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Best wishes
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CHAPTER 11

HYDRAULIC ENGINEERING AND WATER SUPPLY

ANDREW I. WILSON

SINCE the beginnings of agriculture and urbanization, the control and management of water has been vital to all societies. Natural rivers and springs were exploited wherever possible, but where they were lacking, alternative means of water supply were needed. In the highly urbanized Greco-Roman world, artificial techniques of water supply not only supported large city populations but also shaped the amenities that defined urban living. Many of the achievements of Greek and Roman civilization would not have been possible without the infrastructure based on skills in hydraulic engineering.

WELLS

Wells were the earliest and simplest form of artificial water supply, consisting in their most basic form of a simple hole dug down to the water table. Neolithic wells are known from Cyprus (ninth and eighth millennia B.C.), Crete (Peltenburg et al. 2001; Manteli 1992), and Israel (Garfinkel et al. 2006), and until the invention of rainwater-collection cisterns, wells remained the sole artificial technique of water supply; later, they continued to be important alongside other technologies. Wells were nearly ubiquitous throughout the ancient world, wherever groundwater could be reached at moderate depth by sinking a shaft (Jardé 1907; Hodge 1992: 51–58; 2000).

Most domestic wells, and many public wells, were either circular or square, just large enough for the digger—about 0.80–1.0 m across. Where the geology was sufficiently stable, the shaft would simply be cut into the rock, but in unstable sands, earth or gravels the sides would need lining (called "steining"); this was frequently the case in the upper part of the shaft above bedrock. In the Athenian agora from the fourth century B.C. onward, some wells were lined with terracotta rings made of three curved sections, each with a handle that served as a foothold when put in place (Lang 1968: 6–7). More often, however, the well was stabilized with a lining of mud bricks or steined with masonry. In northern Europe during the Roman period, wooden barrels with their ends knocked out were sometimes used to line wells dug in clay or soft earth, as at Roman Silchester or numerous sites along the Rhine *limes* (Marlière 2002: 40–89). Alternatively, wooden shoring or framework was used.

Depths varied considerably; wells up to 15 m deep are not uncommon, and although wells of more than 25–30 m are rare, examples are known of Roman wells about 60 m deep in the Aurès region of Algeria, and even 80 m in the case of a Roman well near Poitiers in Gaul. For really deep wells, perhaps the biggest disadvantage was the sheer effort required to haul the water up (Hodge 2000: 30). To prevent people falling in accidentally, the top of a well was usually surrounded with a wellhead or *puteal*—either of terracotta or stone; the latter in some cases elaborately decorated. Some stone well-surrounds show deep scoring marks from the friction of ropes where the jars were pulled up by hand. A stone or wooden framework might support a pulley to ease the task of hauling up the water jars. Cuttings in stone well-surrounds sometimes indicate that the well could be covered with a metal or wooden cover (e.g., on the Odeon Hill at Carthage).

Larger wells are occasionally encountered. In some cases they might take the form of a deep and wide excavation with a staircase leading down to the water table, to enable people to descend into the well and draw water. More often, an exceptionally wide well indicates the use of some kind of mechanical water lifting device (chapter 13). Rectangular wells with an opening about 3 m long and 1 m wide seem designed to house a chain of pots strung over a wheel and moved by draft animals through an angle gear drive (*saqiya*). A Roman example was found in the center of the Square of the Cisterns at Ptolemais (over 11 m deep), and probable Byzantine examples are known from Andarin and Qasr Ibn Wardan in Syria (A. I. Wilson 2004: 120–21). In London, a well 2.6 m square and some 5 m deep housed a mechanical water-lifting device with a series of wooden containers connected by iron chain links, and probably driven through a *saqiya* gear (now lost); it may have served a set of public baths (Blair and Hall 2003). The well itself was lined with wood and cross-braced with timbers that could also have served as a kind of ladder to enable descent for maintenance or cleaning.

Domestic wells were usually located centrally in the house, often in peristyle courtyards; sometimes a well shaft placed between two rooms might have an arched

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opening within the wall to allow access from both sides. The quality of well water depended on the local geology, and also on population density and the drainage technologies in use. Urban wells were at risk of contamination if sewage or refuse was discharged back into the aquifer via cesspits; this potential problem did not deter their use, and the consequent risk of disease may have been little appreciated in antiquity. It was understood, however, that overextraction from a well could have an effect on neighboring wells. One of Solon's laws decreed that if there was an existing public well within 4 *stadia* (720 m) one had to use it rather than dig another; otherwise people could dig their own wells. But if water was not found after digging to a depth of 60 ft, the party could draw water from a neighbor's well twice a day (Plutarch, *Sol.* 23.5-6).

CISTERNS

Cisterns were developed as an alternative to wells, storing rainwater collected from the roofs, courtyards, or other paved areas of buildings. Domestic cisterns were widespread around the Mediterranean in the Greek and Roman worlds, although less common in the wetter regions of northern Europe.

Among the earliest rainwater-collection cisterns are examples from the MM III period at Zakro, and from the LM III period at Tylissos. Both are open and circular, with steps for access; the Tylissos example had a rectangular settling tank (Biernacka-Lubanska 1977: 27–28). Later cisterns were usually covered, to reduce contamination and evaporation; a common form in the Greek and Roman worlds was the bottle- or carafe-shaped cistern (depending on proportions), with a narrow neck or shaft at the top and a wider body below. Depths commonly range between 3 m and 7 m, and volume was achieved by widening the body of the cistern as far as the solidity of the rock into which it was cut would allow. In Athens, bottle cisterns make an appearance perhaps in the early fourth century B.C., and from the middle of that century onward increasingly came to replace wells in the agora (Camp 1982: 12). In the Hellenistic period a different form of cistern became common in North Africa and the western Mediterranean—long and narrow, often with rounded ends, its width was limited by the constraints of roofing with cover slabs either laid flat or pitched against each other in pairs. Depth compensated for the narrow width to achieve sufficient storage capacity. Examples are found in Hellenistic Cyrenaica (Berenice) from the second century B.C. onward, in the Punic world (e.g., Carthage and Ampurias), Cosa in the third century B.C. (Capitolium cistern), and even in southern Gaul (Ensérune, first century B.C.). Rectangular cisterns roofed with slabs carried on a series of arches first make their appearance in the Hellenistic period (Delos), and later spread to the Nabataean kingdom and other parts of the Near East (Oleson 1991: 57–58; 1995).

The introduction of cisterns was made possible by the invention of waterproof lining mortars, allowing the cistern to retain water even where the rock it was cut into was permeable. With the exception of the large, open circular cisterns associated with the fourth-century B.C. ore washeries in the mining region of Laurion, where the mortars have been shown to contain high proportions of lead litharge, a by-product from the silver extraction process (Conophagos 1980, 1982), very little analysis has been done on ancient Greek waterproof mortars. Better understood are the Punic hydraulic linings—often a bluish-gray mortar derived from marl clays, mixed with ash, and bulked out with a gravel aggregate. The Carthaginians used a pinkish cement, containing crushed terracotta, for cement floors, and although this material was later to become standard Roman cement for waterproof linings (often referred to in modern archaeological literature as *cocciopesto* or *opus signinum*), the Carthaginians themselves seem to have preferred the ash and gravel mortars as waterproof linings.

At Carthage in the third century B.C., many domestic wells were replaced by cisterns, at considerable effort and expense, and disused wells were reused as soakaways for cistern overflow (A. I. Wilson 1998: 65–67). This change may have been the result of either climatic change (lowering of the water table) or increasing population pressure (leading to greater abstraction, or to contamination of the water table). A similar switch from wells to cisterns in the Athenian agora in the fourth century B.C. has been attributed to drought (Camp 1982), but this hypothesis encounters the objection that increased reliance on rainfall collection seems a poor response to drought. In the case of Carthage, at least, increasing population pressure on groundwater resources seems a more likely explanation.

Other forms of cistern include tunnel cisterns, where a well-like shaft leads down to two (or occasionally more) rock-cut tunnel chambers branching off the base. The depth of such cisterns depends on what depth a sufficiently solid rock stratum could be reached in which to excavate the lateral chambers. An early Hellenistic cistern at Euesperides (Benghazi, Libya) with four arms was barely over 2 m deep. Tunnel cisterns are common in late Republican and early Imperial Italy, especially in Latium where they could be dug into the soft volcanic bedrock, and in Campania, as at Pompeii; they are also found at Roman sites in North Africa such as Lepcis Magna (Walda 1996: 126). These tunnel cisterns, like the other types described above, stored collected rainwater; but in Italy a variant type might be dug down into the aquifer, collecting groundwater seeping through the sides of the chambers. The greater the surface area of the walls, the greater the collecting ability of such a cistern; consequently, some were developed as networks of parallel or intersecting tunnels, particularly in Latium and Campania (Devoti 1978; Döring 2002a).

The Roman period saw an important technological advance in cistern construction, with the introduction of mortared rubble building techniques and vaulting, which allowed much larger covered cisterns to be constructed. The volume of earlier cisterns had been constrained by the limitations of roofing methods or rock-cut techniques, but now barrel and cross vaults allowed much greater widths to be spanned, and multiplying the number of chambers could increase

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volume further. The strength and durability of mortared rubble construction meant that, with thick walls and external buttresses to counter the lateral pressure exerted by the water inside, cisterns could now be built partly or wholly above ground, rather than necessarily being sunk underground. This not only allowed their construction in areas where groundwater was close to the surface, but also meant that water could be run out by gravity flow from large aboveground cisterns, allowing irrigation of gardens or orchards, rather than having to be lifted out arduously by hand.

The most common type of Roman cistern is, therefore, rectangular and barrel-vaulted, with one or more chambers, and a draw-hole about 0.50 m square in the center of the vault. Terracotta supply pipes or cement-lined built channels from the roof or courtyard enter above the spring of the vault; tide marks on the lining mortar suggest that most cisterns were rarely filled above the spring of the vault. Like wells, cistern mouths were usually protected by a surround or *puteal*, and a frame with a pulley was often set over them.

Cisterns of all kinds were waterproofed by the application of mortar linings; the most widespread type used in the Roman world was the pinkish *opus signinum* containing crushed terracotta, but in parts of North Africa the Punic ash-based bluish-gray mortars remained in use alongside this formula. The joints between wall and floor were sealed with a quarter-round molding, and the corners were rounded internally to assist cleaning; sometimes a circular sump was provided in the floor to assist removal of sludge.

Domestic cisterns collected water from the roof and courtyard of the house in which they were located; the amount of water they collected was therefore determined by the local rainfall combined with the roof area or *impluvium* available for rainwater collection. Rural cisterns might have specially constructed paved or plastered areas acting as collection *impluvia*, as for example in Hellenistic and Byzantine cisterns on Yeronisos Island, Cyprus (Connelly and Wilson 2002).

The so-called *astynomoi* inscription from Pergamon in Asia Minor (a Trajanic regulation repeating a Hellenistic decree) illustrates the importance of domestic cisterns to the overall water supply of a town; among other duties the town magistrates were required to keep a register of all private cisterns in the town and check annually that they were kept in good order (Klaffenbach 1954). The importance of rainwater collection as a complementary water supply technique alongside wells, springs, and aqueducts is highlighted not only by the virtual ubiquity of domestic cisterns in the Mediterranean region, but also by the fact that many public buildings with a large footprint were equipped with large rainwater-collection cisterns. In Delos, the Hellenistic theater supplied runoff water to a large cistern roofed with slabs carried on cross arches (Oleson 1995: 716–17). In Roman North Africa, theaters and odea at Bararus, Thugga, and Carthage were provided with cisterns under the stage, fed by runoff from the cavea and orchestra, while the third-century A.D. amphitheater at Thysdrus in Tunisia acted as an *impluvium* for cisterns some 100 m to the north. Large paved public spaces, such as the forum at Pompeii, the precincts of the Temple of Saturn at Thugga, or the South Forum Temple at Sabratha, also collected water for large cisterns (A. I. Wilson 1997: 59).

The quality of water stored in rainwater collection cisterns was acknowledged to be inferior to that from wells or sources of running water (Pliny, *HN* 31.21.34; Oleson 1992: 887–88). Standing water became stagnant and less aerated, and although the underground placement of most cisterns helped to keep the water cool and away from sunlight, inhibiting somewhat the growth of algae and insects, ancient authors often recommended boiling cistern water before drinking it, or adding salt. The water collected in large cisterns fed from public spaces must have been nonpotable, and indeed it is likely that, where other sources were available, cistern water was used primarily for purposes other than drinking, such as washing floors or watering gardens. Basic methods of water purification were employed, such as metal grilles on the inlets of feed pipes, and settling tanks, and large quantities of charcoal found in domestic cisterns in Thysdrus and Leptiminus in North Africa may suggest the addition of charcoal to cistern water to remove odors by the absorption of colloids, a practice still current in the nineteenth century (A. I. Wilson 1997: 81). Vitruvius (*De arch.* 8.6.15) recommends adding salt to cistern water to purify it.

AQUEDUCTS AND LONG-DISTANCE SUPPLY

The Near Eastern Background

The Assyrian empire saw the development of ambitious water supply schemes involving long-distance artificial canals, usually derived from perennial rivers, and led through intervening ridges by means of tunnels several hundred meters, or even several kilometers, long. The longer tunnels were dug between pairs of vertical shafts, which enabled the overall course of the tunnel to be surveyed on the surface. This shafts-and-gallery tunneling technique broke up the problem of underground surveying into short, manageable sections, and the shafts were set at sufficiently close intervals that the tunneling gangs could find each other underground. They served also for the removal of spoil, and to assist ventilation (cf. chapter 12).

The Assyrian king Assurnasipal II (884–859 B.C.) dug a canal 19.5 km long from the Upper Zab river to supply Nimrud; it passed under a rock ridge at Negoub via a tunnel 7 km long dug between pairs of vertical shafts. The system both supplied the city of Nimrud and irrigated the fields around it. Two later tunnels in the region seem to be repairs or additions to this scheme: one was cut by Tiglath-Pileser III (744–727 B.C.), but later blocked, and the other by Esarhaddon (680–669 B.C.), whose construction inscription records that the earlier tunnel of Assurnasipal II had silted up. Renovation and maintenance are constant themes in both ancient and modern water-supply systems.

Similar techniques were used for the water supply for Arbela in eastern Iraq. This tapped water from three rivers at Bastura and included a tunnel dug between vertical shafts; an inscription on the entrance of the tunnel records construction by Sennacherib (704–681 B.C.). Traces of what may be a comparable system were recorded at Babylon by Rassam in the late nineteenth century; he mentions four wells lined with rings of red granite, in a straight line, which communicated with a subterranean aqueduct. The source of the aqueduct was not established with certainty, but it was thought to have come either from the Euphrates or from a canal northeast of the main mound at Babylon. Suggested dates for the system range from the late eighth to the mid-fifth century B.C. (Dalley 2001–2002).

Sennacherib's aqueduct to Nineveh, completed in 690 B.C., was a long and wide canal used for both irrigation and (probably) urban supply, tapping the waters of the Gomel River at Bavian. It crossed a wadi at Jerwan on a bridge over 280 m long and 22 m wide, built in ashlar masonry with five corbelled arches (Jacobsen and Lloyd 1935). Hezekiah's approximately contemporary tunnel (715–696 B.C.) that brought water into the city of Jerusalem from an underground spring is a 537-m winding spring-capture tunnel (chapter 12).

The Assyrian water supply schemes involving tunnels dug between sets of vertical shafts have a bearing on the vexed question of the origin of *qanats*. *Qanats* are one of the most important developments in the history of water engineering; they have enabled human habitation and agriculture in some of the most inhospitable, arid areas on earth. A *qanat* is an underground gallery that collects groundwater and leads it by gravity flow to emerge where the ground surface level is lower, hundreds of meters or even many kilometers from the source (figure 11.1). The long underground tunnels were dug in relatively short sections between pairs of vertical shafts, again using the shafts-and-gallery tunneling technique, just as in the tunnels on the large Assyrian aqueducts. The difference lies in the water source, which is not a flowing river or spring, but groundwater, usually tapped at a considerable depth in a piedmont zone in an arid region. *Qanats* are found from China to the Sahara and North Africa; they were even introduced to the New World by the Spanish, and, despite the increasing use of motorized pumped wells, they are still used today in many arid regions.

It was long held that the *qanat* must have originated in Persia, largely because that is where the largest numbers of *qanats* are found; and their origin has frequently been attributed to the Achaemenids. More recently, several archaeologists working in the Arabian Peninsula have argued that *qanats* (*aflaj*) originated there, claiming to have discovered pre-Achaemenid *qanats* of the early first millennium B.C. (Magee 2005). To date the arguments are inconclusive; some *qanats* in southeastern Arabia seem to be spatially associated with sites dated by pottery to the Iron Age II period, but that period extends from about 1000 to 600 B.C., and there is no conclusive proof that the *qanats* in question were created at the beginning rather than the end of it. A late date within this bracket would still allow the possibility of Achaemenid introduction to the region. It is true, however, that no *qanat* in Iran has yet been shown to be of Achaemenid date—although the significance of this

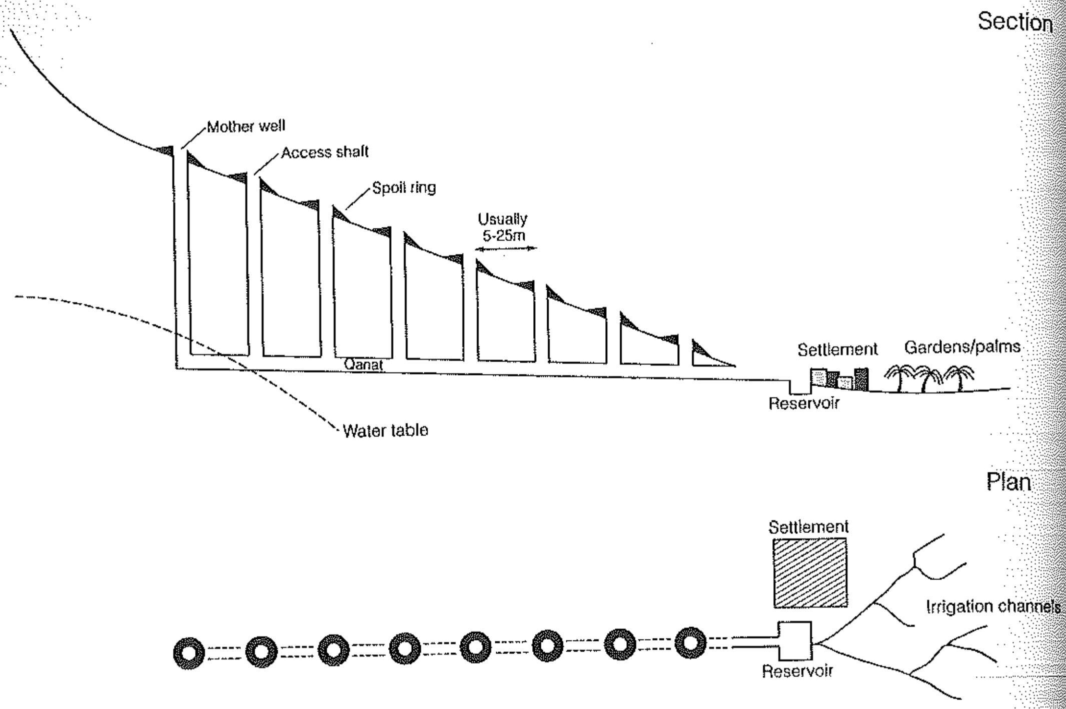
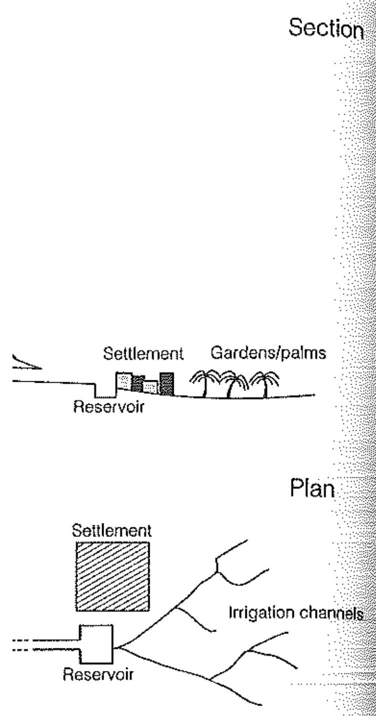


Figure 11.1. Diagram of a *qanat* or *foggara.* (Drawing by Alison Wilkins, reproduced by permission.)

observation diminishes when one remembers that almost no *qanats* in Iran have been investigated archaeologically.

The earliest securely dated *qanats* belong to the Achaemenid period at Ayn-Manawir in the Kharga Oasis in Egypt, where remains of 22 ancient *qanats* are known. They are dated both by stratigraphic finds and by associated *ostraka* recording the sale of water rights from 443 B.C. onward (Wuttman 2001). Polybius (10.28), describing campaigns in Media in 210/209 B.C. between the Seleucid king Antiochos III and the Parthian king Arsaces II, clearly refers to *qanats*, whose construction he says was encouraged by the Achaemenid kings by tax concessions on the land thus brought under cultivation.

In his fundamental study of *qanats*, Goblot (1979) proposed that the technique was spread to regions around the Mediterranean by invading peoples or refugee groups; thus the Romans would have introduced *qanats* to North Africa, while refugees from Persia introduced them to the Sahara in the early Middle Ages. More recent work provides a very different model. The spread of the technique to Africa was due not to transfer through the Mediterranean, but to diffusion along Saharan trade routes. In the late first millennium B.C., *qanats* (*foggaras*) formed the agricultural basis of the emergent Garamantian state in Fazzan (Libyan Sahara); the technology had probably been introduced from the oases in the western desert of Egypt, where, as we have seen, it was already in use in the Achaemenid period. From



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Fazzan it later spread to the Algerian Sahara, and diffused northward to Roman North Africa (A. I. Wilson 2005, 2006a), where some Roman aqueducts display a blend of traditional *qanat* technology with Roman techniques of reinforcement of the water channel. Very similar *qanat*-aqueducts are found in the region around Trier and Luxembourg and may have been introduced there from North Africa (Luxembourg: Kohl and Faber 1990; Kohl et al. 1995; Faber 1992; Schoellen 1997; Germany: Kremer 2005; Grewe 1988: 93). Elsewhere in the Roman world, however, the use of the *qanat* was largely limited to Syria, Judaea, and Egypt. Further east, its spread from Iran to Afghanistan at an unknown but probably early date may also have been facilitated by trade contacts along the Silk Road.

The development and spread of *qanats* is important because—as the Achaemenid examples at Ayn Manawir show—it demonstrates the availability and use at an early date of complex and difficult engineering water schemes in communities outside the main civic centers. In many parts of the ancient world the *qanat* was the only long-distance water supply technology available prior to the Hellenistic or Roman periods.

As we have seen, already in the early ninth century B.C. Assyrian water engineers were able to dig tunnels several kilometers long using the same principle as for the tunnels of *qanats*. The evidence currently available suggests two possibilities. Either the Assyrians developed the shafts-and-gallery tunneling technique, which was later applied to the realization that groundwater found at depth in one place may nevertheless lie above the ground surface elsewhere and could be led out to the surface via a tunnel that could be dug only by the shafts-and-gallery technique; or the *qanat* was invented as a package both of the shafts-and-gallery technique and the realization that groundwater found at depth could be transported elsewhere. Until further early *qanats* have been reliably dated, certainty is impossible, but a priori the first of these two possibilities seems easier to believe. Furthermore, if the Assyrians invented the shafts-and-gallery technique and it was only later applied to the *qanat*, the separate diffusion trajectories of the *qanat* and the shafts-and-gallery tunneling technique become easier to understand: the shafts-and-gallery tunneling technique spread to the Greek and Etruscan worlds while the *qanat* did not.

GREEK WATER SUPPLY SYSTEMS

The archaic period saw the first public water projects of the Greek world, with the development of springs with fountain houses at Megara by the tyrant Theagenes (ca. 640–620 B.C.; Pausanias 1.40.1), and perhaps the monumentalization of the spring of Lower Peirene at Corinth, although this is not closely dated (Hill 1964). For Samos and Athens, long-distance aqueducts were constructed. The projects at Megara, Samos, and Athens were all initiated by tyrants wanting to secure popular favor by public works engineering schemes that were both grandiose and useful. The aqueduct at Samos, 2.5 km long and built by the tyrant Polycrates (ca. 550–522 B.C.), is best known for the famous tunnel named after its designer, Eupalinus of Megara (Herodotus 3.60), a 1-km-long gallery just before the aqueduct enters the city (Kienast 1995). The height of the overlying hill prevented construction by the shafts-and-gallery technique, so the tunnel was surveyed from opposite ends, meeting near the middle (chapter 12). The aqueduct itself tapped water from a spring, and apart from the tunnel of Eupalinus it largely runs along the contours; significantly, for considerable stretches immediately up- and downstream from the tunnel of Eupalinus the structure takes the form of an underground tunnel dug in the shafts-and-gallery technique. Given the cultural and technological contacts between the Persian Empire and eastern Greek states at the time, it seems that this must represent an adoption of shafts-and-gallery tunneling methods from the Achaemenid practitioners of this Assyrian technique.

The Enneakrounos seems to have been a monumental fountain house for the local Callirhoe spring, sponsored by Pisistratus (Thucydides 2.15.2–3; Pausanias 1.14.1); its location is disputed. In the late sixth century the Pisistratids also built a long-distance aqueduct, bringing water from over 8 km away in the Ilissus valley in a conduit made of ceramic pipes laid, for much of its length, in a tunnel. Calcareous deposits extending only halfway up the pipe walls show that the pipeline did not run full or under pressure. In any case, the openings in the top of each pipe section, which allowed the workmen to insert a hand to plaster the inside of the joints, and were closed by ceramic covers that were not watertight, made that impossible (Tölle-Kastenbein 1994, 1996).

The archaic-period aqueducts seem to have fed only public fountain houses, but already in the fifth century B.C. it seems that people had begun to tap them illegally for private uses; Themistocles as *hydaton epistates* at Athens in 490 B.C. fined those who diverted water from the public system (Plutarch, *Them.* 31.1). How quickly, and when, aqueduct networks developed to serve uses other than public fountains remains unclear, since accurately dated Greek aqueducts are rare between the archaic and Hellenistic periods, and relatively few residential areas in Greek cities have been systematically investigated. The aqueduct of Priene in Asia Minor may be contemporary with the refoundation of that city on its present site in the late fourth century B.C.; the aqueduct consisted of a terracotta pipeline laid in a ditch covered with stone slabs. It fed a reservoir inside the walls in the upper part of the city, which in turn supplied public fountains and numerous private houses through a network of terracotta pipes. At Syracuse, the three earliest aqueducts probably belong to the reign of Hieron II (270–215 B.C.); all take the form of rock-cut tunnels with access shafts, although curiously with a second gallery excavated just above the one carrying water (R. J. A. Wilson 2000: 12–14).

Although Greek architects occasionally employed the arch (Boyd 1978; Hellmann 2002: 266–77), they did not use it to create arcades to carry aqueducts across natural depressions in the terrain. Greek aqueducts, therefore, largely followed the contours of the landscape, either in rock-cut channels or, more commonly, terracotta pipelines, which were not primarily intended to run full under pressure

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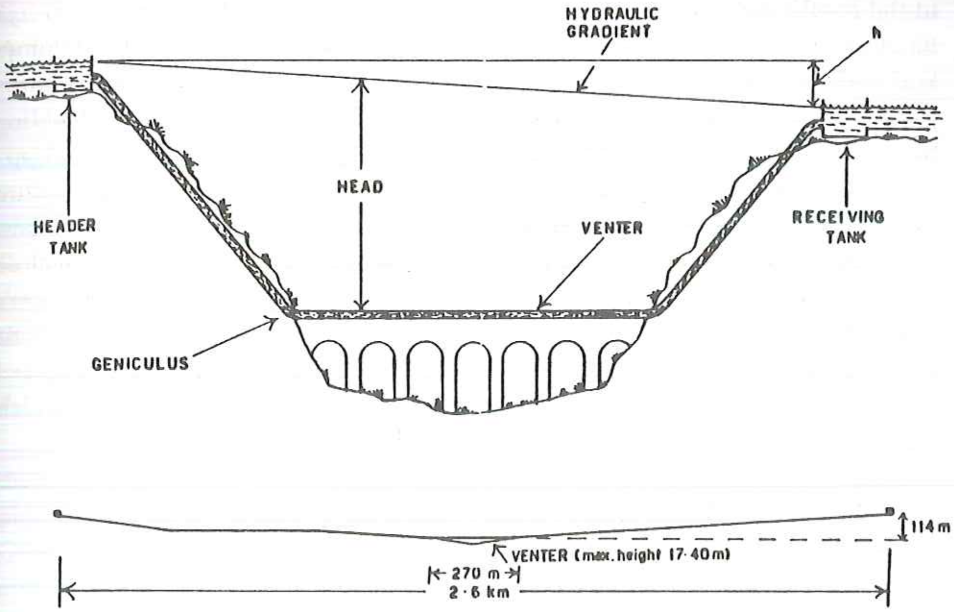

Figure 11.2. Diagram of an inverted siphon (h: loss of head). (After Hodge 1992: 148, fig. 102, by permission of A. T. Hodge.)

but nevertheless allowed a greater latitude in surveying accuracy than did an open channel. Large-gauge pipelines of about 15 to 25 cm internal diameter were used for main long-distance conduits; a double or triple line allowed for greater capacity. Greek aqueducts were, however, of relatively limited scale. The development of more ambitious, long-distance projects with complex engineering works was pioneered by the twin centers of Rome and Pergamon. Republican Rome (discussed below) led the way with the channel aqueducts of the Aqua Appia (312 B.C.) and the Anio Vetus (272–269 B.C.), while Hellenistic Pergamon developed large-scale and long-distance pipeline systems, although there was probably mutual influence between the two centers (Lewis 1999).

A key development that helped liberate aqueducts from the tyranny of the contours by enabling the crossing of deep valleys was the invention of the inverted siphon. Some of the earliest known large-scale examples are at Pergamon, although there is a small inverted siphon 10 m deep on the 8 km pipeline supplying Olynthus, dating between the sixth and fourth centuries B.C. (Lewis 1999: 157. n. 49). This structure employed the principle that water could be conveyed across a depression in a closed pipe and would rise at the other end to nearly the same level at which it entered the pipe (figure 11.2). Five Hellenistic pipelines are known at Pergamon, all later than the two earliest aqueducts at Rome. The first two Pergamene systems supplied the lower city: the Attalus line (before 200 B.C.; a single clay pipeline ca. 20 km long); the Demophon (early second century B.C.; a double pipeline also ca. 20 km long), both with inverted siphons of between 20 and 25 m depth. To bring water to the royal palace on the citadel, the engineers working for Eumenes II (197–158 B.C.) constructed an aqueduct from a spring on the Magra Dağ hill that ran for 42 km, initially in a single pipeline, but then in a double pipe and after 15 km in three parallel terracotta pipes (16–19 cm internal diameter)—perhaps as a result of adding tributary branches. The system had to cross a depression 3.5 km long and approximately 200 m deep just before it reached the citadel. The considerable pressure that the siphon had to withstand precluded the use of terracotta pipes, so it was built instead of lead pipes held in place by pierced stone framing blocks set at close intervals. Broadly contemporary with the Madra Dağ aqueduct was Pergamon's Apollonius line, followed in the later Hellenistic period by the Selinous West pipeline, both without siphons. The Madra Dağ aqueduct may well have inspired the 150 m deep inverted siphon on the Karapinar aqueduct at Smyrna, which probably belongs to the second century B.C. (Lewis 1999).

ROMAN AQUEDUCTS

Although aqueducts are often considered a quintessentially Roman engineering accomplishment, we have seen that they have a long tradition in the ancient Near East and in the Greek world, including gravity flow conduits, tunnels, pipelines and inverted siphons. The Roman contribution consisted of innovations that together enabled a much wider and more effective uptake of the basic technology: the use of arcades to carry channels over valleys and low-lying terrain; the availability of concrete as a cheap and adaptable building material; the adoption of waterproof cement linings from the Punic world or Hellenistic Sicily; the expanded use of lead piping and of bronze stopcocks on distribution systems; and the introduction of settling tanks and storage and regulation reservoirs on the network. Increasing levels of state and personal wealth helped fund the construction of numerous aqueducts, for which increasing urbanization generated demand. Aqueducts also fostered the growth of a culture of public bathing, doubtless with a feedback effect whereby the increased popularity of public baths in turn generated a need for more copious urban water supplies; by the early Principate, aqueducts and public baths had become linked features of Roman urbanism. The ornamental use of water in public fountains and *nymphaea* also became a striking feature of Roman civic architecture—coexisting with the practical function of these structures.

Bathing and ostentatious display were certainly not the driving forces, however, behind the three earliest Roman aqueducts, which were constructed long before public baths or display fountains. Rome's first aqueduct, the Aqua Appia, was built in 312 B.C.; it ran for about 16 km from springs east of Rome, and seems to have run entirely underground in a vaulted conduit until it reached the city. We do not know what structures it fed; presumably a few public fountains, and it provides indirect

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but suggestive evidence for the growing needs of the city. It was followed by the Anio Vetus (272–269 B.C.), a vastly more ambitious project, running originally for 81 km from the Anio River along the contours of the landscape, although later modifications, with tunnels and arcades, shortened its course considerably by cutting across valleys. The next aqueduct, the Aqua Marcia (144–140 B.C.), was funded with the booty obtained from Rome's defeat of Corinth and Carthage in 146 B.C. and ran for about 91 km, mostly underground, but with the final approach into Rome for some 10 km on substructures and arcades. In all, some 1.5 km were on substructures and 9.5 km on arcades (Aicher 1995: 36–37). For the Anio Vetus and the Marcia, the irrigation of suburban *horti* may have been a subsidiary motive, but this can hardly apply to the Aqua Appia, which ran underground and, in the time of Frontinus, distributed very little of its water outside the city.

In the later second century B.C. (126–125 B.C.), the Aqua Tepula was added, drawing water from warm springs in the Alban hills; for much of its course it piggybacked on the arcade of the Marcia. Three further aqueducts were added by Octavian/Augustus—the Julia (33 B.C.), again superimposed on the Marcia/Tepula arcade; the Virgo (22–19 B.C.) and the Alsietina (2 B.C.). The latter brought poor quality lake water from the Lacus Alsietinus northwest of Rome, which was used for irrigation and Augustus' *naumachia*. The continued development of Rome, with growth in population and an increase in the public bathing habit, prompted the construction of four more aqueducts: the Aqua Claudia and the Anio Novus (both begun by Caligula and finished by Claudius in A.D. 52), the Aqua Traiana in 109, and the Aqua Alexandrina in 226. The network not only became larger, but increasingly complex, with cross-links between aqueducts within Rome, to enable continued delivery of water if one aqueduct was under repair.

Rome's political and economic dominance of Italy enabled her to lead the way in developing ambitious water-supply schemes on a scale unmatched in the Greek east except by Pergamon. But in the second half of the second century B.C., other towns were beginning to follow suit. The censor L. Betilienus Varus was honored around 130/120 B.C. by his home town of Alatri for various gifts, including an aqueduct, whose final stretch carried water to the hilly citadel in an inverted siphon of lead pipes, 3 km long and 100 m deep. It has similarities with the Hellenistic inverted siphons of Madra Dağ at Pergamon and Karapinar at Smyrna, in that it follows rises in the intervening depression to reduce the length run at maximum pressure, and Lewis has suggested a Pergamene link. But at Alatri the two deepest points along the course of the inverted siphon were crossed by arcades, and the channel leading to the inverted siphon was a built conduit (Lewis 1999: 153–54, 161–62).

By the first century B.C., the use of aqueducts was spreading, perhaps slowly, throughout Italy. Research on the Pompeii aqueduct suggests that its initial phase dates from the colony founded by Sulla around 80 B.C. (Ohlig 2001)—it ran almost entirely underground from the vicinity of Avella to the north of Pompeii, feeding some public fountains and, presumably, public baths. In a further four towns of central Italy, allegedly Republican inscriptions (but not closely dated) refer to aqueducts or water supply systems built by local magistrates or decurions: Firmum

Picenum (fermo, Marche), Interamna Nahars (Terni, Umbria), Praeneste (Palestrina), and Superaequum (*ILLRP* 594, 615, 659, 671).

We begin to see Roman aqueduct construction outside Italy with Caesar's aqueduct at Antioch on the Orontes (Lassus 1983: 211; Downey 1961: 153), but the real proliferation of the technology began in the Augustan period. This development might be attributable to a concatenation of factors: increased prosperity after the cessation of civil war, the spread of the public bathing habit, and perhaps most importantly, the foundation of numerous veteran colonies which exported the Roman urban model, with its bathing and amenities, to the provinces—although not all Augustan colonies built aqueducts immediately. Augustan aqueducts at new colonial foundations within Italy include Venafro (*CIL* X.4842 = *ILS* 5743), Lucus Feroniae, Minturnae, Bononia, and Brixia (Keppie 1983: 114–16; Potter 1987: 144–45). The largest was the Serino aqueduct, a complex network running for 96 km, drawing water from sources at Serino and Avella and delivering it to several towns, including Naples, Puteoli, Nola, Cumae, Pompeii, Atella, Acerrae, Baia, and Misenum (Sgobbo 1938; Döring 2002a; 2002b), a striking example of regional planning. Augustan water-supply schemes overseas include the Cornalvo aqueduct at Mérida (Grewe 1993) and possibly the vast, doubtless aqueduct-fed La Malga cisterns at Carthage. Other projects of the Augustan period include Sextilius Pollio's aqueduct at Ephesus and the pipeline "Aqueduct C" at Berenice in Cyrenaica, probably privately funded (Alzinger 1987; Lloyd 1977: 199). The technical aid given by Rome to client kings to assist in developing showpiece Roman-style towns seems also to have included the services of water engineers: the aqueduct at Iol Caesarea (Cherchel, Algeria) was probably built by Juba II (Leveau and Paillet 1976: 151–53; Leveau 1984: 61–62), while Herod's building projects in Judaea included aqueducts at Jerusalem (also using Roman military labor) and possibly Caesarea, and his own palace/fortresses at Jericho and Herodion (Amit 2002; Porath 2002; Patrich and Amit 2002). During the first century A.D. numerous aqueducts were built in Italy, and increasingly in the provinces, but the bulk of dated provincial aqueducts date from the late first through second centuries. New aqueducts were still being built in the Severan period, but very few new constructions postdate A.D. 230, although existing aqueducts were repaired. There was some resurgence in aqueduct construction in the Byzantine period, especially under Justinian and especially in the east. In the west, the maintenance even of existing aqueducts seems increasingly to have been beyond the resources of most cities from the fifth century onward. In Rome, only four of the city's eleven aqueducts were repaired after they had been cut and blocked in the Gothic siege of 537, and their restoration and (intermittent) maintenance was a burden assumed by the popes.

The interaction between Hellenistic and Roman aqueduct traditions is shown by the fact that book 8 (on water) of Vitruvius' *De architectura* is largely derived from Greek sources, probably in particular a source from Hellenistic Pergamon. But for this reason Vitruvius' text is a poor reflection of current aqueduct technology in Roman Italy at the time he wrote. Although he has added some of his own

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material on water distribution, his account of conduit design omits all mention of arcades, the most distinctive feature of Roman aqueducts for a century before he wrote (Lewis 1999).

For most of their course Roman aqueducts usually took the form of built masonry or concrete channels, vaulted or roofed with flat slabs or gabled slabs or tiles (figure 11.3) (Hodge 1992; Bodon et al. 1994; R. J. A. Wilson 1996; A. I. Wilson. 1997, 2000a). As far as possible, the course would follow the contours of the terrain, running just below the surface in a back-filled trench. This was the simplest and cheapest method of construction, while at the same time minimizing obstacles to movement at surface level. Legal regulations protected its course from planting, to avoid the channel being fissured by roots or damaged by agricultural activity. Where the land surface rose significantly above the level of the channel, the channel had to be tunneled, using techniques described in chapter 12. In other places the aqueduct might cross lower-lying terrain, out of necessity or because this afforded a shortcut, instead of winding along the contour up one side of a valley and back down along the other. In these cases, the channel would run on a low wall or substructure, up to a height of about 2 m; beyond this height, an arcade was used, since it required less material and allowed movement through the structure. These aqueduct arcades—the modern image of the Roman aqueduct—were frequently ambitious affairs, either in their length (Aqua Claudia from Romavecchia to the city, 10 km; Carthage at Oued Miliane, 2 km; figure 11.4), or their height, achieved either through bracing arches between piers (Mérida, Los Milagros, 28 m; Cherchel; Dougga) or by stacking arcades at two or even three levels (Tarraco, 26 m; Segovia, 28 m; Pont du Gard, 49 m). The Pont du Gard on the Nîmes aqueduct is the tallest surviving aqueduct arcade, made of three levels of different sized arches; it approaches the limits of stability for an arcaded structure. As Roman engineers grew more confident in the use of the audacious arcade, in the later first or during the second century A.D., some aqueducts were shortened by replacing a section that ran upstream along one side of a valley and back down the other with an arcade straight across (e.g., at Chabet Ilelouine on the Cherchel aqueduct, and the Hadrianic Ponte S. Gregorio on the Anio Novus). Such shortening of a route reduced maintenance costs.

For reasons of both stability and cost, Roman engineers employed inverted siphons to cross valleys deeper than 50 m, or a combination of inverted siphon and arcade bridge (possibly termed *venter*), as at Aspendos and Lyon. The inverted siphons usually employed lead pipes, frequently in a battery of multiple pipes laid side by side to achieve the same capacity as the open channel and to achieve redundancy in case of pipe failure. The transition between open channel flow and the pipeline was usually achieved by means of header and receiving tanks, of which good a example can be seen near Soucieu on the Gier aqueduct at Lyon. On the aqueduct of Termini Imerese (Sicily) the siphon seems to have started as a large-diameter concrete tube dropping vertically from the base of the channel (Belvedere 1987: 61–62). In the eastern Mediterranean region, inverted siphons were frequently

Figure 11.3. Channel of the Aqua Traiana in Rome. (Photograph by A. I. Wilson.)

built as stone pipelines, constructed of squared blocks with a hole bored through and fitted together with male–female joints. These were once thought to be Hellenistic; they are now nearly all recognized as Roman in date. Many of the blocks have small holes bored through their walls, stoppered by small plugs set in mortar, probably to facilitate cleaning. Examples have been reported from other parts of the Roman world, too: Dalmatia, Italy, Gaul, North Africa (figure 11.5), and Spain (Stenton and Coulton 1986: 45–53; Hodge 1992: 33–41; A. I. Wilson 2000a: 599). The reasons for the preponderant use of lead pipes in the west as opposed to stone pipe blocks in the east remain unclear but may be related to the greater availability of lead in the western Mediterranean (chapter 4).

Small-scale aqueducts, especially those serving rural estates, might consist entirely of terracotta pipes. In the provinces of northwest Europe, some aqueducts consisted of timber pipes made from hollowed out tree-trunks and jointed together with iron rings (R. J. A. Wilson 1996: 21–23; A. I. Wilson 2000a: 602).

Ideally, aqueducts maintained a fairly consistent gradient along their course, although in practice gradients varied considerably along the course of a single aqueduct. Recorded extremes vary between falls of 0.07 m and 16.4 m per km. Where an aqueduct needed to lose height rapidly, a series of cascades or drop-shafts was used to dissipate energy (Grewe 1985; Hodge 1992: 171–97; Chanson 2000).

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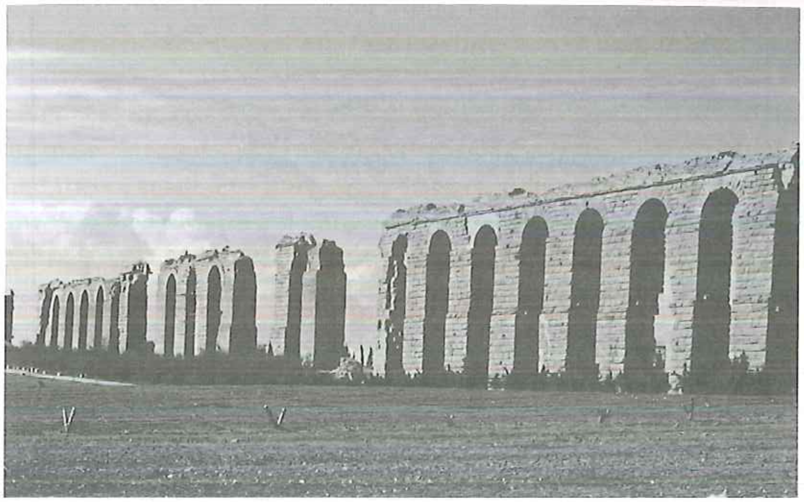


Figure 11.4. Arcade of the second-century A.D. Zaghouan-Carthage aqueduct, crossing the valley of the Oued Miliane. (Photograph by A. I. Wilson.)

Roman aqueducts often tapped sources of water with high levels of dissolved calcium carbonate and other minerals. These precipitated out of solution in the aqueduct, leaving calcium carbonate deposits (sinter) on channel walls and floor; turbulence and heat increased the rate of precipitation. As Frontinus mentions (*Aq.* 122), such deposits needed to be cleared if flow was not to be reduced and ultimately blocked, and piles of sinter fragments around shaft openings of the aqueducts in the Roman Campagna (Ashby 1935: 44) and along the course of the Nîmes aqueduct testify to such maintenance. But equally, the massive thickness of the sinter deposits elsewhere on the Nîmes aqueduct (at the Pont du Gard) and on numerous other systems, suggests that such maintenance was neither universal nor perfect.

Efforts to improve or protect water quality were made, but they took the form of mechanical rather than chemical purification. Settling tanks were sometimes provided along the course of an aqueduct, where sediment could settle out (e.g., on the Aqua Virgo and the Anio Novus; Hodge 1992: 123–24), or small basins were provided in the floor of the channel (on the Zaghouan-Carthage aqueduct), or as an afterthought added to the aqueduct (as at Siga in Algeria; Grewe 1998). Mesh filters might also be provided on distribution tanks (see below), or on the outlet pipes of reservoir cisterns (e.g., Carthage, Bordj Djedid, and Dar Saniat; A. I. Wilson 1997: 81–82) and there are occasional instances of water being filtered through sandbags (at Cirta) or through a bank of potsherds and shells (Dar Saniat, Carthage). Some improvement in the taste and odor of water could also be achieved by aerating it, for example by running it over a stepped cascade as it entered a storage or distribution cistern (A. I. Wilson 1997: 81–82).

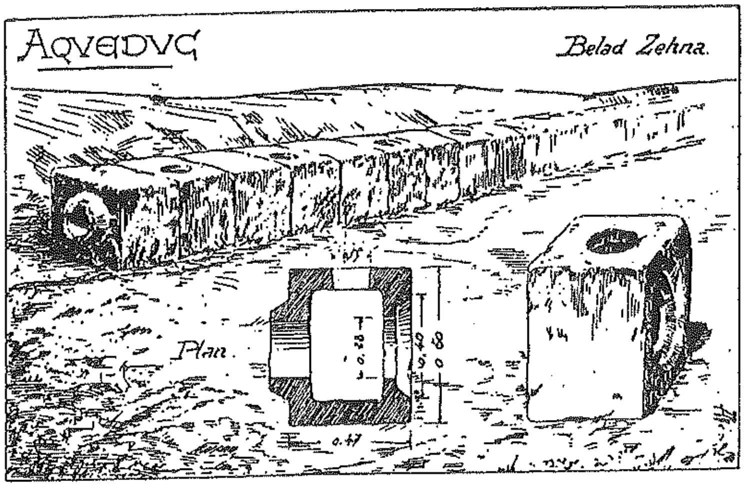
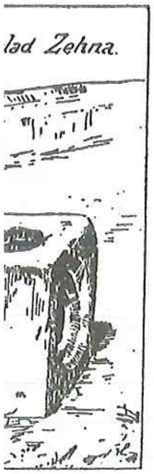


Figure 11.5. Stone pipeline aqueduct at Bled Zehna, near Dougga in Tunisia, possibly part of an inverted siphon. (After L. Carton, "Études sur les travaux hydrauliques des romains en Tunisie," *Revue Tunisienne* 312 [October 1896]: 544, fig. 17.)

THE URBAN DISTRIBUTION NETWORK

Distribution to the end user almost always occurred through closed pipes. In some larger cities areas of the town were served by branch channels, but ultimately water was delivered to most fountains and all houses through pipes (Last 1975; Eschebach 1983; Lassus 1983; Hodge 1992; A. I. Wilson 1998, 2001; Jansen 2000). The transition from main channel to a multiplicity of pipes was often made by means of distribution tanks or basins (*castella divisoria*). The earliest known such *castellum* is at Pompeii, consisting in its first phase (ca. 80 B.C.?) of an open circular basin into which the aqueduct discharged, and from which three lead mains led to different parts of the town. In its second, Augustan phase, the basin was enclosed within a roofed building and arrangements were added to allow manual regulation of flow into the different pipes; screen filters were also provided to trap debris (Ohlig 2001). At Nîmes, a circular distribution basin with five pairs of pipes leading off, presumably to different quarters of town, was also equipped with filter grilles. At Rome, the only terminal distribution tank whose form is known seems to be the elevated terminal basin of the Aqua Claudia, drawn by Piranesi before its destruction by fire; numerous lead pipes departed from a rectangular tank, elevated on tall vaulted substructures, into which the main aqueduct discharged. Smaller circular distribution chambers on the Aqua Marcia near Porta Viminalis and on the Aqua Traiana seem to belong to subsidiary branches or to have been placed upstream of the main terminus of the aqueduct (Ashby 1935: 149; Lanciani 1881: 459–61). In none of the archaeologically known *castella* is there any support for Vitruvius' principle of delivery to different classes of user being handled differently, and his proposed



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arrangements for distribution of water from a *castellum* (*De arch.* 8.6.1–2) must be treated as idiosyncratic suggestions that may never have been realized in practice (Ohlig 2001).

At Pompeii, the city whose distribution network is best understood, the pipes from the main *castellum* led to a series of 12 subsidiary distribution points, which took the form of small lead tanks (now lost) of about 1 m^3 capacity, elevated on brick towers. Pompeii is on a sloping site, the lowest parts of the town some 20 m below the *castellum*, and if the piping system had gone straight from the *castellum* to the houses in the lowest part of the city the head of pressure would have been 20 m, inconvenient for users and making operation of stopcock taps difficult. The use of intermediate open tanks, elevated on towers about 5 m high, broke the system up into segments where the head on the section to the final user was no more than 5 m, reducing the problem of excess pressure while retaining enough pressure to supply the upper stories of houses in the vicinity of each tower. Herculaneum had a similar system, but such a systematic use of intermediate pressure towers is not paralleled elsewhere. One suspects, however, that the dendritic schema of this distribution system, with a primary *castellum* from which a few pipes led to subsidiary distribution centers, from which connections led to multiple end-users, was found at other sites. This was not, however, the only model. Some aqueduct networks, such as the second-century A.D. Zaghouan aqueduct at Carthage, had distribution networks which—in their primary divisions—consisted of a binary division or bifurcation of a subsidiary channel off the main channel, with a small chamber in which sluice gates could regulate the flow into one or the other channel (A. I. Wilson 1998). Despite Frontinus' insistence that all connections to an aqueduct had to be made from a *castellum* (*Aq.* 103.4, 106.1; Rodgers 2004: 135–36, 289; cf. Vitruvius, *De arch.* 8.6.1–2), this is an administrator's ideal and did not always happen in practice. At Carthage, Volubilis, Pompeii, and elsewhere, numerous piped connections were made directly from the main channel, either inside or outside the city (A. I. Wilson 1998, 2006b).

In the eastern Mediterranean, the Greek tradition of ceramic pipe distribution networks persisted in the Roman period, and ceramic pipes were normal for urban distribution systems. By contrast, in the Roman central and western Mediterranean the use of lead pipes for distribution systems was much more prevalent. Although lead pipes on extramural lines had been used in the east at Ephesus in the archaic period (Alzinger 1987: 180) and in the inverted siphon of the Madra Dağ line at Pergamon, it is unclear when their use became common, especially for intramural distribution. The use of lead piping in the west was doubtless facilitated by the opening of large silver and lead mines in Spain in the late Republic, although lead sources are not lacking in the east. Lead piping was probably a feature of the Pompeian distribution system even in the original phase, around 80 B.C.

As with lead-pipe networks, the date of invention of stopcocks or taps, and the process and rate at which their use spread, remains unknown. The stopcock may be either a Hellenistic or a Republican invention (Hodge 1992: 322–26). Roman taps consisted of a bronze cylinder set vertically across the pipeline, in which sat a

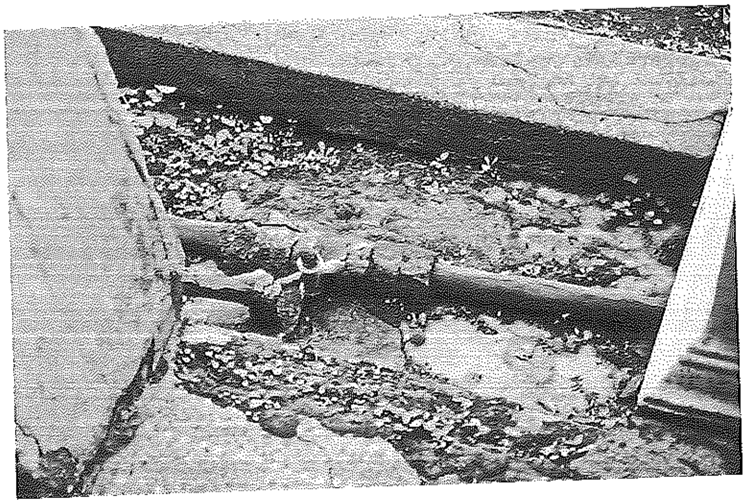

Figure 11.6. Bronze stopcock on a lead pipe supplying an ornamental fountain in the peristyle of the House of the Vettii, Pompeii. (Photograph by: A. I. Wilson.)

bronze plug pierced by a hole (figure 11.6). When the hole was aligned with the pipe, water could flow; a quarter-turn either way would shut the flow off; the action is easy, precise, and can handle fairly high pressure. Such taps are found both as stopcocks along the course of a pipe and as discharge taps to turn a fountain or spout on and off at the point of use. The widespread use of taps on urban distribution systems in the western Mediterranean seems to be a feature of the first centuries B.C. and A.D. Taps were common at Pompeii by A.D. 79, one house having as many as 33 (Hodge 1992: 322–26; Fabio and Fassitelli 1992[?]; Jansen 2002: 50–53).

Piped water was distributed to a minority of elite private houses—at Pompeii, some 10 percent of households—and was evidently a sign of status, as well as—or even more than—utility. Where domestic piping systems are traceable, there seems to be more emphasis on feeding ornamental fountains or pools rather than supplying water to kitchens (A. I. Wilson 1995; Jansen 2002; Jones and Robinson 2005).

RESERVOIR CISTERNS

Very large cistern complexes are sometimes found on aqueduct networks, which served as reservoirs. These reservoir cisterns are found in the Mediterranean region, and not in northern Europe, because of patterns of use and of precipitation. They fall into two categories: terminal reservoirs, into which the entire aqueduct discharges, and which therefore govern the entire distribution system downstream from them; and reservoirs on branches or subdivisions of the urban distribution network, which regulate supply only to their particular branch. These latter are frequently connected with large bath complexes.

Terminal reservoir cisterns are found in North Africa and very occasionally in other arid regions (Aptera, Crete; Sepphoris, Israel; Resafa, Syria), where seasonal fluctuations in aqueduct delivery affected the whole distribution network. They usually consisted either of multiple parallel, barrel-vaulted chambers communicating through arches pierced in the division walls so that they formed a single hydraulic space, or of a large cross-vaulted chamber with the arches supported on piers (figure 11.7). At the outlet, one or more lead pipes passed from the main reservoir through the wall into a chamber where the outflow could be controlled by means of stopcocks on the pipes (e.g., Hippo Regius; Rusicade; A. I. Wilson 1998, 2001). Terminal reservoir cisterns in North Africa could have a capacity of up to 50,000 m^3 (Carthage, La Malga), although most fell in the range of 3,500–13,500 m^3 (A. I. Wilson 1997: 79–80). The large reservoir cistern at the end of the Serino aqueduct, at Bacoli on the Bay of Naples, held some 12,600 m^3 and probably supplied the fleet stationed at Misenum (Hodge 1992: 276, 279). Because of rainfall on the karst aquifer from which they drew their water, the delivery of the Byzantine aqueducts of Constantinople was subject to such considerable seasonal fluctuations that several large reservoirs, so vast they could not be roofed over, were constructed within the Theodosian walls to provide a seasonal reserve capable of supplying much of the city; the reservoirs were named for Aëtius (A.D. 421; 270,000 m^3), Aspar (pre-471; 230,000 m^3), and St. Mocius (A.D. 419–518; 250,000 m^3). In the reign of Justinian, these were supplemented by several very large, covered reservoir cisterns, closer to the imperial palace, with brick roofs supported on numerous columns reused from classical buildings. The most famous is the Yerebatan Saray (A.D. 532; 83,500 m^3) and the Binbirdirek cisterns (57,800 m^3) (Procopius, *Aed.* I.11.10–15; Freely and Çakmak 2004: 55–56, 146–51).

Large reservoir cisterns specifically associated with large bath complexes are found throughout a wider area, and illustrate a solution to supplying these water-thirsty complexes while minimizing the impact on the rest of the distribution network. If these cisterns were filled overnight, the baths could run on the stored reserve during the following day, meaning that the full delivery of the aqueduct was available for distribution to fountains and private users during the day. Reservoir cisterns for baths are particularly common in North Africa and Italy, where they are associated with baths of the imperial *thermae* type: the Sette Sale, for Trajan's Baths (7,000 m^3); the cisterns of the Baths of Caracalla (11,500 m^3); the Botte di Termini, serving the Baths of Diocletian in Rome; the Bordj Djedid cisterns for the Antonine Baths at Carthage (20,000 m^3). Large supply cisterns are found elsewhere in Italy, at Chieti, and in Crete at Aptera. Aqueduct-fed cisterns on a smaller scale, 100–400 m^3 capacity, are commonly found associated with medium-sized baths (e.g., the Baths of Julia Memmia at Bulla Regia, Tunisia).

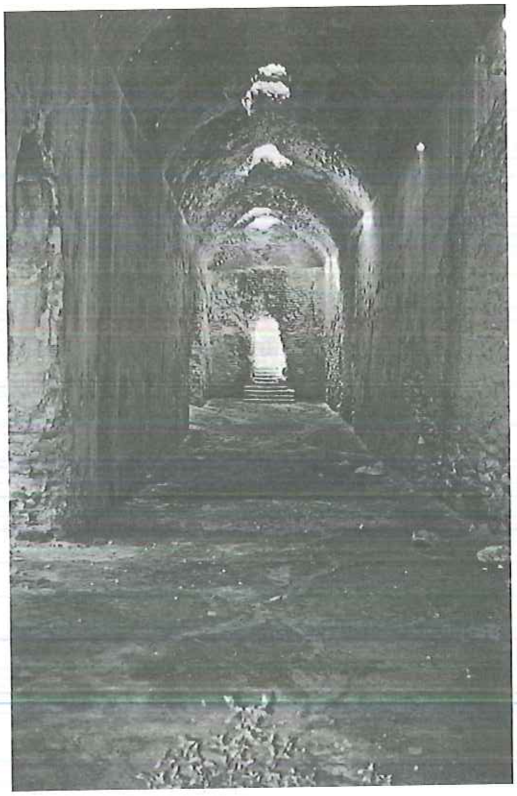

Figure 11.7. One of seven parallel vaulted chambers in the large reservoir cisterns at Oudhna (ancient Uthina) in Tunisia. (Photograph by A. I. Wilson.)

FOUNTAINS AND NYMPHAEA

The most important destination within the urban water network was public fountains. For many people, perhaps the majority of urban dwellers, these represented their main source of drinking water. We have seen that fountains were the major destination of the Greek and Hellenistic aqueducts, and of the earliest aqueducts at Rome. Many of the street fountains at Pompeii probably belong to the early phase of that system (ca. 80 B.C.); simple and functional, they consist of a stone basin with a spout, often emerging from a decorative plaque or head. Over the course of the first century A.D., however, first in Rome and then in the provinces, fountains grew more elaborate and decorative, and they were increasingly ornamented with statues, sculpted motifs, and colonnades. Nero's colossal *nymphaeum* along the east side of the base of the Temple of Divus Claudius, whose overflow fed the lake of the Domus Aurea on the site of the later Colosseum, was a precocious example of the trend. By the early second century, *nymphaea* with elaborate facades were appearing in provincial cities, initially in coastal Asia Minor and later in North Africa. These often incorporated basins in front of a curved, colonnaded backdrop with statues of deities, the imperial family, and local dignitaries who had paid or helped to pay for the aqueduct. There was every conceivable gradation along a range from functional to ostentatious, ranging from the simple street fountains of Pompeii, Herculaneum, and Saepinum to the elaborate *nymphaea* of Lepcis, Perge, or Olympia. But we should not allow the lavish architecture of the largest *nymphaea* to blind us to their utility. An inscription from Cirta (Constantine, Algeria) makes the point. Part of an inventory of the city's wealth, it lists in the *nymphaeum* 40 gilded letters and 10 punctuation points (doubtless from the inscriptions honoring the emperor or private person who paid for the aqueduct), six chained goblets with gold inlay, a fountain basin inlaid with gold, six bronze statues and a Cupid, six marble statues, six bronze Silenus-head water spouts, and six hand towels (*CIL* 8.6982 = *ILS* 4921b). This account reflects a level of wealth and display (the gold inlay and other metal ornaments) lacking in the surviving archaeology. While the lavish use of colored marbles is attested by surviving remains, precious metals have invariably been looted. The inscription also hints at the ways in which the fountain was used on a daily basis: people went to drink from the chained goblets, splashed their faces and hands from the basin, and then dried themselves on the towels, doubtless handed out and retrieved by a public slave, in whose absence they would rapidly have disappeared. Doubtless, the fountain was also a place of gossip and social exchange. At Pompeii, the importance of the unostentatious public fountains to the city's life is indicated by the fact that most houses are within 50 m of a street fountain. By the late first century A.D., Rome had 39 display fountains (*munera*) and 591 street fountains (*lacus*) (Frontinus, *Aq.* 78), and the fourth-century Regionary Catalogues list between 1,216 and 1,352 fountains (*lacus*) and 15 nymphaea. (Jordan 1871–1907: 539–74).

BATHS

From the late Republic onward, public baths were among the most demanding consumers of water on an urban aqueduct network. Greek public baths had consisted of many individual hip-baths in the same room, in which bathers would have water that had been drawn from a well poured over them by attendants. Roman baths differed in that the bathers shared large pools, and the water could be heated in large lead boilers mounted over furnaces, whose exhaust gases also heated rooms and pools by means of the hypocaust. In this arrangement, pools and floors were supported on a series of (usually) brick piers, allowing hot air from the furnace to circulate beneath before escaping up flues in the walls. The temperature of the water in hot or warm pools could be maintained by a device called a *testudo*, a bronze half-cylinder open at one end, which communicated with the pool near its base, so that it was full of water. The other end of the *testudo* was mounted over the furnace, heating the water within it; the heated water escaped upward into the pool, being replaced by cooler water so that circulation was achieved by convection. To the *frigidaria*, *tepidaria*, and *caldaria* (cold, warm, and hot rooms) of early baths, later baths sometimes added sweating rooms and indeed suites of exercise areas, lecture halls, and libraries to form veritable leisure centers. While smaller public baths were sometimes supplied from wells, usually with the aid of water-lifting machinery (chapter 13), the larger ones had to be fed by aqueducts, and the largest elaborately decorated imperial *thermae* of Rome and other major cities could accommodate hundreds or even thousands of bathers, and demanded special arrangements, such as large reservoir cisterns to minimize their impact on the rest of the network (DeLaine 1988; Nielsen 1990; Yegül 1992; Fagan 1999). The cutting of Rome's aqueducts by the Goths in the siege of A.D. 537 put the city's baths out of action, and although four of the aqueducts were subsequently repaired, public bathing never regained its former importance in the early Middle Ages. Elsewhere, public bathing also declined as the aqueducts fell out of use.

THE PURPOSE OF ROMAN AQUEDUCTS

Were aqueducts necessary to Roman cities, or were they a luxury? Early aqueduct studies assumed that these elaborate systems were primarily useful, and a marker by which Rome's civilization could be judged. From the 1970s onward, the tide of scholarly opinion began turning in favor of a view that saw them as useless luxuries, built primarily to advertise Rome's control over natural resources, to use water as an ostentatious symbol of conspicuous consumption, and to support an urban lifestyle in which public bathing played a major role—in other words, aqueducts were ideological symbols of empire (Leveau and Paillet 1976: 167, 181; 1983; Leveau 1987; Shaw 1984, 1991; Corbier 1991: 222). But today, with more attention paid to the role of public fountains in the overall pattern of water supply and to the regulation of delivery using terminal reservoirs and bath-related reservoir cisterns, this binary opposition between utility and luxury appears too stark (A. I. Wilson 1997, 1998: 89–93; 1999, 2001). The priorities of early aqueduct systems were not baths and display. Even as civic and social ostentation became important (with private display developing before civic display), the very utility of aqueducts increased their ideological impact. Much more detailed research is needed on the chronology of the spread of aqueducts throughout the Roman world, and on the chronology of the spread and development of cities in the western provinces of the empire, but at least for Rome, Pompeii, and North Africa it appears that urban growth and the building of aqueducts went hand in hand. Cause and effect cannot be completely disentangled, but we have no reason to reject the idea that aqueducts

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IRRIGATION SYSTEMS

Although the major riverine civilizations of the ancient Near East had relied on complex state-controlled systems of irrigation from major rivers, most irrigation in the Greco-Roman world took other forms (Hodge 1992: 246–53; Oleson 2000). The exception was Egypt, where the Nile flood was the main source of water for agriculture, and irrigation canals derived from the river. *Shadufs* (tip-beams with buckets lifted by a counterweight) were used to raise water out of the river or its canals, and they were joined in the Ptolemaic period by other, more effective forms of water-lifting machine (see also chapter 13 on water-lifting devices).

One of the most common forms of passive irrigation was agricultural terracing, which inhibited erosion and retained water in the soil. In arid zones such as the Negev desert or the Tripolitanian pre-desert, stone and earth walls built on the *hamada* or rock-desert plateaus concentrated on a small area runoff water from a catchment zone many times the size, thus increasing the effective rainfall equivalent on the cultivated plot. Small check dams built across the wadi floors retained water and soil from flash floods, creating fertile parcels of soil in the wadi beds that could be farmed; excess water was directed into cisterns and stored (Barker 1996; Glueck 1959; Evenari et al. 1982; Avner 2001–2002). Such systems supported a considerable expansion of settlement into these pre-desert or desert areas in the Roman and late Roman periods. On the more arid fringes of the Greco-Roman world—in the oases of the Egyptian western desert, on the southern flank of the Aurès range in Numidia, and in the Garamantian lands of the Sahara—*qanats* or *foggaras* provided water for both settlements and irrigation.

Much irrigation, everywhere, was small-scale and has left little archaeological record. The exceptions we can trace are the large-scale schemes, often representing massive investments of time, labor, and money. In the Roman period, large irrigation systems shared much with aqueduct technology. The main differences were conditioned by the requirement for larger quantities of water than for urban supply, but with less concern for quality; hence there was a greater propensity to take irrigation water by diversion from rivers, as in the Ebro valley (Spain) or the Safsaf plain (Algeria). Diversion dams are found both on permanent water courses and, in northern Tunisia, in wadis which run for only part of the year, or in spate after occasional rainfall (du Coudray de la Blanchère 1895). Other, larger dams, as at Kasserine in Tunisia, may have retained water for irrigation purposes; large concrete dams in Tripolitania may have served a similar purpose, or, as at Lepcis Magna, protected sites downstream from the erosive force of spate floods.

Irrigation channels frequently were not covered over, and they were often wider than urban aqueducts—the Alcanadre channel in the Ebro valley is 2.5 m wide with a water depth of 1.1 m (Dupré 1997: 726–29). Indeed, the Ebro valley was home to a number of large irrigation schemes; the first-century B.C. *Tabula Contrebiensis* is a bronze table recording the settlement of a dispute between two communities about building an irrigation canal over land purchased from a third (Richardson 1983; Birks et al. 1984), and a bronze inscription from Agón, northwest of Zaragoza, discovered in 1993, is a Hadrianic law regulating the use of a large irrigation system (Beltrán Lloris 2006). The Agón system drew water from the river Ebro and was evidently a large-scale irrigation system involving several communities (of which two, Agón and Gallur, were between 5 and 10 km apart) that contributed to its upkeep. The central organization and planning of this system, with legal regulations and a local court, anticipates the much better known hydraulic communities of Islamic Spain. While this inscription describes the general legal framework for the use and upkeep of the system, another (stone) inscription from Lamasba (Algeria) records the specific irrigation schedule for a local community, in the reign of Elagabalus, with details of which estates were to receive water between which hours (*CIL* 8.18584; De Pachtère 1908; Shaw 1982; Meuret 1996).

One of the underground aqueducts of Carthage, from La Soukra in the Ariana plain, was equipped with large wells or shafts (3 m x 1 m) at intervals along the channel. These shafts are much larger than normal access shafts on Roman aqueducts, and the most likely explanation is that water-lifting machinery was installed over the shafts to raise water from the aqueduct to irrigate the intensively cultivated, centuriated land northwest of Carthage. The size, shape, and chronology of the shafts suggest the use of bucket-chains, coupled with the animal-driven angle-gear (*saqiya*; chapter 13). In the early twentieth century, French colonists mounted wind-pumps over these shafts and used them once again for irrigation (Renault 1912: 471–75; Fornacciari 1928–1929). The archaeological evidence, while not closely dateable within the Roman period, confirms Tertullian's evidence for the pre-Islamic use of the *saqiya* in North Africa (*de Anima* 33.7; mules and donkeys driving *aquilegas rotas*).

While some systems were constructed specifically for irrigation, urban aqueducts were also sometimes tapped for the irrigation of estates along their course. The evidence for this practice is clearest for the network of aqueducts serving Rome (Frontinus, *Aq.* 76, 92, 97; A. I. Wilson 1999). Two inscriptions from Rome or its suburbs record the scheduling of rights to draw water to particular estates (*CIL* 6.1261; 14.3676), but the practice was more widespread. The aqueduct serving Amiternum seems to have provided off-take *castella* for several estates through which it ran, and scattered evidence indicates the use of aqueduct water by rural villas and estates in other provinces (A. I. Wilson 1999). Some villa estates in Italy, Spain, and North Africa constructed their own small-scale aqueducts to supply water for drinking, bathing, and the irrigation of vegetable plots—the latter often regulated from aqueduct-fed cisterns of 100–1,000 m^3 capacity (Thomas and Wilson 1994; A. I. Wilson forthcoming).

SEWERS AND DRAINAGE

The emergent city-states of archaic Greece made use of much the same range of drainage elements as the urban civilizations of the ancient Near East—soakaway drains for foul water, and terracotta pipes for overflow water from fountains. Until the classical period, street drains were rare in Greek cities. Athens' "Great Drain" began as a storm-drain for the agora in the fifth century B.C., but even in the fourth century B.C. much domestic waste water was discharged straight into the streets (Aristotle, *Ath.Pol.* 50.1). Although many cities (e.g., Smyrna, Euesperides) did without street drains well into the Hellenistic period, the classical era saw the adoption at some sites of integrated drainage networks, in which domestic drains fed into street drains that united in main collector drains under the principal streets, eventually discharging outside the city. In the Roman world, the foundation of numerous new colonies often allowed a more systematic adoption of planned, integrated drainage networks, with under-street drains often built of masonry. Rainwater entered the drains through gratings, either functional or with holes in a decorative petal design. Overflow from aqueduct-fed fountains helped flush the sewers, but the gradient was usually insufficient to prevent accumulation of solid wastes, and street drains periodically had to be cleared manually by public slaves or contractors. The need for access and maintenance determined a relationship between the size of drains and the manner in which they were roofed. Drains large enough to walk through might be vaulted, while smaller ones were covered with flat slabs that could be removed. Yet despite the relative sophistication of Roman hydraulic engineering, some cities still continued to have open drains until the second century A.D. Ancient drainage systems are related to increasing urban complexity, but drainage follows urban development with a considerable time lag, due to the need for strong political control, a developed legal framework of property law, and access rights prior to implementation of integrated drainage networks (A. I. Wilson 2000b).

Large land-drainage schemes in the Mediterranean region predate the archaic period; the Bronze Age drainage of the Kopais basin in Boeotia channeled surface waters to natural swallow-holes in the limestone. By the reign of Alexander the Great (336–323 B.C.) this system had failed, and an engineer, Crates, was engaged to drain the area again, a project left unfinished because of strife among the Boeotians (Strabo 9.2.18). His scheme has been identified with a partially completed outlet tunnel, with 16 vertical shafts descending to stretches of an unfinished horizontal gallery. The same kind of shaft-and-gallery tunneling technique, already familiar from Assyrian aqueducts and the aqueduct of Samos, is implied in a contract between the city of Eretria and the engineer Chaerephanes for a scheme to drain the marshes of Ptechae (*IG* 9.9.191.1; Argoud 1987). Chaerephanes was to drain the marsh by means of surface channels discharging into a collecting reservoir; this could then be drained to the sea by means of an outlet tunnel, controlled by a sluice gate that enabled the water in the reservoir to be used for irrigation in the spring. The contract stipulates what land Chaerephanes can and cannot use; he must purchase the land necessary for the access shafts to the outlet tunnel.

The same kind of shaft-and-gallery tunneling technique was used for the Etruscan *cuniculi*, underground drainage galleries that either diverted one stream under a ridge into an adjacent valley, or drained the marshy bottoms of valleys in the easily-eroded tufa landscape of South Etruria, where natural surface drainage was poor (chapter 12; cf. Judson and Kahane 1963; Bergamini 1991). The large Roman lake drainage schemes, which relied on tunneling an outlet channel (*emissarium*) through a ridge, are dealt with in chapter 12.

Extensive Roman land drainage and wetland reclamation schemes have been identified in numerous areas of Roman centuriation (in the Ager Falernus, the Campania, and the Po Valley), and also in Britain, with wetland reclamation in the Severn estuary and the partial drainage of the East Anglian fens. Here, a large drain, the Car Dyke, acted as a collector for smaller land drains from the high ground to the west, and discharged the water through a series of canalized natural streams into a roughly parallel system, the Midfendic, several miles further east. The Midfendic, protected from the sea by a sea bank, stored the water until it could be released into the sea at low tide. The backflow of water into the Car Dyke at high tide could be prevented by sluice-gates on the cross-streams. The whole system anticipates the *ringvart* systems of the medieval and later Netherlands; it was probably connected with the establishment of salt workings on imperial estates in the Fenland under Hadrian (Simmons 1979).

Notable advances were made in hydraulic engineering during the last six centuries B.C., involving not only new inventions—waterproof cement compounds, the inverted siphon, lead piping, taps, and means of conserving and distributing water—but also their increasingly widespread uptake. In the sixth century B.C. major hydraulic engineering works were exceptional projects undertaken by a handful of rulers with the necessary resources, but under the Roman Empire long-distance water supply lines and public water distribution networks became very common, so that many Roman cities had a water-supply system that was not equaled again until the nineteenth century. Ancient concepts of hygiene and public health were deficient, but the spread of organized water supply enabled a level of urban growth and development that could hardly have been achieved or sustained without reliance on long-distance aqueducts that tapped remote sources. The level of hydraulic development achieved in the ancient world is one of the key reasons why the regions making up the Roman Empire saw a greater degree of urban settlement at that period than at any subsequent time before the eighteenth century.

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