A Multidisciplinary Approach to the Characterisation and Accelerated Remediation of Nuclear Contaminated Sites: Less Intrusive Techniques and Better Use of Geographical Information System (GIS) Model Development

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ABSTRACT

Rapid, cost effective decommissioning and associated remediation of many nuclear licensed sites requires the physical and chemical characterisation of a range of bulk materials including natural soils, sediments, cementitious materials, miscellaneous historically buried waste and natural waters (surface and groundwaters). Conventional techniques (such as cable percussion drilling, rotary coring of building materials, extensive soil sampling campaigns and [ground]water sampling and analysis) tend to be expensive, time consuming, in many cases provide insufficient data and typically take several months to implement. The high level aim of the work is to reduce the overall time and cost of site characterisation, whilst maintaining quality of information and increasing the safety of field and laboratory personnel. We describe here the integrated technical approach being adopted and developed within Nexia Solutions Ltd. to provide a full *in situ* site characterisation and modelling capability, resulting in significantly reduced costs and acceleration of the Life Cycle Baseline (LCBL) of many United Kingdom (U. K.) nuclear licensed sites. The evolving technical toolbox includes many off-the-shelf technologies, as well as innovative technologies which have either been originally conceived or have been effectively adapted from a range of technical disciplines. All of the techniques here are either in use or are being actively developed and commissioned. All information gained via *in situ* techniques is used to iteratively update the Geographical Information System (GIS) conceptual model, allowing further targeted site investigation, informed decision making and optioneering.

INTRODUCTION

The characterisation, conceptual model development and subsequent remediation of nuclear-licensed sites, as a result of the inherent risks posed is both expensive and time consuming. The radiological safety risks and costs associated with the characterisation of potentially contaminated man-made and natural materials, analysis of samples for radiometric and chemotoxic determinands, and the disposal of large quantities of waste materials, forms a large part of any nuclear decommissioning budget.

Current U. K. baseline methods for identifying the extent and nature of radiologically contaminated land include the use of conventional site characterisation technologies, typically involving extensive grid sampling of surface soils and waters, large scale drilling equipment (cable percussion and rotary drilling rigs, backhoes etc.), exploratory trenches, trial pits and bailed water samples from groundwater monitoring wells. These operations often produce large quantities of secondary waste, which must be disposed of, with the potential associated radiation dose uptake by site workers. Samples are then physically and chemically analysed and, several weeks later if required, further more focussed sampling of target areas is performed. In addition to dose uptake during sampling, laboratory staff have the potential for further dose uptake during the preparation and analysis of radiologically contaminated materials.

Recent changes in the structure of U.K. nuclear management have resulted in the Nuclear Decommissioning Authority (NDA) taking control of site characterisation and remediation activities at almost all U.K. nuclear licensed sites. Individual sites have a Life Cycle Baseline (LCBL), dictating all activities required until final closure of each site, including site cleanup and remediation. In the interest of safety, saving both time and cost, and in order to accelerate these site cleanup and decommissioning activities, Nexia Solutions Ltd. are developing a technical toolbox of less-intrusive technologies capable of rapid deployment across the U.K.. These techniques will allow the necessary evaluation of radiological and chemical composition of natural soils, sediments and historic waste under almost real time conditions. Techniques have either been successfully adapted to nuclear licensed sites or, in several cases, have been developed from conception to the application of commissioned equipment. The ever expanding technical capability includes small-scale concrete and waste profiling equipment, laser induced breakdown spectroscopy analysis, remote sensing of contaminated soils, electrokinetic methods, global positioning system assisted surveys and *in-situ* Geographical Information System (GIS) modeling and evaluation of the target survey area. The results of these surveys are immediately incorporated into our customised data management system to provide integrated GIS models of the study area, 3-dimensional models of contaminated land geology, geochemistry and contaminant distribution. This combined approach has allowed rapid, good quality environmental data to be acquired, effectively modeled and used to underpin remediation strategies at key U.K. nuclear sites. The rationale described here is consistent with the Triad Approach, now being increasingly adopted within mainstream organisations including the U.S. Environmental Protection Agency (USEPA), where Systematic Project Planning, Dynamic Work Strategies and Real-time Measurement Technologies allow the development of accurate conceptual and risk based models of site contamination. This paper is intended as a general overview of an ongoing development programme which aims to evaluate, develop and apply less-intrusive technologies capable of providing cost effective, quick and safe data acquisition to underpin remediation strategies of U. K. Nuclear licensed sites.

LESS INTRUSIVE TECHNOLOGY TOOLBOX

The range of sampling and analytical techniques being applied to the characterisation of natural solids, solutions and man-made materials at nuclear licensed sites across the U.K. is evolving rapidly. Making use of fast, efficient and inexpensive tools can provide almost real time *in situ* information, take pinpoint samples of potentially contaminated materials and provide spatial physical and chemical data to be directly added to a GIS database and associated conceptual model of the target site. These technologies and their application, described in Table I, may be divided into several categories, reflecting the site characterisation process. The main categories, in terms of usage, include (i) Health, chemotoxic and radiological safety evaluation, (ii) Sample retrieval, and (iii) the *in situ* (and / or *ex-situ*) physical and chemical analysis of samples. In addition to the categories mentioned, the range of techniques may also be classified as Off-the-Shelf, Developing / Emerging and Innovative technologies. Individual techniques are described in the following sections.

In many cases, *in situ* analysis is performed on up to 75 % of solid and solution samples either during or after collection, the remainder of samples (including appropriate duplicates) being transported to external facilities for analysis by conventional laboratory based techniques. This ensures consistent quality of analytical data and compliance with regulatory controls.

Health, Chemotoxic and Radiological Safety Evaluation

In situ radiometric determinations are made using a combination of total alpha/beta and total gamma (including gamma emitter speciation) measurements taken using a UMo LB123 Monitor and portable Ortec HPGe gamma spectrometer, respectively. In addition to radiological hazards, the potential risk from conventional landfill gases, including methane and volatile organic carbon (VOC) species, is evaluated using portable Flame-Ionisation detectors (FID) and Photo-Ionisation detectors (PID). Should sufficient concentrations of volatile organic carbon be detected, a portable gas chromatograph may then be used to determine individual organic species. These measurements are used to define conventional chemical and radiological hazards and are transposed into an appropriate risk assessment and method statement, necessary for all site work.

Sample Retrieval Methods

Low-flow purge

Samples of surface waters may be collected quickly and easily using conventional methods. However, obtaining representative groundwater samples from monitoring wells may be problematic due to elevated concentrations of suspended solids and the need to purge several volumes of standing water prior to taking a sample. The low-flow purge technique for sampling groundwater has proved useful to take representative samples of water in combination with a multi-parameter solution measurement system, providing real time *in situ* chemistry information on the groundwater samples being taken to ensure a representative aquifer sample is retrieved. Comparison of this method with conventional well purge and bail methods has shown the water chemistry data to be good, but the low-flow system now used allows greater resolution of water chemistry variations to be identified within a single screened borehole.

Micro-Drilling

The excavation and sampling of geological materials, concrete and miscellaneous waste is usually time consuming and generates significant amounts of secondary waste in addition to the required sample. A small-scale drilling system (Micro-drill) has now been developed and significantly improved from an existing concrete / brick profiling system [1]. The original system involved the use of a rotary hammer drill with hollow stem drill bit. Using a t-connection, drilling detritus is extracted from the t-connector, and an in-line Hepa filter captures all particulate material larger than 0.45 μm. All material removed by the drilling process then becomes sample material and, as a result, no secondary waste is generated. The new generation vacuum assisted sampling unit (Micro-drill) has been modified and upgraded to enable the sampling of miscellaneous building waste, trench fill material and natural geological materials, in addition to brick and concrete matrices. A cyclonic filter is used to capture drilling detritus, allowing a large amount of material to be excavated. The system may then be switched to vacuum mode to allow sample acquisition within an in-line Hepa filter. This system has so far been successfully used in a number of situations including nuclear site clean up and decommissioning, as well as the sampling of miscellaneous buried waste.

Table I. Time and Indicative Cost Comparison between Baseline Technologies and Less Intrusive Techniques.

Where the Timescales and Costs Appear Similar, Either the Quality of Data or Amount of Secondary Waste (and associated dose uptake) have been Significantly Reduced

TASK	BASELINE TECHNOLOGY	TIMESCALE	COST	LESS INTRUSIVE	TIMESCALE	COST
Location of subsurface geological and man-made features						
Target site geology[1]	Grid of boreholes	Months - years	£1 M - £ 20 M	Combined geophysics, boreholes & GIS models	Months	£1 M - 5 M
Buried structure / trench position[1]	Trial pits, grid of boreholes	Few months	£1 M - £2 M	Combined geophysics, aerial photogrammetry & GIS models	Few weeks	
Buried metal distribution[1]	Grid of boreholes, metal detection devices	Few months	£50 k - £250 k	Combined electrical resistivity, OhmMapping, EM61 metal detection & GIS models	Few weeks	£50 k - £100 k
Soil / sediment / rock sample and subsequent elemental / chemical and radiometric analysis						
Surface sample (0-10 cm)	Trowel, hand sampler	Few months	£1 k - £3 k per sample	Portable Laser Spectroscopy, portable XRF	Few Hours[**]	Low £ 100's per sample for 75 % of samples[2]
Contaminated soil location[1]	Trowel, hand sampler; grid of sample locations	Few months	£ 30 k - £100 k	Portable Laser Spectroscopy, portable XRF	Few weeks[**]	£ 5k - £20 k
Shallow subsurface sample (10 cm - 1 m)	Hand auger, excavator	Few weeks	£1 k - £3 k per sample	Vacuum drilling technique, portable Laser Spectroscopy, portable XRF	Few Hours[**]	Low £ 100's per sample for 75 % of samples[2]
Deep subsurface sample (1m - 100 m)	Cable percussion and / or rotary drilling rig	Few months	£ 50 k per borehole	Sonic drilling	Few months	£20 k per borehole
Concrete / cementitious waste / miscellaneous building materials						
Surface sample	Hand tools	Few days	£5 k - £10 k	Portable LIBS and XRF	Few hours[**]	Low £100's
Concrete core (from slab / plinth)	Diamond core rig	8 hours per 1 m core	£1 k - £2 k	Vacuum drilling technique	45 mins per 1m core	Low £100's
Concrete wall profile	Diamond corer	Few hours	£1 k - £2 k	Vacuum drilling technique	Few minutes	Low £100's
Groundwater sampling and subsequent elemental / chemical and radiometric analysis						
Groundwater flow direction[*]	Groundwater monitoring well installation	Months - years	£ 1 M - £2 M	Ground based and airborne geophysics surveys	Few weeks	£ 30 K - £100 K
Fluid leak detection	Aquifer monitoring well(s)	Months - years	£ 100 k - £ 1 M[1]	*In-situ* leak detection	Few days	£ 200 k - £300 k
Major element chemistry	Bailed water samples with well purge	Weeks to months	£ 2 k - £3 k per sample	Low flow purge sampling (no well purge)	Weeks to months	£ 2 k - £3 k per sample
Trace element chemistry	Bailed water samples with well purge	Weeks to months	£ 2 k - £3 k per sample	Low flow purge sampling (no well purge)	Weeks to months	£ 2 k - £3 k per sample
In-situ parameters	*Ex-situ* measurement on sample	Few hours	Low £100's	Profiler (pH, Eh, °C, TDS etc.)	Few minutes	Low £10's

* Indicative time and cost depends upon size and complexity of target site. ** Indicative time and cost applies to approximately 75 % of samples taken.

In Situ Characterisation and Chemical Analysis

Geophysical Site Characterisation

A combination of standard geophysical techniques have been used to great effect within radiologically controlled areas. These techniques include EM61 metal detection, high resolution shallow (0 - 100 m) seismic and moderate to deep (200 - 300 m) seismic surveys, direct contact- and induced electrical resistivity surveys, gravity profiles across a range of features, ground penetrating radar (GPR) and magnetic surveys. Appropriate combinations of these techniques have quickly provided site characterisation information on buried metallic waste / structures, localised lithology distribution, kilometre scale geological structures and the nature of shallow buried materials.

Groundwater Profile Analyser

A multi-parameter sensor [2], allowing simultaneous solution measurements, has been used to gather *in situ* information on static water bodies as well as to profile boreholes without the need to sample the water and take *ex situ* laboratory measurements hours to days following sampling. The most useful combination of parameters has so far been dissolved oxygen, conductivity (Total dissolved solids), temperature, pH, redox conditions, nitrate, chloride and ammonium concentrations. Stratification of water within boreholes and the detection of chemically distinct groundwaters *in situ* allows the addition of such data to be rapidly incorporated into an existing GIS database, aiding conceptual model generation.

Field Based Metal Analysis

Major- and trace metal analysis may be performed on non-radioactive powder pellets using our portable XRF instrument, allowing the duration from sample acquisition to preliminary chemical information to be reduced to several tens of minutes. One limitation of this method is the sample preparation required (mortar and pestle to powder samples and pellet manufacture by pressing), which may potentially lead to contamination and increased contact with samples. In order to mitigate these limitations, *in situ* laser induced breakdown spectroscopy (LIBS) is being developed to allow instant semi-quantitative chemical analysis. This method will provide an effective screening tool and will be used to reduce the total number of samples taken. This method also reduces contact with sample materials and the necessity to excavate surface samples for analysis.

In-situ Gas Analysis

A routine requirement for the characterisation of miscellaneous trench and landfill waste and organic-rich contaminants within geological porous media is the analysis of volatile organic carbon (VOC) species. The current baseline technology in the UK is to sample gases from new excavations using both portable Flame Ionisation detectors (FID) and Photon Ionisation Detectors (PID). In addition to these techniques, we are also using a small portable gas chromatograph in order to assess the concentration of total organic carbon as well as determine individual organic species.

Portable Laser Induced Breakdown Spectroscopy (Portable LIBS).

A system is currently being developed to allow the rapid screening of potentially contaminated soils and building materials. The semi-quantitative chemical analysis method utilises laser induced breakdown spectroscopy, with fibre optic delivery of laser light to the sample surface. This method was originally described for the detection of explosives residues [3] but is equally applicable to soils and sediments. Large areas may be quickly screened to determine the location of soils potentially contaminated with heavy metals, organics and radionuclides. This will allow targeted soil sampling campaigns to be carried out with savings in time and the cost of chemical analysing "clean" samples. This method would not replace the laboratory analysis, but will provide a useful screening tool for rapid site characterisation of an unknown area.

Combined Small-Scale Vacuum Drilling with Chemical Analysis

The Portable LIBS system is being adapted to enhance our vacuum drilling equipment (see previous section) to allow semi-quantitative *in situ* chemical analysis of natural and manmade materials during small-scale, shallow drilling surveys. This will provide effectively real-time chemical information and allow the nature of materials encountered to be partially characterised without the need to remove the drill string from the hole, or immediate *ex situ* analysis, reducing potential dose uptake and minimising contamination of the surface area at the drilling location.

In addition to the techniques described, additional techniques are being developed which may form part of the evolving less intrusive toolbox. These include the application of neutron probes to determine the spatial distribution and identity of materials, as well as their radiological speciation. 3D underground mapping is envisaged as a field based product to augment geophysical investigations in on nuclear licensed sites.

Geographical Information System Databases and Models

Geographical and spatial site characterisation information is currently used to generate conceptual models of the target site in the form of an ESRI ArcGIS geodatabase. This conceptual model may be updated and fine-tuned using newly acquired data, placed directly into customised layer files. Spatial interrogation of Health Physics data, *in situ* chemical and geophysical information may then be displayed within 3-dimensional ArcScene displays.

Survey locations are determined using a sub-meter accuracy global positioning system (GPS) integrated with ArcGIS to allow real time updates of site information and layer files. The GPS system is used to supply data acquisition and survey locations. This system includes GIS software, allowing surveys and additional information to be added to layer files in the field. Survey locations and newly acquired chemical information may then be used to update the evolving conceptual model.

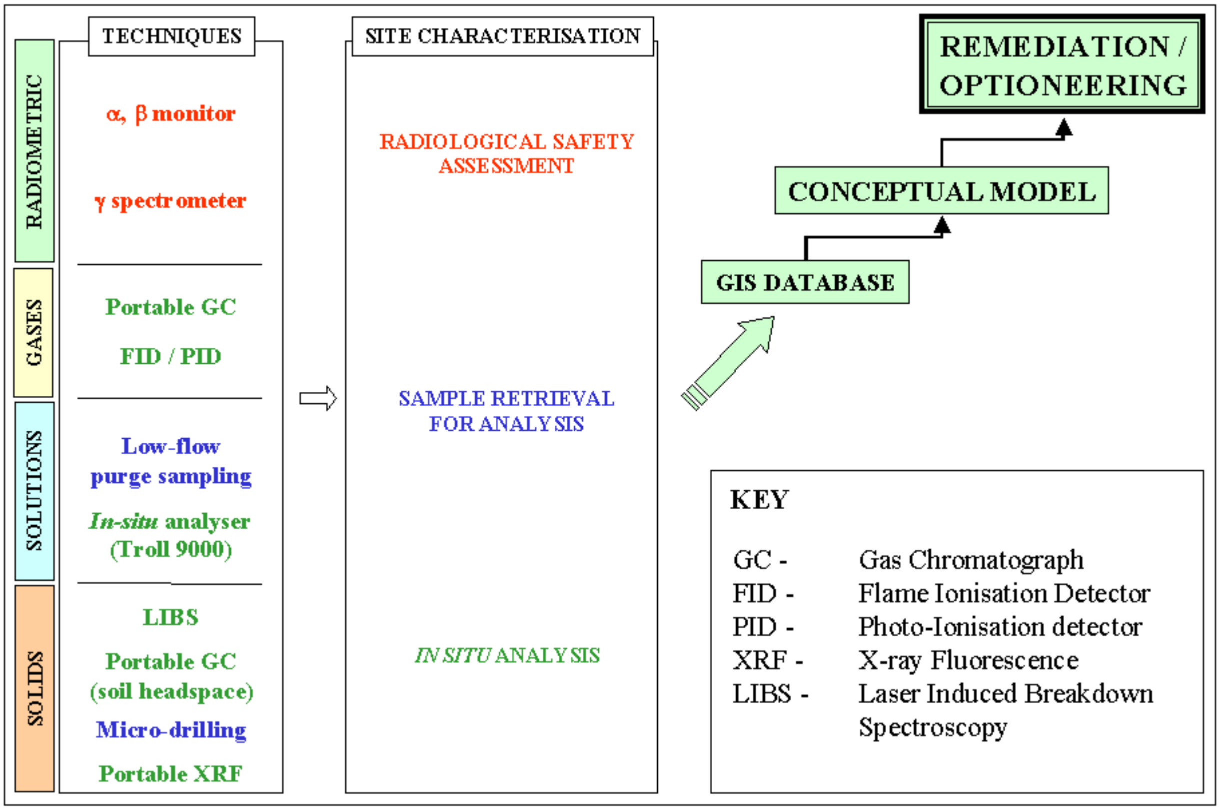

Fig. 1. Summary of less intrusive *in situ* techniques used and their input to site characterisation, associated GIS models and subsequent conceptual model development.

CASE STUDY : HISTORIC WASTE TRENCHES: CHARACTERISATION AND GIS MODELING

Selected techniques from the multidisciplinary approach described above have been successfully used to characterise a series of historic waste trenches within a radiologically controlled area at Sellafield. These trenches contain, for the most part, building rubble and miscellaneous wastes including a significant percentage of metal objects disposed of during the 1950s. The objectives of the work were to delineate the exact position of the trenches in relation to Ordnance Survey coordinates and to determine their depth and the areal distribution of any buried metal. The resulting information was fed directly into a 3-dimensional model of this area, and used to underpin proposed stabilisation and site remediation strategies.

The trench cap is currently used as scaffold storage compounds with a busy access road for vehicles. Physical access to the area for site characterisation work was therefore difficult due to the presence of scaffold stillages and regular transport movements. The use of conventional large scale drilling equipment would have required the site to be completely cleared and traffic movement prevented for several months during the drilling and site works. Hundreds of kilograms of waste materials would also have been generated. It was therefore decided to apply a combination of geophysical, aerial photogrammetrical and other less intrusive techniques to establish the physical characteristics of the trenches, and compare these parameters with existing information.

Required Site Characterisation Information to Underpin Remediation Strategies

Due to the minimal requirements for accurate site records at the time of the construction and filling of the disposal trenches, accurate site coordinates were not available. The exact depth of each trench was not recorded during trench construction, making the volume of stored waste material impossible to calculate. The quantity and distribution of metal within each trench was also uncertain, resulting in a lack of definitive inventory information. The specific site location, trench depths and distribution of buried metal were required in order to construct a realistic conceptual model of the trench system.

Technologies Employed

A summary of techniques employed is provided in Table II. Aerial photogrammetry was initially used as a general method of assessing the depth of any open trench recorded during previous works. This was only possible for one of the trenches (photographed during operations). A prior extensive site characterisation programme resulted in the installation of several tens of boreholes in the immediate vicinity of the trenches, but unfortunately none in the trench area. A combination of geophysical methods were chosen in order to take advantage of the shallow trench depth, partially metallic composition of the trench infill and the local geological setting. One shortfall of the non-intrusive geophysical surveys is the lack of any waste inventory specific information to determine the nature and extent of any radiological contaminants present. This was addressed by the use of the Micro-drilling method described previously, to allow the extraction of waste samples from the buried heterogeneous waste.

Table II. Summary of Surveys Carried Out as part of the Less Intrusive Site Characterisation.

Survey	**Equipment used**	**Purpose of survey**
Health Survey		
Landfill gas survey	Flame Ionisation Detector (FID) Photo Ionisation Detector (PID)	Detection of landfill gas accumulation within enclosed areas above the historic trenches
Health Physics Surveys		
α, β & γ surveys	DP6 Health Physics monitor	Measurement of radiation dose at the surface of the scaffold compound areas above each trench
Subsurface geophysical surveys and assessment of geophysical techniques in the Separation Area		
Buried Metal Detection	Time Domain Metal Detection System	Determine spatial distribution of metal within the trenches
Ground Penetrating Radar	Radar system (250 MHz antenna)	To determine the spatial distribution and orientation of trench fill
Microgravity	High Precision automated gravity meter (1 microgal resolution)	Measurement of microgravity anomalies along transects over trenches to determine trench width, density of trench fill and depth of individual trenches
Electrical Resistivity	Ohmapper towed resistivity array.	Determination of trench distribution and depth

Example of Site Characterisation Information Obtained

Fig. 2 illustrates the nature and effectiveness of the geophysical surveys of trenches in an area difficult to access. A combination of data obtained using different methods, including aerial photogrammetry, multiple geophysical surveys and targeted small scale drilling, resulted in a well defined conceptual model of individual trenches and the areal distribution of buried metal within them. Information about the local geological environment allowed interpolation of lithology distribution across the trench area.

In comparison to exploratory drilling and trench excavation within the trench area, the geophysical techniques provide a far higher resolution of spatial information, albeit somewhat interpretive until ground-truthed by physical sampling. Apart from the lack of information density required in the trench area, conventional methods would simply not have been possible in this radiologically controlled area with persistent traffic movements.

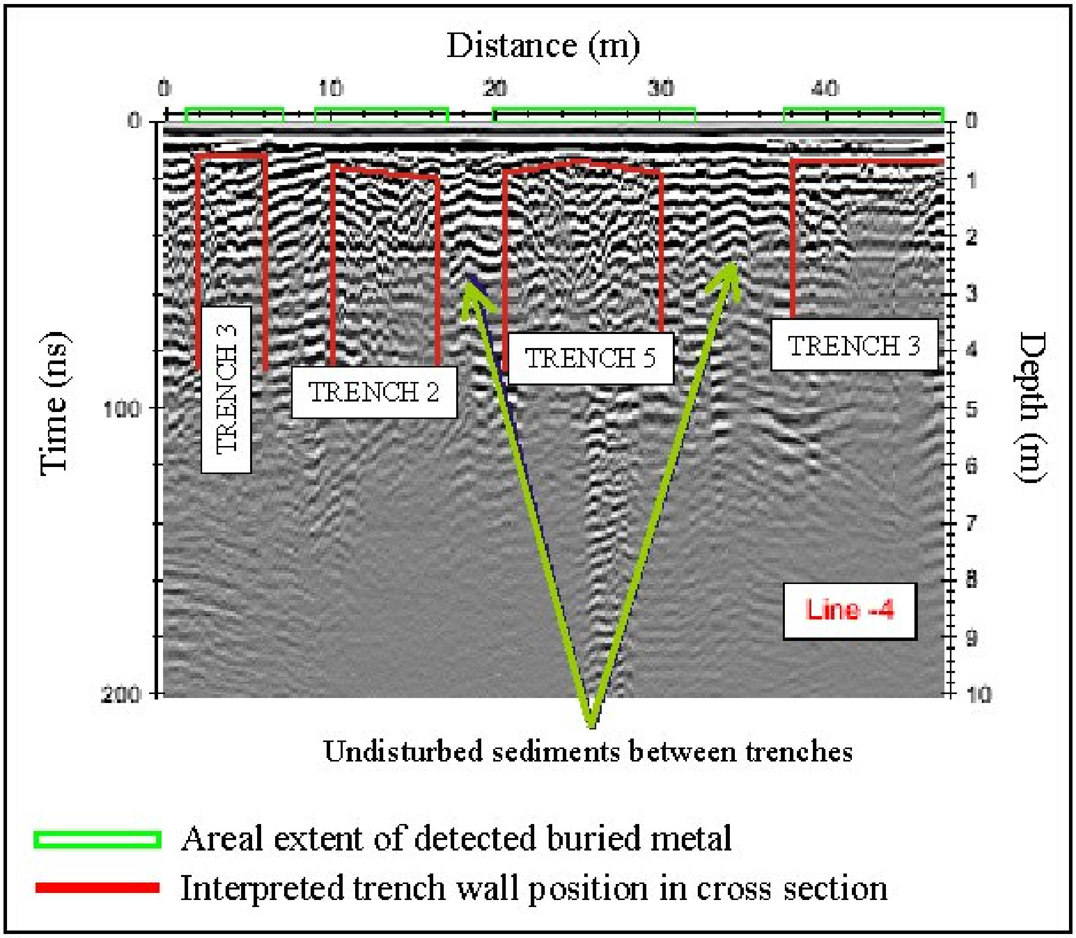

Fig. 2. Example of interpreted trench locations (from ground penetrating radar (GPR) in relation to buried metallic waste signatures along a transect of four buried waste trenches. Trench wall locations were interpreted from combined GPR, EM61 (metal detection) and archive aerial photographs.

Resulting 3-D GIS Representation and Conceptual Model of Trench Area

In order to evaluate effective remediation strategies for the trench area and buried waste materials, a combination of the geology, hydrogeology, aquifer distribution, trench dimensions (and therefore buried waste volumes), location and surrounding utilities and local land usage had to be combined. A conceptual 3-dimensional model was therefore developed using a combination of existing site information and newly acquired data (Fig. 3).

The general geological framework was constructed using fence diagrams and electrical resistivity and shallow seismic information tied directly to site characterisation drilling logs in the immediate vicinity of the trench area. Geological cross sections were then balanced and compared with ground penetrating radar information to delimit the extent of between-borehole lithologies and unconsolidated sands and gravels. The resulting model was consistent with that accepted for the general area and includes up to 20 m of glacial sediments unconformably overlying sandstone bedrock. Fluid flow pathways through the trench area were confirmed by comparison of water chemistry and effectively chemical tracer testing upstream and downstream of the trench area. All geophysical information was then placed into this physical model, resulting an a 3-dimensional conceptual model which allows representation of several complete datasets simultaneously. Fig. 4. schematically illustrates the basic components of the model.

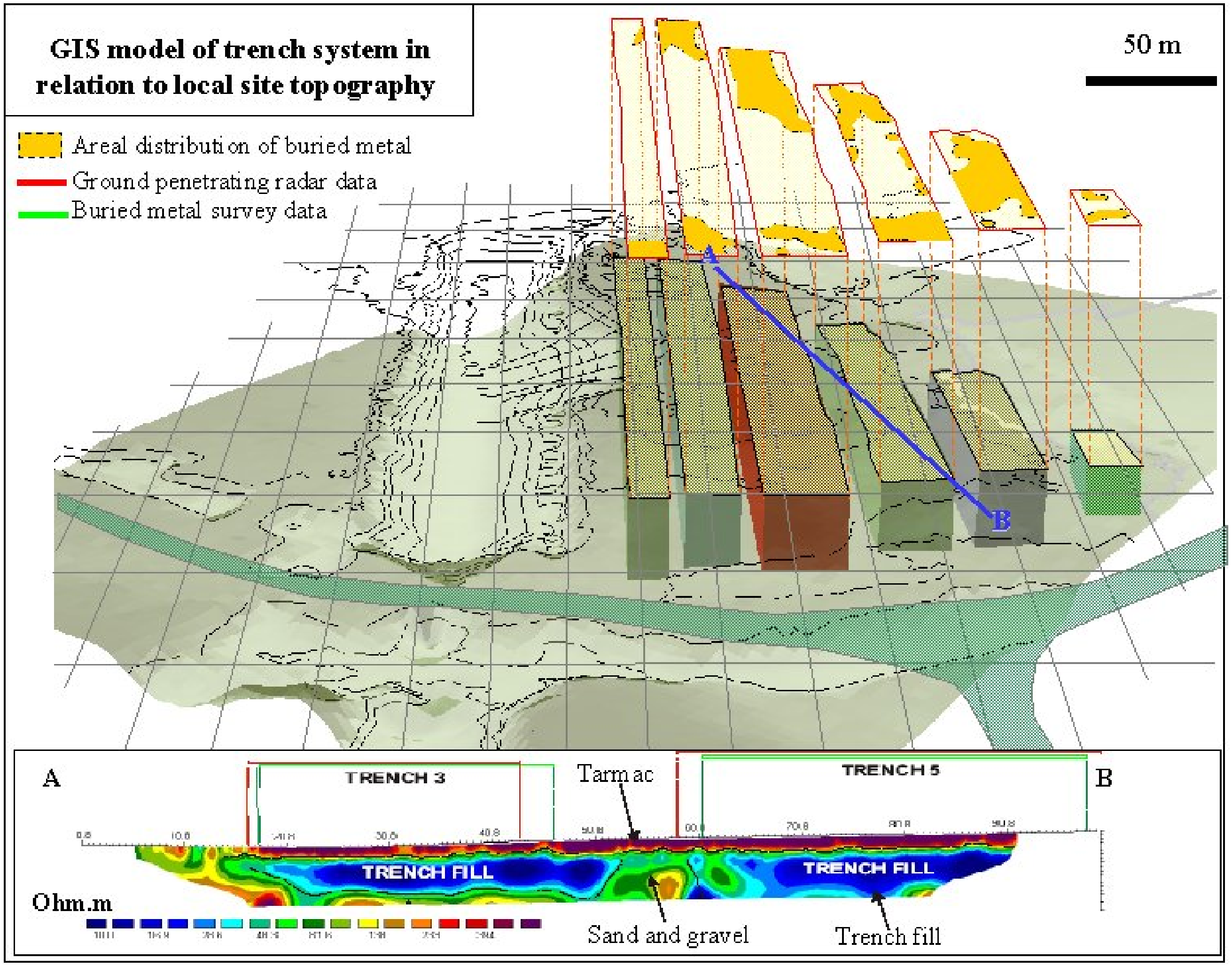

Fig. 3. Schematic diagram illustrating the use of multiple data sets to produce a cohesive 3-dimensional model of the historic waste trenches. This allows a robust conceptual model to be developed and forms the basis for targeted characterisation and remediation strategies.

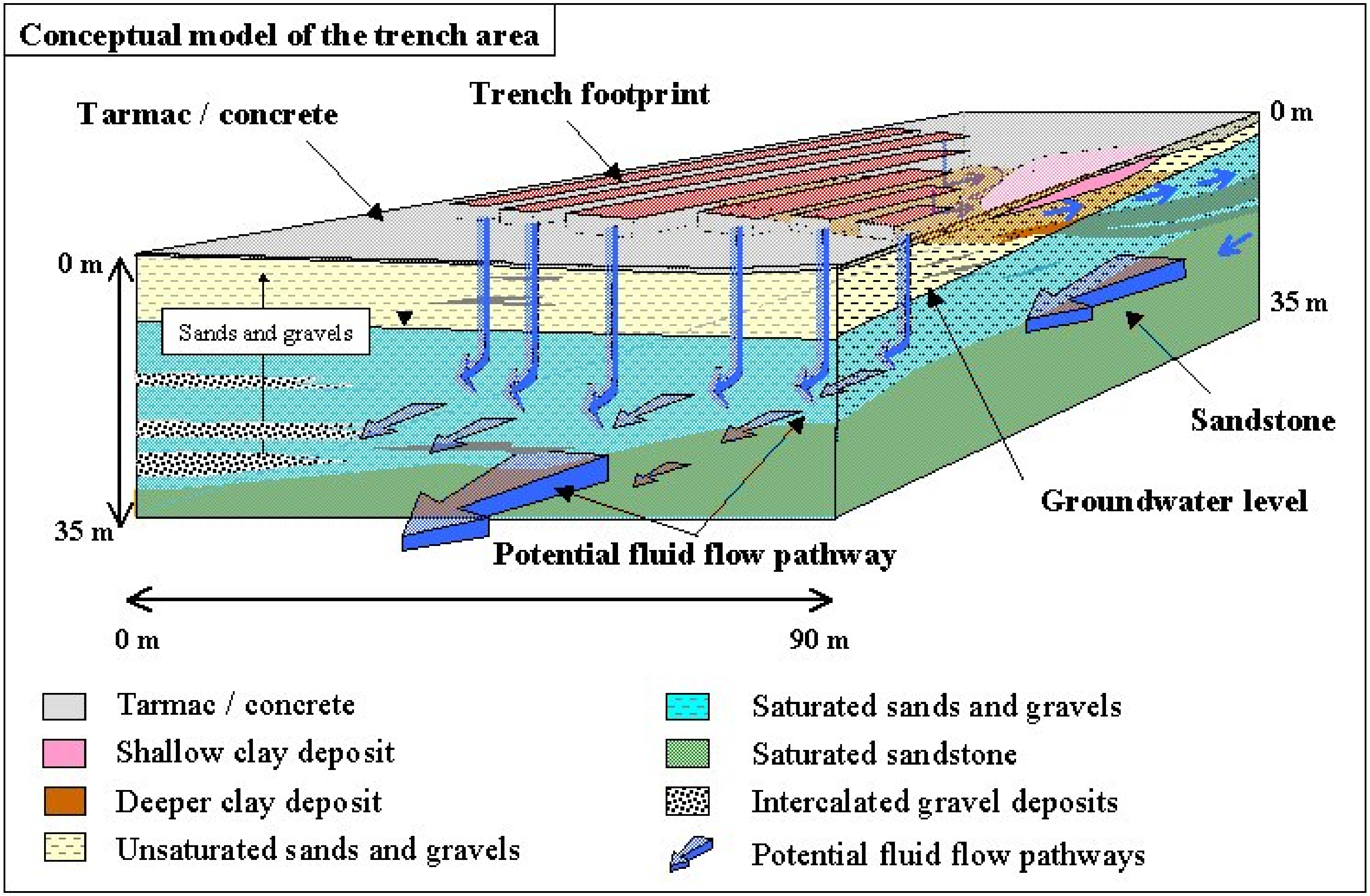

Fig. 4. Conceptual model of the disposal trenches resulting from the combination of geological, hydrogeological, geophysical and geochemical data sets.

BASELINE ACCELERATION, COST SAVINGS AND ADDED VALUE

Following a detailed cost-benefit analysis of this work to establish time and cost savings, as well as overall benefit, the following conclusions were reached. As a direct result of the less intrusive site investigations, the project area had:

- A better understanding of the uncertainties and liabilities associated with Source Term
- Acceleration of remediation optioneering process against the accepted site Life Cycle Baseline Plan
- Demonstrated rapid cost effective characterisation techniques that can be applied to other nuclear licensed sites.
- Demonstrated reduction in dose to operators/safer working practices for site characterisation
- Demonstrated significant reduction in waste generation during site characterisation
- Reduced regulatory pressure by demonstrating proactive management of significant liability

It was calculated that current baseline methods, including conventional borehole drilling within this area to delimit trench fill materials and depths, would have cost in the region of £7 M, and would have taken several months to a year to complete. Using a combination of geophysical methods, aerial photogrammetry and small scale sampling, the same amount of information was gained for approximately £200 k. In addition, this data was retrieved within 3 weeks and without core logging and the generation of several hundred kilograms of waste material requiring disposal.

CONCLUSIONS

Significant improvements in the speed of site characterisation and development of conceptual models of sites are possible using an appropriate combination of less intrusive technologies. These technologies may not, in many cases, fully replace conventional methods but at least allow a more informed site characterisation approach to be taken without significant delays or hold points within a programme.

In the case study discussed, the site specific information gathered effectively increased the confidence in the physical and chemical characteristics of the trenches, and so directly informed, underpinned and accelerated suitable remediation strategies for this area. This was achieved with minimal radiological dose uptake and produced higher resolution spatial information than possible with baseline methods.

The technology toolbox is continuously evolving to incorporate emerging technologies and is envisaged to become the standard approach to site characterisation and remediation in the U.K.

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