

At the matrix scale, the properties of the aquifer, although poorly known, are likely to have an insignificant effect on flow and storage in the aquifer. On the scale of metres to hundreds of metres or kilometres the aquifer is dominated by the conduit systems and aquifer properties may be extremely unpredictable, particularly in the more karstic areas. Boreholes will be productive, possibly with very high yields, if they intersect conduits and non-productive if they fail to do so. Pumping tests on boreholes may be analysed to provide values of transmissivity and storage coefficient, but the theoretical requirements required by the analysis may well be violated to the extent of making the results meaningless (for example if the borehole happens to penetrate a single large conduit). Packer tests may provide meaningful data on single fractures, but the information is strictly only pertinent to the immediate vicinity of the borehole.

As the scale of interest increases a point will be reached where the aquifer can be considered as a predictable system (in that it will behave predictably when stressed hydraulically). It may be that in some areas large-scale operations such as quarry dewatering could be used to obtain regional average aquifer properties. However such information is not at present available, and if it were it would naturally only be of use for large-scale models.

The unpredictability of the aquifer has meant that water use from the aquifer has been mainly from springs; boreholes are relatively rare, and aquifer properties data from borehole measurements are very rare.

Given the problem of aquifer complexity, compounded by the lack of data, it is pertinent to consider whether presenting hydrogeological aquifer properties data for the Carboniferous Limestone serves any purpose. In terms of the remit of this report, which is to present and comment on such information as does exist, the collation and presentation of the information is justified. However this does imply any endorsement as to the use of the data, and in fact the paucity of the information actually serves to highlight the difficulties of attempting to characterise the Carboniferous Limestone in terms of traditional hydrogeological terminology.

A further problem, of particular importance to pollutant transport studies in the Carboniferous Limestone is that standard aquifer properties data can only provide information on the behaviour of the rock mass as a whole; they can neither delineate actual flow paths nor give specific information concerning the form and distribution of the individual conduits. Flow paths in karstic aquifers can only be determined by using tracer techniques; conduit morphology can only be identified if the features are big enough to be explored directly, although to a very limited extent techniques such as borehole logging, geological evidence or spring hydrograph analysis may be used to obtain some insight into the types of fractures contributing to groundwater movement.

In view of the above problems, and because the Carboniferous Limestone aquifer is not considered to be a major aquifer except in the Mendips, South Wales and the Peak District, this chapter has been restricted to consideration of these areas only.

9.2 THE MENDIPS

Of all the British outcrops of Carboniferous Limestone, the hydrogeology of the Mendips has been the most extensively studied. In view of this, and the fact that its karstic behaviour is typical of the aquifer, this area is dealt with in the most detail.

9.2.1 Physiography and geology

The Mendips are a range of low hills aligned approximately east–west, extending over a distance of around 50 km, from Weston-super-Mare in the west to Frome in the east and with a maximum width of 10 km. The main Carboniferous Limestone outcrop lies between the Cheddar region and Frome (Figure 9.2.1). The Mendips comprise smooth rounded hills with several low summits ranging in altitude up to 325 m above sea level (Blackdown), with a surrounding plateau at around 260 m.

Structurally the Mendip hills consist of a series of en echelon periclines, aligned approximately east–west, which were produced by northerly directed compression at the end of the Carboniferous Period. The cores of the periclines comprise Silurian volcanics, shales and siltstones and Devonian shales, sandstones and conglomerates (Figure 9.2.1). These rocks form smooth summits which rise above the main plateau. They are flanked north and south by Carboniferous Lower Limestone Shale and in turn by the Carboniferous Limestone. The limestones and shales on the northern flanks of the hills are more steeply dipping than those to the south, and are overturned in places (Harrison, Buckley and Marks, 1992).

The Dinantian succession in the Mendips at Cheddar (Harrison, Buckley and Marks, 1992) is as follows (thickness in brackets):

Hotwells Limestone (32 m)
Clifton Down Limestone (150 m)
Burrington Oolite (210 m)
Black Rock Limestone (270 m)
Lower Limestone Shale (150 m)

The Carboniferous Limestone aquifer principally comprises thinly bedded to massive limestones of the Black Rock Limestone, Burrington Oolite, Clifton Down Limestone and Hotwells Limestone, and is underlain by the interbedded shales and thin limestones of the Lower Limestone Shale.

The Upper Carboniferous Quartzitic Sandstone Group and Coal Measures overlie the Carboniferous Limestone

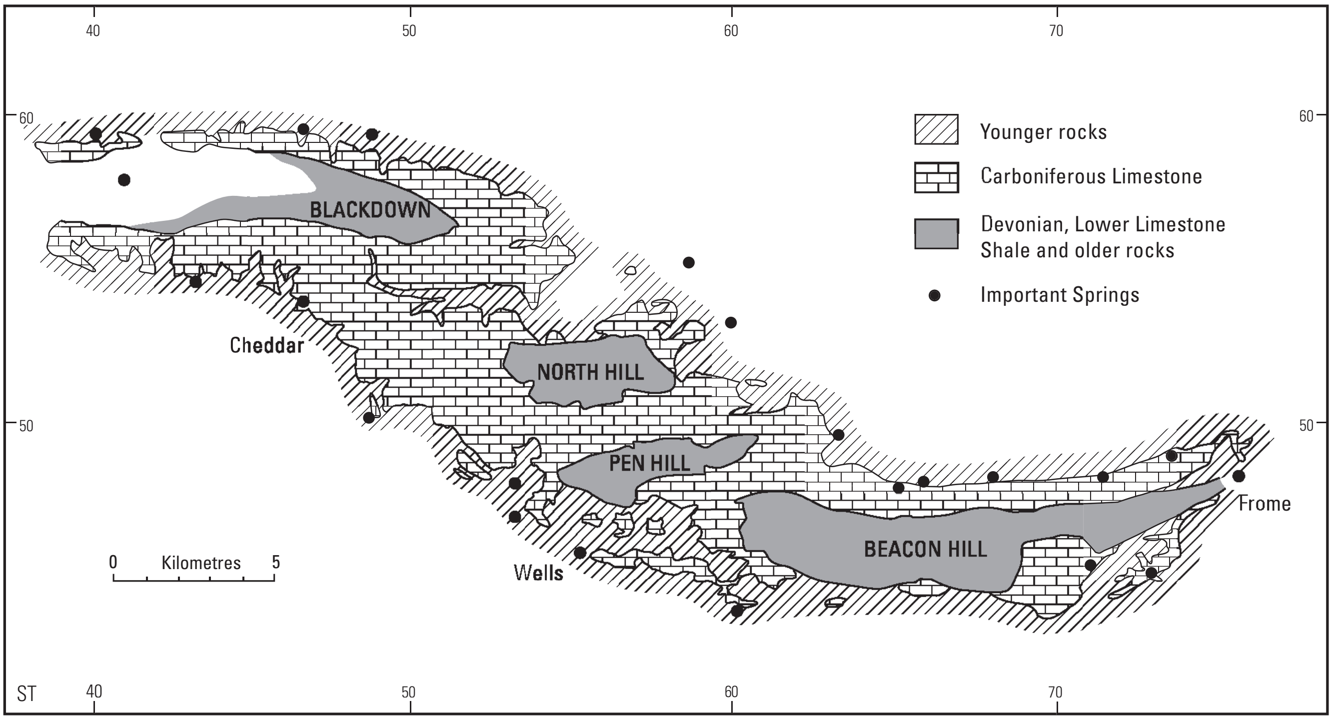

Figure 9.2.1 Simplified geological map of the central and eastern Mendips (after Barrington and Stanton, 1977).

but have a limited outcrop in the Mendips. These are in turn unconformably overlain by the Triassic Dolomitic Conglomerate followed (in the east) by Jurassic limestones.

9.2.2 Hydrogeology

Previous studies

Much of the hydrological and hydrogeological research into the Carboniferous Limestone aquifer of the Mendips has been undertaken by Bristol University. This has included pioneering work in water tracing to define groundwater catchments and to demonstrate connections between swallets and springs (e.g. Atkinson, 1970; Atkinson et al., 1973). There have also been several studies examining the partitioning of rainfall recharge in the limestones, and in particular the role of the unsaturated subcutaneous zone (the zone of intense chemical weathering normally within the upper 10 m of the limestone) has been recognised as important in the storage of infiltrating waters (Friederich, 1981).

The Mendips provide an important source of limestone, and several studies have been undertaken to investigate the possible effects of quarrying on local groundwater movement. These studies have been mainly associated with quarries in the eastern Mendips, where the effects of quarry deepening have been investigated.

A particularly useful study of the Mendips from the point of view of aquifer properties information was that of Hobbs (1988).

Mendip hydrogeology

The Carboniferous Limestone is the most important aquifer in the Mendips area, providing significant groundwater supplies from major springs. The Mendip hills lie in an area of high rainfall, but most of the drainage of the hills is underground. Streams which rise on the (mainly) Devonian cores of the anticlines flow over the Carboniferous Lower Limestone Shales and recharge the Limestone via swallets. These waters, and recharge from precipitation directly onto the limestone travel to discharge areas in the form of springs at the periphery of the hills (Figure 9.2.1). Atkinson (1977) identified 15 major and 36 minor springs, mainly occurring where the Carboniferous Limestone dips beneath Triassic mudstones around the hills. On the southern side of the Mendips major springs occur at Cheddar, Wookey hole and St Andrews Well at Wells (Figure 9.1). North of the watershed the limestone outcrop occupies a much smaller area and there are no comparable large springs, although Banwell, Langford and Rickford springs in the west and central area are important.

Figures 9.2.2a and 9.2.2.b show general conceptual models of the physical framework of the conduit systems in the Carboniferous Limestone in the Mendips and the hydrogeological system. The limestone plateau is characterised by a large number of closed depressions which focus internal drainage underground, and by a network of dry valleys which are active only after storms and which lead to the heads of marginal gorges, e.g. Cheddar Gorge, Burrington Combe. Diffuse recharge into the limestone plateau will largely move towards the discharging springs, possibly via the conduits that act as trunk drains (Figures 9.2.2a, 9.2.2b).

In the Mendips the influence of both bedding and tectonic structure can be seen in the form of the conduit network (Figure 9.2.2a). Ford (1968) noted that the relatively steep dip of the bedding caused a phenomenon which he described as 'phreatic looping' in which conduits developed steeply down dip, then cut along joints to descend again along another bed. Ford noted that the amplitude of the looping decreased with depth and suggested that this was associated with lowering of the water table.

The depth of conduit formation (and therefore essentially the depth of the base of the aquifer) is not well known in the Mendips. Atkinson (1977) reported that the amplitude of phreatic looping was 30 m at Wookey Hole, and cave divers have examined passages to around 40–50 m below the present water table (Harrison, Buckley and Marks,

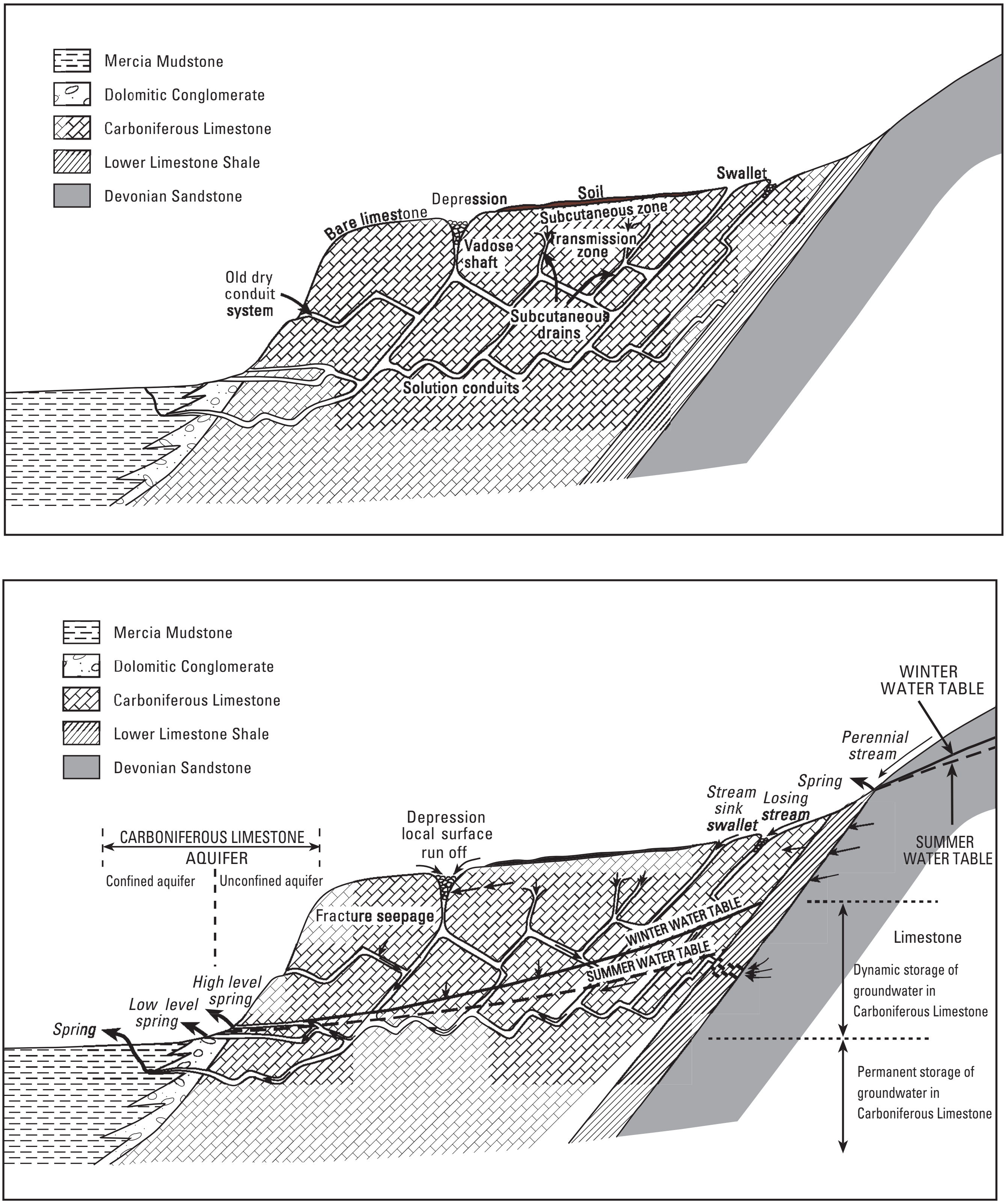

Figure 9.2.2 A conceptual model of Mendip limestone hydrogeology, a) physical framework, b) flow systems (after Harrison, Buckley and Marks, 1992).

1992). Drilling in quarries in the Mendips has apparently shown voids to exist at greater depths, but whether they form part of the drainage network is unknown (Harrison, Buckley and Marks, 1992).

The regional variation in conduit development (and therefore, by implication the regional variation in aquifer properties) in the Carboniferous Limestone of the Mendips can only be assessed in broad terms. Hobbs (1988) noted that, on the basis of surface features such as closed depressions, sinkholes and vadose shafts, the central area of the Mendips is likely to have the best-developed conduit network. This is also supported by the peaky hydrograph of the Cheddar Spring, indicating rapid flow in well-developed conduits (Figure 9.2.2b). Hobbs suggested that landscape immaturity in the east, and steeper slopes in the west have inhibited karstic development, although conduits are found throughout the Mendips.

Many water tracing experiments have been undertaken in the Mendips, and by 1980 around 90 connections between streams and springs had been proven (Stanton and Smart, 1981). Water tracing has established conduit connections over distances in excess of 10 km (in a straight line —actual flow paths would be longer than this) and flow velocities up to 21 km/d. Figure 9.2.3 shows connections established by tracing, and allows groundwater catchments to be delineated — which do not accord with surface catchments.

Water supply

Large quantities of water are discharged from the springs (known locally as risings) at the foot of the Mendips, and significant quantities are used for public water supplies. Examples of spring flows are Cheddar (6.8×10^4 m^3/d), Rickford (1.1×10^4 m^3/d), and Wookey Hole (1×10^5 m^3/d) (Green and Welch, 1965). In contrast to the large supplies obtainable from springs however, well and borehole yields are generally small because of the infrequency of large water-bearing fractures in the limestone, and yields in excess of around 10 m^3/d are exceptional (Green and Welch, 1965). It might be expected that converging flowlines in valley bottoms, and particularly near to springs might increase the chances of locating productive fractures at reasonable depths, but even here hydrogeological conditions can vary appreciably, and unpredictably. For example Green and Welch (1965) give instances of two boreholes at approximately the same elevation drilled some 370 m apart in the Shipham Gorge Valley which had to be drilled to 153 m and 55 m respectively before water was struck. The rest water levels were markedly different (28 m below ground level and 19 m below ground level), and the boreholes had substantially different specific capacities; 25 m^3/d/m and >350 m^3/d/m.

9.2.3 Aquifer properties

Aquifer properties of the Beacon Hill Pericline

The aquifer properties of the most eastern pericline in the Mendips, Beacon Hill, were investigated in some detail by Hobbs (1988). The investigation was made possible by the significant number of boreholes in the area, drilled mainly in order to monitor and predict the effects of sub-water-table quarrying. The results of the study are considered below in some detail, as they form a rare study of Carboniferous Limestone aquifer properties.

The Beacon Hill pericline comprises a core of Silurian volcanics, Devonian sandstone and Lower Limestone Shale, overlain by Carboniferous Limestone which dips at 70–80° to the north and 30–40° to the south. The Carboniferous Limestone dips under the Coal Measures to the north, and is overlain by the Jurassic Inferior Oolite aquifer to the east and south. The area is more faulted and has lower relief than areas further west in the Mendips.

Slug tests

Slug Bailer tests were carried out on 30 boreholes in the Beacon Hill Carboniferous Limestone (Hobbs, 1988). The average hydraulic conductivity values obtained from each site varied between 0.00074 m/d and 110 m/d, with an arithmetic mean of 8.5 m/d and a geometric mean of 0.3 m/d. The data were approximately log-normally distributed. There is limited evidence that the values from the northern limb of the pericline tend to be lower than those from the south. If this difference is real, then it might suggest that bedding planes are the main control on permeability development, since fewer would be intersected by boreholes in the more steeply dipping northern limb (Hobbs, 1988).

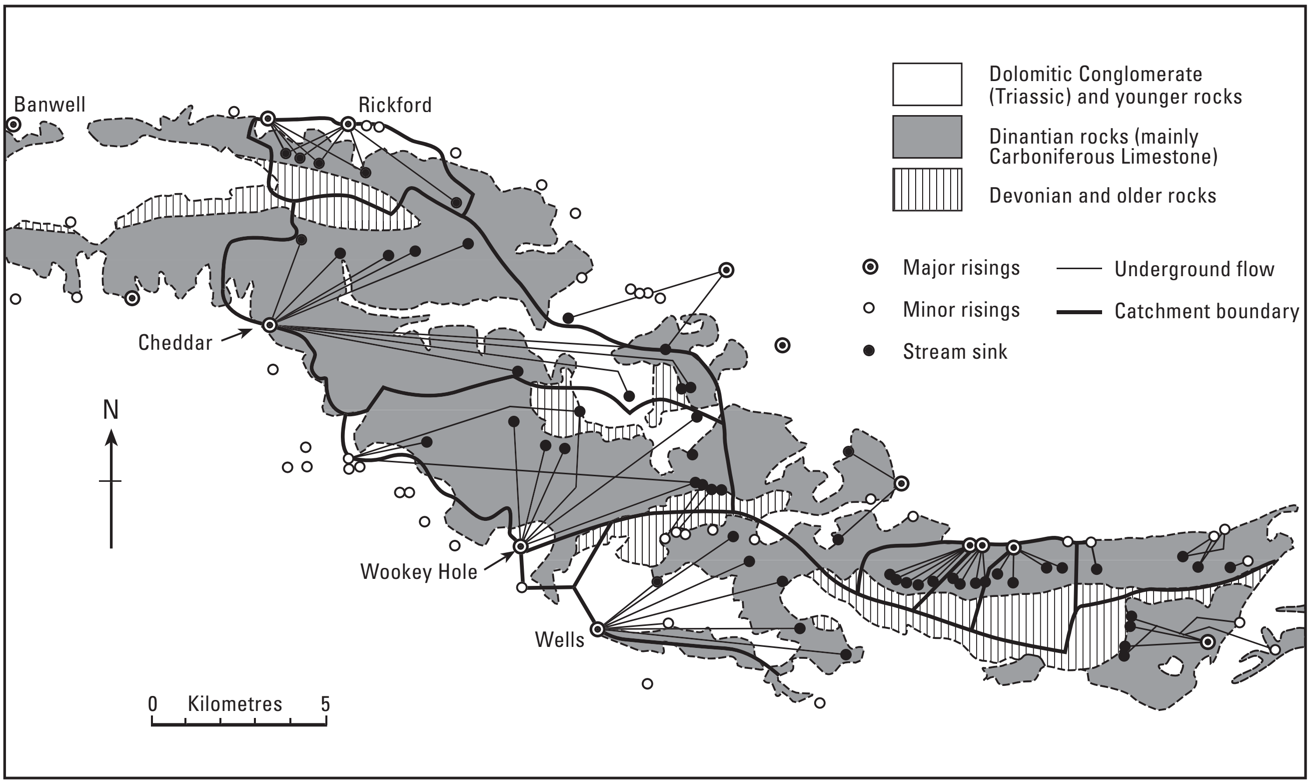

Figure 9.2.3 Groundwater connections established by tracers in the Mendips (after Gunn, 1986).

Pumping tests

Hobbs (1988) reported on pumping test data (made available by Foster Yeoman Ltd) for a site at Tunscombe, on the south side of the pericline. Hydraulic conductivity values obtained after five days of pumping are shown below, along with slug test results on the same boreholes.

An aquifer thickness of 50 m was assumed. The average storage coefficient of the aquifer from the pumping test was calculated to be 4×10^{-3}.

The cone of depression of the pumping test was calculated to extend for 1200 m, while that of the slug tests was considered to be of the order of 10 m (for homogeneous conditions).

Table 9.2.1 Hydraulic conductivity data for Tunscombe.

Borehole	Transmissivity (m^2/d)	Pump test hydraulic conductivity (m/d)	Slug test hydraulic conductivity (m/d)
Tunscombe ABH	433	8.7	34
Tunscombe OBH1	470	9.4	15
Tunscombe OBH2	410	8.2	109

Packer tests

Packer tests were carried out at a site in the southern limb of the Beacon Hill pericline by BGS (Bird and Allen, 1989). The results suggested that a 35 m section of borehole had a total transmissivity exceeding 1250 m^2/d, of which 99.8% could be attributed to three major fractures, one of which had a transmissivity of the order of 900 m^2/d (its hydraulic conductivity would be at least ten times this value). Essentially unfractured material was found to have hydraulic conductivity values of the order of 0.01 m/d. All major fractures detected on a calliper log showed large permeabilities, however some minor enlarged zones showed low permeabilities and were thus considered to be separate from the fracture network. The tests were carried out by injection in the unsaturated zone; however similar heterogeneities are known to occur in the saturated zone.

Borehole water level analysis

Analysis of borehole water level responses to storm events were used by Hobbs (1988) to estimate the specific yield of the aquifer around the borehole (the analysis involved measurements or estimates of precipitation, evapotranspiration, change in soil moisture deficit and water level). The results, from 17 boreholes, showed a range from 0.006 to 0.038, with a mean of 0.02. The values from the north side of the pericline had a mean of 0.025 (standard deviation 0.007), while those from the south were lower, with a mean of 0.013 (standard deviation 0.005).

Catchment analysis

Water levels and discharge for a catchment on the south side of the pericline were used by Hobbs (1988) to calculate catchment specific yield. A value of 0.009 was obtained, slightly lower than that obtained by borehole analysis, but not dissimilar. A value of transmissivity for the catchment was also calculated, using aquifer discharge, aquifer geometry and hydraulic gradient. The method produced a value of 475 m^2/d, a value similar to that obtained from the Tunscombe pumping test.

Modelling

A finite difference model was used by Hobbs (1988) to examine the effects of varying transmissivity on water levels. Hobbs found that transmissivities used in the model could be varied without significantly affecting the results, provided that certain regional controls such as low transmissivity areas (caused by clay-filled fractures) were used.

Discussion

The results of the extensive aquifer properties testing undertaken by Hobbs on the Carboniferous Limestone in the in the Beacon Hill pericline area lead to the following conclusions:

i) The Carboniferous Limestone aquifer at Beacon Hill is highly heterogeneous, with permeability data depending on the scale of measurement. At the matrix scale, hydraulic conductivities of the order of 10^{-3} to 10^{-2} m/d have been determined from packer tests. Packer tests have also shown highly transmissive (up to nearly 10^3 m^2/d) individual fractures at the metre scale. Single borehole tests (which probably sample at a scale of up to a few tens of metres) show hydraulic conductivity values varying between matrix values and around 100 m/d (i.e. over five orders of magnitude). A pumping test, thought to sample a region of the order of 10^3 m, gave a hydraulic conductivity of approximately 10 m/d, and this agreed well with the value obtained by catchment analysis. These data would therefore suggest that matrix permeability values are very low, values up to a scale of at least tens of metres are very unpredictable, while at larger scales the aquifer may behave in a more uniform way. However the evidence for this observation is very slender (being based on one pumping test) and must be taken as tentative. It should also be pointed out that whatever predictability in aquifer properties that may be ascribed to the Beacon Hill pericline is unlikely to hold true in the more karstified aquifer to the west.

ii) The storage characteristics of the aquifer varied with the method used. The pumping test gave a value of 0.004, whereas near-borehole water level variations suggested values of 0.013 in the same, southern part of the pericline, and catchment analysis showed a value of 0.009. The values may be similar enough to be covered by errors in the technique, but it may be significant that pumping test storage coefficients in another fractured aquifer — the Chalk — often are lower than those derived from drainage analysis, possibly because of delayed drainage. The matrix porosity of the Carboniferous Limestone was estimated by Drew (1968) to be 0.0018, and pore sizes are likely to be very small. It is therefore unlikely that the matrix plays a significant role in storage.

The only other publicly available estimates of aquifer properties in the Mendips are given by Atkinson (1977) who undertook a detailed investigation of the Cheddar Spring. From recession data Atkinson estimated the transmissivity of the aquifer to be 2678 m^2/d (not including conduit contributions), and the storage coefficient to be 0.0092. Assuming an aquifer thickness of 30 m Atkinson derived an estimated hydraulic conductivity of 89 m/d.

9.3 SOUTH WALES

9.3.1 Geological setting

In South Wales the Carboniferous Limestone is preserved in the South Wales Coalfield Syncline — the major east–west fold which dominates the solid geology of much of South Wales. This structure, which includes several en echelon periclinal flexures, extends for around 140 km between Milford Haven in the west and Pontypool in the east (Lowe, 1989). The structure is asymmetrical, with shallower dips in the northern limb, and to the east the syncline develops a markedly westward plunge, as a result of the north–south Usk Anticline to the east (Welsh Water Authority, 1980). The Carboniferous Limestone (also known as the Main Limestone) crops out around the rim of the major syncline (the North Crop and the South Crop) and in subparallel periclinal folds in Pembroke and Gower (Figure 9.3.1). There are further outcrops on the Welsh borders, in the Chepstow/Monmouth area and in the Forest of Dean.

In general the stratigraphy of the area is similar to that of the Mendips, with Devonian sandstones passing up through Lower Limestone Shales to the Main Limestone (nomenclature of Lowe, 1989). This is overlain by Upper Limestone Shales and these in turn by Millstone Grit strata. Locally the geology is much more complex than this, and the Dinantian sequence is only complete in south Pembrokeshire.

The Lower Limestone Shales broadly consist of alternations of calcareous mudstone and thin limestone beds (sometimes impure). The Main Limestone comprises a collection of predominantly pure limestone units, with in some areas a number of mudstone and sandstone horizons of limited extent. The Upper Limestone Shales are not present everywhere around the South Wales outcrop, but where they do exist they represent the return to the lithology of the Lower Limestone Shales.

In the North Crop the whole Dinantian sequence is generally less than 200 m thick, of which only 100–150 m are limestones. The North Crop runs in a broad arc with a width of less than 5 km — and generally less than 1.5 km —from Kidwelly to Abergavenny (a distance of 110 km), with a short westerly extension to the west of Pendine, and with a southerly dip of 5–10°. The area lies at altitudes generally between 300 and 500 m above sea level, in a series of broken cuestas.

The limestones of the South Crop are exposed in southern Pembrokeshire, Gower and the Vale of Glamorgan. They are strongly folded in these areas, with Devonian sandstone outcropping in the anticlinal cores and Millstone Grit preserved in synclines. The sequence is thicker than in the North Crop (>1000 m, on Gower) and the dip is steeper (Crowther, 1989).

9.3.2 Previous studies

The north-east part of the South Wales Coal Basin was the subject of hydrogeological investigations in the late 1970s and early 1980s by Howard Humphreys and Partners for the Welsh Water Authority (Welsh Water Authority, 1979; 1980; 1982). A hydrological study of the caves and springs of the North Crop was undertaken by Gascoine (1989). A hydrogeological study of the Vale of Glamorgan was undertaken recently by Aspinwall and Company for the Welsh Region of the NRA (NRA, 1993). The hydrogeology of south Pembrokeshire was investigated by Howard Humphreys for the Welsh Water Authority (Welsh Water Authority, 1978).

9.3.3 North Crop

The Carboniferous Limestones in South Wales have the most karstic development in the North Crop, characterised by rocky outcrops, underground drainage and a variety of

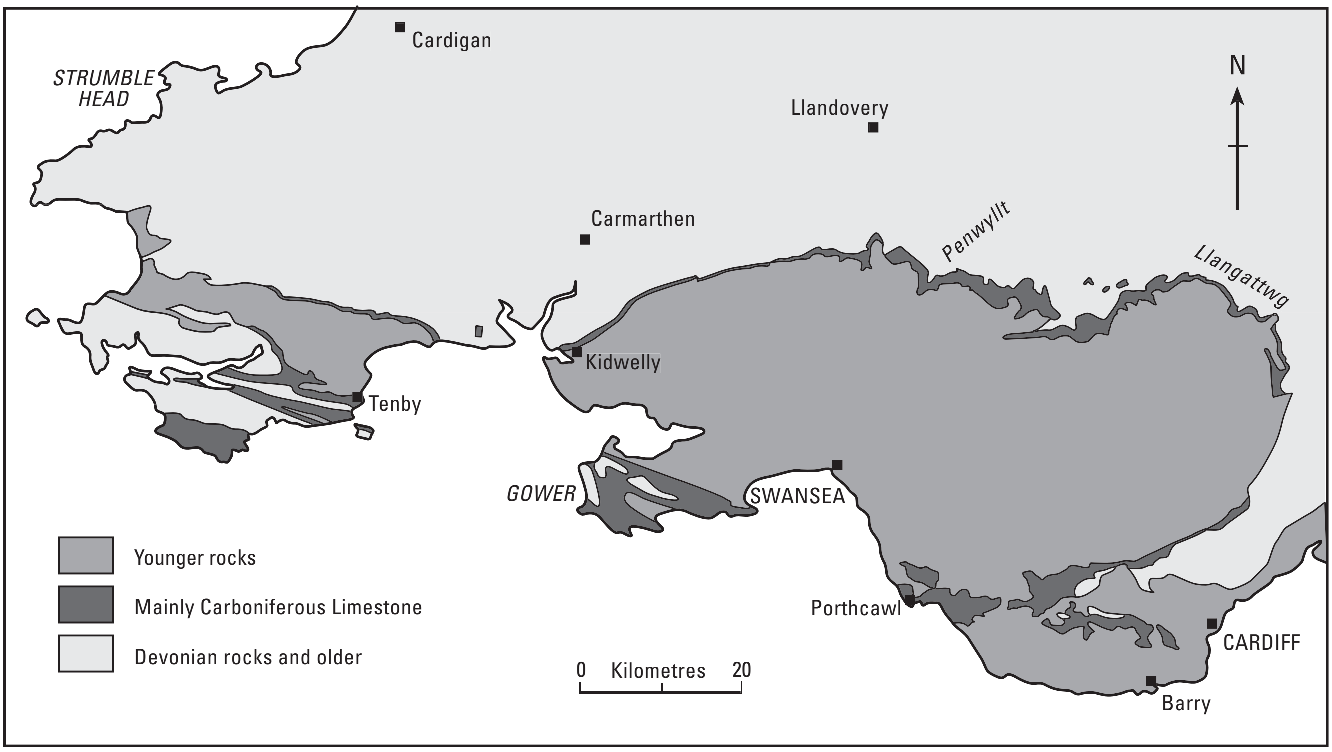

Figure 9.3.1 Generalised map of the solid geology of South Wales (after Lowe, 1989).

solutional forms, ranging from small hollows to dolines. Karstification in this area is aided by high rainfall — up to 2300 mm/year on Black Mountain, reducing to around 1250 mm/year further east (Crowther, 1989). Major conduits have developed here, including Ogof Ffynnon Ddu, which is the deepest (308 m) and second longest (43 km) cave system in Britain (Gunn, 1992). Major conduit development in the North Crop appears to be associated with concentrated recharge from allogenic streams (i.e. streams running onto the limestone from other rock types) (Gunn, 1992). The orientation of the larger (and presumably smaller) solution-enlarged fractures is controlled by a combination of lithology and structure.

A hydrogeological study of the area for the Welsh Water Authority (Welsh Water Authority, 1979) suggested that groundwater in the Carboniferous Limestone had three modes of occurrence:

Swallet water — water which moves rapidly through the limestone in well-developed passages and cave systems to a distinct point of resurgence. It is recharged generally through swallowholes. It can replenish groundwater or contribute to percolation water.

Percolation water — water which infiltrates through the soil and moves slowly down through fractures over a wide area. Found in the unsaturated zone above the saturated aquifer.

Resident groundwater — moves by slow percolation towards low-level springs with more rapid flow where open fractures occur.

It has been suggested (Welsh Water Authority, 1979) that the zone of greatest water movement occurs just below the water table, along strike-oriented passages and that this zone of conduits tends to move downwards with time. It was suggested that unsaturated drainage was down dip, with groundwater in the saturated zone flowing mainly along the strike-oriented conduits towards springs on the flanks of the Carboniferous outcrop.

In terms of aquifer properties, this postulated flow system suggests that a region of high permeability exists in the zone of water table fluctuation. Below the permanent water table, permeability reduces with depth as the frequency of conduits reduces.

The effect of structure on this system is unknown, although it has been suggested (Welsh Water Authority, 1980) that there is a correlation of springs with faults; but whether this is due to faults acting as zones of high transmissivity, or as barriers, is not known.

Few boreholes have been drilled into the limestone of the North Crop, and there is very little aquifer properties information. At Rhymney Bridge [SO 105 099] where the aquifer is confined, a transmissivity of 10–20 m^2/d and a storage coefficient of $4–9 \times 10^{-4}$ was obtained from a pumping test (Welsh Water Authority, 1979). This low transmissivity value suggests poor solution development of fractures, and this was thought to be typical over the confined aquifer.

A borehole was drilled into unconfined Carboniferous Limestone at Trefil [SO 1236 1255] about 3 km to the north-east of the Rhymney Bridge borehole (Welsh Water Authority, 1982). Despite the area showing evidence of significant subsurface dissolution of the limestone, a pumping test on the borehole gave poor results, with an estimated long-term yield of only 2 l/s, and indicated poor aquifer properties, with transmissivity calculated to be only 10 m^2/d, possibly as a result of fractures being filled with sediment from the Millstone Grit. No storage coefficient could be obtained from the pumping test, but water level responses to rainfall in the area suggested a value of 0.01 for specific yield. A borehole 0.5 km to the south-west at Dros-y-Lynn [SO 1212 1212] also provided a low estimate of transmissivity (35 m^2/d). As a result of these tests it was concluded that, in the region investigated, the fractures in the Carboniferous Limestone aquifer are mainly developed above the water table, and that while they provide conduits for rapid throughflow to springs and resurgences they do not provide a water-bearing system at depths suitable for exploitation by boreholes (Welsh Water Authority, 1982).

Further to the east, a borehole at Rhydw [SO 1995 1244], around 8 km from Trefil, proved to be more successful, and a transmissivity of 130 m^2/d was obtained for the aquifer, which is overlain by over 100 m of Coal Measures and Millstone Grit. It was thought that the Carboniferous Limestone and the overlying sandstones were in hydraulic continuity (Welsh Water Authority, 1982).

In conclusion, the aquifer properties of the Carboniferous Limestone of the North Crop are very poorly known, and the transmissivity estimates available from the few available borehole tests cannot be used to realistically predict aquifer behaviour elsewhere in the outcrop. Also the limited data contradict intuitive attempts to use surface karstic features or depth of burial as a guide to predicting aquifer properties variation.

9.3.4 Cardiff–Porthcawl area

This region lies on the south side of the South Wales Coalfield Syncline, where a number of associated folds and faults result in an intermittent outcrop of the Carboniferous Limestone. Generally the structure of the area consists of a broad fold forming the Cardiff–Cowbridge anticline, running westward from Cardiff and with a westerly plunge. This and other minor structures has caused the Carboniferous Limestone to be exposed in three main areas (Figure 9.3.2). These have been classified into three aquifer units (Aldous, 1988); the Llanharry–Machen Aquifer Unit (on the southern margin of the South Wales Coalfield), the Cowbridge Aquifer Unit (including the southern limb of the Cardiff–Cowbridge anticline) and the Porthcawl–Schwyll Aquifer Unit, comprising the western block around Porthcawl.

The Carboniferous Limestone in the region comprises thick, blocky, massive limestones. A geological succession is given in Table 9.3.1.

Llanharry–Machen Aquifer Unit

This unit is poorly known hydrogeologically, with little aquifer properties information. Several sets of springs occur in the unit often associated with faults. The Taffs Well Spring in the eastern part of the area [ST 1190 8370] is thermal, with temperatures varying between 13 and 22° centigrade, indicating mixing between warm and cold waters, with an origin for the warm water at a depth of about 600 m (Holliday, 1986).

The hydrogeology of western part of the unit has been influenced by iron mines. These appear to have been associated with significant fractures in the limestone, and when working yielded large volumes of water — averaging 3.1×10^4 m^3/d — (Aldous, 1988). A spring in the south-west of the unit — the Pwllwy Spring — was an important supply source (now provided by a borehole with a resultant decrease in spring discharge).

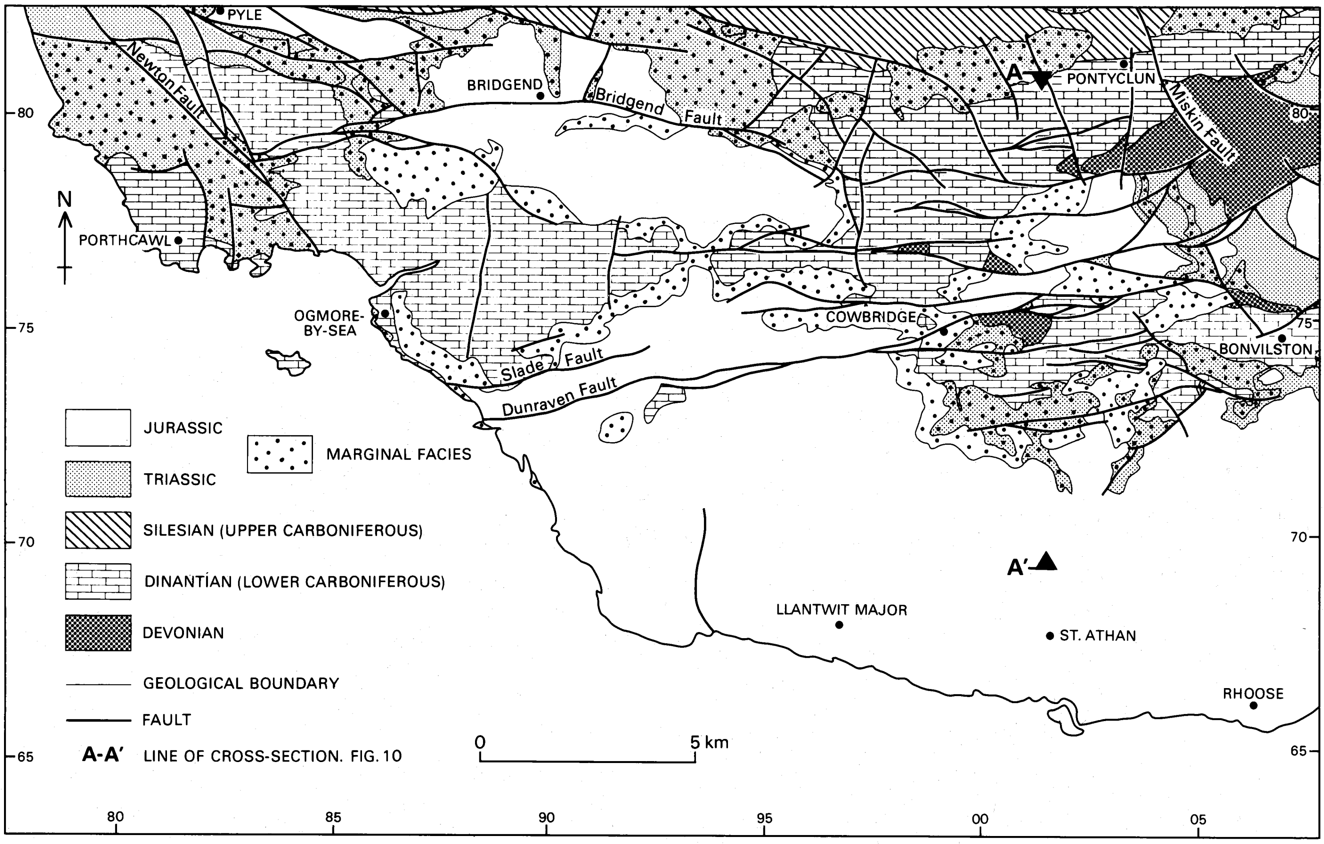

Figure 9.3.2 General geology of the Cardiff–Porthcawl area (after Wilson, Davies, Fletcher and Smith, 1990).

Table 9.3.1 Dinantian succession in the Cardiff–Porthcawl area (based on Aldous, 1988).

Unit	Description	Thickness
Unconformity		
Carboniferous Limestone		
Main Limestone		
(Upper Division)	Undolomitised and some patchily dolomitised limestone	0–105 m
(Lower Division)	Dolomite or dolomitic limestones and limestones	12–425 m
Lower Limestone Shales		
Upper Mudstone Division	Mainly mudstone with some thin limestones	21–45 m
Lower Limestone Division	Mainly limestones with some mudstone	0–60 m

Cowbridge Aquifer Unit

This aquifer unit comprises several limestone outcrops which are thought to be continuous beneath overlying Triassic material. There is little hydrogeological information for the area, which has no public supply sources. Several springs are found in the area, and the Carboniferous Limestone has been extensively quarried.

Porthcawl–Schwyll Aquifer Unit

This aquifer unit lies at the western end of the Cardiff–Cowbridge anticline, and is affected by further folds and faults. There are several springs in the region, of which the most important is the Schwyll Spring complex [SS 8880 7706], with a mean discharge estimated to be around 33.7×10^3 m^3/d (Hobbs, 1993). The spring provides a source of good quality water for Bridgend and parts of the Vale of Glamorgan. The aquifer is also used for several private sources of water supply, and the Carboniferous Limestone is extensively quarried.

Aquifer properties

Most of the aquifer properties information for the Cardiff–Cowbridge Block is derived from the study of the Vale of Glamorgan by Aspinwall and Company (NRA, 1993).

Where the Carboniferous Limestone aquifer outcrops in the aquifer units outlined above it is thought to be unconfined. Where it is overlain by sandy material it may remain unconfined, but is thought to be confined where the concealing material contains clay bands, and where it is overlain by Lias strata. The Dinantian strata in the area reach thicknesses approaching a kilometre, but it is thought (NRA, 1993) that only the upper 100 m is likely to be effective in transmitting water — although the thermal springs at Taffs Well indicate that deeper flows can occur.

Few aquifer properties data exist for the region, and therefore data from the three aquifer units are treated together. Pumping test data for six boreholes have been obtained, which show transmissivities varying between 4 and 130 m^2/d, with a geometric mean of 34 m^2/d. In addition, transmissivities have been estimated from specific capacity data for a further four boreholes known to penetrate the Carboniferous Limestone (NRA, 1993). These lie in the range 37–177 m^2/d with a geometric mean of 102 m^2/d — however the data are not considered very reliable because of the crude method of analysis. By applying the Darcy equation for flow between Bridgend and the Schwyll Spring, Aldous (1988) estimated a transmissivity of around 5000 m^2/d for the area, suggesting the presence of highly permeable conduits.

In the Vale of Glamorgan study (NRA, 1993) hydraulic conductivities were estimated from the pumping test data, and values between 0.1 and 5 m/d were obtained. The values were considered to be overestimates because of partial penetration effects.

An illustration of the difficulties in predicting the aquifer properties of the Carboniferous Limestone was given by Aldous (1988) who reported that three boreholes at a site at Bridgend, in the Porthcawl–Schwyll aquifer unit had specific capacities ranging between 12 and greater than 88 m^3/d/m.

No storage coefficient data from pumping tests exist for the aquifer, but calculations based on water level responses to rainfall at a site near Tythegston in the Porthcawl–Schwyll aquifer unit by Young and Connor (1978) suggest a specific yield of 0.06–0.08 in the upper 5 to 10 m of the limestone, with values of 0.005–0.02 below this.

9.3.5 Gower Peninsula

The limestone of the Gower Peninsula forms a broad plateau cut in the south by a number of north–south-trending, well-defined valleys characterised by intermittent surface drainage; in the north streams sink directly into the plateau surface with little or no valley incision (Ede, 1975). Karstification in this area is impeded by the presence of thick glacial drift. There is no aquifer properties information for the region.

9.3.6 South Pembrokeshire

A hydrogeological study of south Pembrokeshire carried out in the 1970s (Welsh Water Authority, 1978) was able to make only limited comments on the aquifer properties of the area because of the lack of hydrogeological data. The study divided south Pembrokeshire into three limestone provinces; namely a Northern Province (including the Ritec Fault), a Central Province (the Pembroke syncline), and a Southern Province (Figure 9.3.3).

Northern Province

Limestones of Northern Province are divided by major structural feature, the Ritec Fault which runs approx west–east from Pembroke Dock to Tenby. In the east of the area the St Florence syncline lies to the south of the fault. Here the Carboniferous Limestone shows karstic features (minor dry valleys and swallowed streams) and is drained to the east by the Ritec River, which is augmented by limestone springs, which used to supply Tenby.

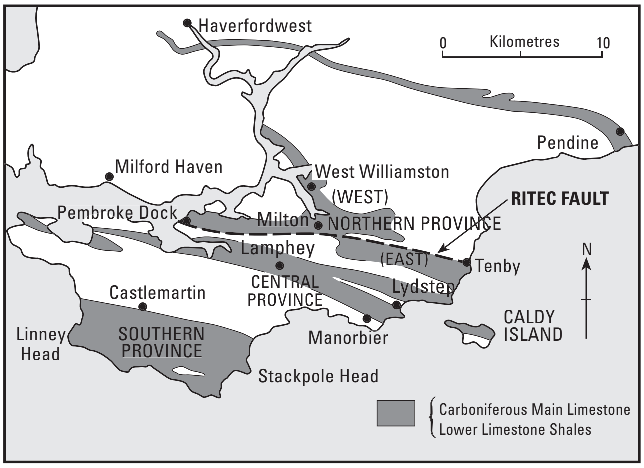

Figure 9.3.3 Carboniferous Limestone provinces of south Pembrokeshire (after Welsh Water Authority, 1978).

In the west of the northern province the Carboniferous Limestone is dominated by the Carew anticline, with a core of Devonian sandstones. The southern limb of the anticline is truncated by the Ritec fault, while the northern limb dips beneath the complex syncline of the Pembrokeshire coalfield.

The Carboniferous Limestone outcrop around Milton, near the eastern end of the anticline, shows karstic features such as swallowholes, dry valleys and sinkholes. There is a large spring system at Milton (with a flow of around 6×10^3 m^3/d) and the area is considered to have good aquifer properties (Welsh Water Authority, 1978). Pumping tests were carried out on a borehole in a valley site at Milton in 1978 (Welsh Water Authority, 1978) and gave an estimated value of transmissivity of 5900 m^2/d with an estimated storativity of 0.01. A figure for transmissivity of 4000 m^2/d was considered to be more representative of the region around Milton away from the faulted zones of the valley. These figures indicate a fractured aquifer with little matrix storativity. The observation well responses suggested a symmetrical cone of depression, and indications that transmissivity varied inversely with pumping rate suggested that permeability decreased with depth.

Central Province

The Pembroke syncline, plunging gently eastwards, is the main feature of the Carboniferous Limestone of the Central Province. Two main sets of springs occur in the area, north of Lamphey, and west of Manorbier. Both sets of springs are thought to be associated with faulting (Welsh Water Authority, 1978). There are no aquifer properties data for the area.

Southern Province

The Southern Province comprises the greatest extent of Carboniferous Limestone in south Pembrokeshire. The outcrop area is around 33 km^2, and is mainly a flat uplifted plateau with thin soils and no surface drainage. There are two main spring systems in the area, one to the south-west of Castlemartin near the west coast and one near the south-east coast at Broadhaven. A borehole near to the eastern spring indicated a transmissivity of 500 m^2/d (Welsh Water Authority, 1978).

9.3.7 Chepstow Block

The Carboniferous Limestone of the Chepstow Block extends westwards of Chepstow in a broad syncline, crossed by a northerly trending anticline from the Great Spring [ST 508 875]. To the west of this northerly fault lies an aquifer unit, the Caerwent Basin, comprising the western half of the Chepstow Block. The main faults in the area trend north, north-east, or west-north-west (Clark, 1984). The Carboniferous Limestone is predominantly limestone, with subordinate sandstones at the top and with shales throughout, particularly at the base. Two horizons of especially massive type have been identified, the Drybrook Limestone in the upper part and the Lower Dolomite near the base. The Carboniferous Limestone may be regarded as a single aquifer as a result of a pervasive network of productive fractures in the otherwise dense crystalline rock.

The discharge from the limestone occurs as springs, by far the largest of which is the Great Spring, with a discharge of 5500 m^3/d on average. The aquifer properties of the Carboniferous Limestone in the region are largely unknown. Swallow holes around the periphery of the Caerwent Basin indicate the karstic nature of the aquifer, and it is thought that flows occur principally along solution enlarged fractures parallel to the main fault directions, with most flow directed ultimately to the Great Spring (Clark, 1984). A tracer test to the Great Spring from an injection point 7 km away indicated flow was through a complex fracture system rather than purely through large conduits (Clark, 1984).

9.4 THE PEAK DISTRICT

9.4.1 Geographical and geological setting

The outcrop of the Carboniferous Limestone of the Peak District lies in a region bounded approximately by Castleton in the north, Buxton in the west and Matlock in the east. The outcrop is up to 20 km wide and 40 km from north to south (Figure 9.4.1). The area forms uplands mostly lying between 200 m and 400 m above sea level.

The Carboniferous Limestone consists mainly of limestones, but includes a varying proportion of interbedded mudstone. The limestone thickness varies from less than 100 m, to an estimated maximum of about 1900 m in the northeast of the region (Aitkenhead et al., 1985).

The limestones are very varied lithologically and show rapid vertical and lateral facies changes. The rocks lie in two main provinces, the shelf province and the off-shelf province. The shelf province is characterised by thick limestones. It includes most of the Dinantian outcrop, and extends eastwards beneath later cover. The off-shelf province comprises interbedded limestones and mudstones and lies to the west and south of the shelf province. Reef-limestones occur in formations belonging to both shelf and off-shelf provinces and a discontinuous reef belt typically occurs between the two (Aitkenhead et al., 1985).

The Carboniferous Limestone of the Peak District contain a suite of hydrothermal mineral deposits which have been worked, mainly for lead, since Roman times. These mineral deposits are mainly found towards the eastern side of the region, with the main ore deposits occurring as fracture fillings.

9.4.2 General hydrogeology

The drainage of the main mass of the limestones is eastwards towards the Derwent. In the west and south the rivers Dove, Hamps and Manifold drain the area, while Peakshole water and Bradwell Brook drain to the north. Dry valleys are present over most of the limestone and karst features are widespread.

The river flow in the limestone area of the Peak District is almost entirely fed by groundwater discharge, with both identifiable discrete springs and direct discharge to river channels being important (Edmunds, 1971). The largest natural springs in the region have discharges not exceeding 9000 m^3/d (Edmunds, 1971).

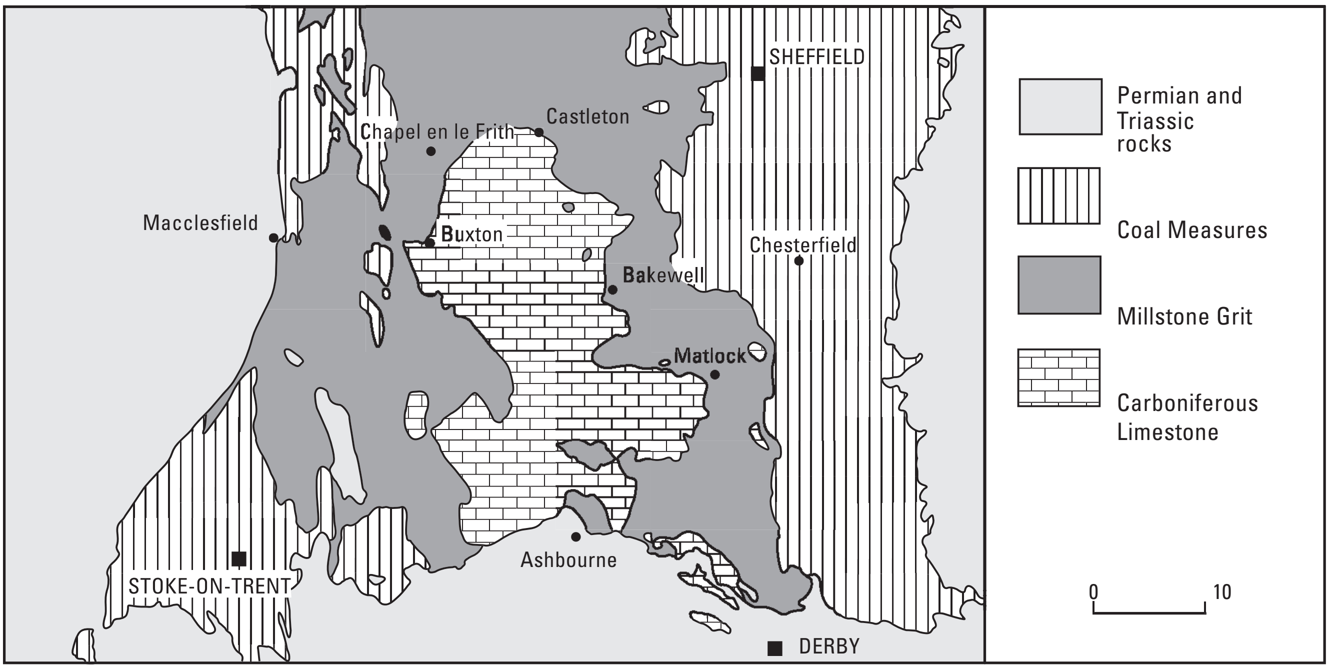

Figure 9.4.1 Geological sketch map of the Peak District (after Aitkenhead, Chisholm and Stephenson, 1985).

Natural drainage, particularly in the northern and eastern parts of the region has been substantially affected as a result of mining activities. Large quantities of ore and gangue have been removed along veins which followed the principal vertical fractures and bedding planes. This has increased east–west groundwater flows. In addition tunnels (locally termed 'soughs') were constructed during the course of mining to drain water from the lowest level in the mine to a suitable point at the surface in a neighbouring valley. As the mines were deepened fresh soughs were constructed, resulting in a complex system of tunnels. Sough discharges can be substantial, with four soughs (Magpie Sough, Meerbrook Sough, Yatestoop Sough and Hillcarr Sough) having discharges in excess of 40 000 m^3/d (Edmunds, 1971). The Meerbrook Sough has reached a maximum discharge of around 85 000 m^3/d, draining water from the Carboniferous Limestone and the Millstone Grit (Stephens, 1929). These are the largest discharge points for groundwater in the limestone area.

Edmunds (1971) drew tentative water table contours for the limestone region, using water level data from boreholes, mineshafts, caves and soughs. He concluded that, in general, a water table could be identified (although this was very variable locally) and that this indicated the development of branched fracture systems.

9.4.3 Aquifer properties

The natural aquifer properties of the area (i.e. those unaffected by mining) are dominated by solution enlarged fractures, as elsewhere in the Carboniferous Limestone. Gunn (1992) suggested that there are five main factors influencing the development of underground drainage. The following is a synopsis of Gunn's discussion.

i) *Impermeable cover and its removal* Gunn suggested that conduit development has proceeded episodically since the early Pleistocene and is related to the gradual stripping back of impermeable cover.

ii) *Structure* Flow below the water table is generally along bedding plane strike, particularly in areas of shallow dip.

iii) *Vertical discontinuities* These are principally joints, faults and mineral veins. These are likely to be important for the vertical movement of groundwater, but less so for horizontal flows, unless they form a low angle with the hydraulic gradient.

iv) *Lateral discontinuities* Bedding planes form the main routes for lateral flow in the aquifer.

v) *Lithology* While the above factors determine the position of the conduits in the aquifer, their size and form is more a function of limestone lithology. Gunn suggested (on the basis of an unpublished study) that the greatest degree of cavern enlargement takes place in massive generally fine-grained limestones, particularly where pseudobrecciated horizons are present which may be more readily dissolved than the surrounding homogeneous limestone. The weathering of pyrite in lavas may also produce an acidic aggressive solution which can enhance conduit development.

Pumping tests

Very few pumping test results are available from the Carboniferous Limestone in the Peak District, and the Aquifer Properties Database has details of only six tests (at six sites). Test transmissivities vary from 0.1 to 770 m^2/d; however all values but one are less than 60 m^2/d and the geometric mean is 10 m^2/d. No values of storage coefficient are available. These values are given more to indicate the paucity of data for the region than as representative data, since, as with the other areas of Carboniferous Limestone examined, transmissivity values are likely to be dominated by the unpredictable presence or absence of local fractures.

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