From concept towards reality: developing the attributed 3D geological model of the shallow subsurface

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ABSTRACT

In recent years, engineering geology has been trying to redefine itself in terms of a set of 'core values' or 'special scientific principles.' John Knill (2003) illustrated the essence of engineering geology in the engineering geological triangle. One way of trying to understand the relationships between some of the 'core values' is through the engineering geological ground model, which seeks to combine understanding of the spatial distribution of engineering boundaries with knowledge of rock and soil material, and mass, properties and the geological processes that alter these through time. The rapid development in information technology over the last twenty years and the digitisation of increasing amounts of geological data has brought engineering geology to a situation in which the production of meaningful 3D spatial models of the shallow subsurface is feasible. The paper describes how this can be done and points the way to the next stage that involves the attribution of these spatial models with physical, mechanical and chemical property data. Some new developments in the provision of geohazard susceptibility information at the national scale are also discussed. A future is proposed in which site investigation sets out to test a pre-existing spatial model based on real data, rather than trying to create such a model based on concepts alone.

INTRODUCTION

In his Hans Cloos lecture, Sir John Knill (2003) implied that engineering geology was at a key point in its development. He showed that many of the pioneers of engineering geology in the first half of the 20th century, and leading figures in the second half, struggled to define the “special scientific principles” of Morgenstern (2000) that underpinned engineering geology. Knill tried to set out what he believed was the purpose of engineering geology. He noted that from the 1960’s the profession had developed:

- a simplified, adequate and reliable terminology and descriptive system;
- systematic methodologies;
- consistent, internationally recognised, classification systems.

He also thought that engineering geology had a “proper role … which contributes to minimising risk, cost over-run and delays within the engineering process.” However, he noted that engineering geology was still focussed on case histories, material properties and site investigation. This implies that, at its heart, engineering geology is, still, the application of geology to civil engineering design and construction driven by the continued involvement of engineering geologists in site investigation. Though what is investigated has broadened in the last twenty years, or so, to embrace hazard and risk assessment associated with, for example contaminated land, waste disposal and geohazards, site investigation remains central to what engineering geologists do. This emphasis has also been the main driver for engineering geological research.

A series of Working Parties of the Engineering Group of the Geological Society (in the UK) (for example Anon 1970, 1972, 1977) and, internationally, Commissions of the International Association of Engineering Geology and the Environment (IAEG), the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) and the International Society for Rock Mechanics (ISRM) (for example, Anon 1981a, b) were set up to establish high and consistent standards of mapping, description, classification, investigation and testing. While work is still needed, for example on the classification and description of artificial deposits (Rosenbaum et al. 2003), in developing risk assessment methodologies, and in improving communication to non-geological professionals and to the general public (for example, Rosenbaum and Culshaw 2003), it can be argued that the current phase of research activity is in decline (Griffiths and Culshaw 2004). Indeed, the IAEG is currently (2004/5) reviewing all its Commissions to decide whether they still have a role and, if so, what that role should be (Baynes 2004).

Knill (2003) tried to identify the direction in which engineering geology should be moving now that the 'standard setting' phase is nearing completion. He suggested that one area in which work was needed was with regard to analysis and synthesis of engineering geological information contained in the published literature and in site investigation records and reports. He noted that this activity was now being facilitated by the rapid development of powerful computer hardware and software. However, what he seemed to have had in mind related mainly to the synthesis of available information and experience in relation to specific rock types, such as mudrocks.

This paper seeks to show how information technology now makes the storage, management, validation, analysis and synthesis of large quantities of engineering geological data possible. Examples of some of the outputs that have become available in the last few years will be discussed and pointers to possible future developments provided. Central to these new developments are national, state and regional Geological Survey organisations because of their key role in acquiring geological information in both analogue and (increasingly) digital form, digitising the analogue information and designing, storing and managing the expanding databases. However, equally important is the way in which the assembled information is passed back to the user community.

The paper also seeks to answer a basic question:

> Is the ground so inherently variable, from a geotechnical perspective, that it is not worth trying to build predictive ground models based on actual data?

Or, put another way:

> Is it worth attempting to move from the conceptual ground model of Fookes (1997) towards 'real' ground models?

In attempting to answer this question, the paper will critically examine a modified version of Knill's (2003) engineering geological triangle (Figure 1) to see how near we may be to combining the three elements to produce the ground model (Anon. 1999a) for use by geotechnical engineers. The three elements described by Knill are:

- The geological model: characterising and interpreting geological boundaries (including groundwater) (Culshaw et al. 2002).
- Geological material and mass properties: determining their variability and attributing the geological model.
- Geological processes: for example, forecasting the uncertainty about the location, magnitude and timing of sudden and more gradual ground movements (geohazards) and changes in the quality, quantity and movement of groundwater.

In this discussion, it will be argued that, while the digital 3D geological model of the shallow subsurface attributed with property information is within sight, we are still some way from adding the effects of geological processes.

However, the ability to produce 3D geological models begs a number of questions that were raised in a discussion at the 9th Congress of the International Association of Engineering Geology and the Environment in Durban, following Knill's Hans Cloos Lecture (Baynes and Rosenbaum 2004):

- What are the models for?
- Who are they for?
- What is the minimum content that constitutes a useful model?
- Should there be rules for constructing the models?
- How can the quality of models be assured?
- What metadata should accompany the models?
- How should uncertainty associated with the model and its plausibility be described?
- How can the models be kept up to date as new information becomes available?

These questions put flesh onto the bones of some of the challenges to subsurface characterisation research posed by Rosenbaum (2003):

- "The *representation* challenge: to find ways to express the infinite complexity of the geological environment using the binary alphabet and limited capacity of the digital computer.

- "The *cognition* challenge: to achieve better transitions between cognitive and computational representations and manipulations of geological information – to recognise what is seen.
- "The *uncertainty* challenge: to find ways of summarising, modelling, and visualising the differences between a digital representation and the real phenomenon.
- "The *data* challenge: to respond to the increasing quantity of data being collected and archived, to respond to the increasing sophistication of the data content, and to the demands of complex analysis.
- "The *simulation* challenge: to create simulations of geological phenomenon in a digital computer that are indistinguishable from their real counterparts.
- "The *provider's* challenge: the role of the geoscientist as an information provider (through the use of models) is placing increasing emphasis on the requirement to be customer-orientated; the focus on the 'end-use' of the knowledge that is being imparted – and should the provider interpret the information? Where does responsibility lie?
- "The *user's* challenge: ensuring the end use of a material or product is made clear – to facilitate a 'performance basis' to ensure that the model is both 'fit for purpose' and 'fit for end use' – should the user interpret the information? Where does responsibility lie?"

THE RELATIONSHIP BETWEEN SITE INVESTIGATION PRACTICE AND THE USE OF EXISTING INFORMATION

Broad standards for site investigation were first defined in Britain more than fifty years ago by the Civil Engineering Codes of Practice Joint Committee representing the Institutions of Civil Engineers, Water Engineers, Municipal Engineers and

Structural Engineers (Anon. 1950). This Code of Practice has been revised several times (Anon. 1957, 1981c, 1999b) becoming a British Standard Code of Practice (CP2001) at the 1957 revision. Norbury (2004) pointed out that the Code had only an advisory, rather than compulsory, status but that there is a legal expectation that the Code will be followed when referred to in contracts.

The 1950 Code did recognise the importance of the desk study and the collection of relevant existing information. The committee was aware that the site investigation should be planned, initially, "according to the strata and structures expected to exist as shown by geological maps, reports and records of boreholes in the vicinity…" However, given the availability of data at the time and the amount of understanding of the geological variability of the near-surface, it is inevitable that the standard is, at its heart, concerned with ground investigation as:

i. "The exploration of the foundation conditions to determine the sequence of the strata, the extent of each soil and rock and, if necessary, the geological structure of the site.
ii. "The procuring of representative samples of the soils and rocks so that their characteristics as they may affect design and mode of construction of the proposed structure, can be determined.
iii. "The investigation of ground-water conditions." (Anon. 1950)

This emphasis is understandable, as the amount of, for example, relevant geological information available (in addition to the published academic literature) was largely limited to geological maps at one inch to one mile scale (1:63 360) (and less commonly six inches to one mile scale [1:10 560]) together with sheet memoirs and related unpublished information held on file. Since the publication of the original Code of Practice, this situation has changed significantly in two ways:

Firstly, there has been an increasing recognition of the usefulness of existing information. Forty years ago Roberts (1964) drew a distinction between, what he referred to as, exploration and investigation. The former was carried out in a predetermined fashion, taking little account of existing knowledge and not altering the exploration design as new information was acquired. The latter was planned in phases, beginning with the desk study, with almost continuous review of what was found, after first establishing the “background conditions.” The only advantage of the exploration approach was that it appeared to be cheaper in the short-term. However, Roberts showed that use of this approach was short-sighted, often leading to greater costs later.

Most of those involved in site investigation would agree that the gathering of existing information is vital and yet, only just over a decade ago, and despite the recommendations of various standards, the Institution of Civil Engineers felt it necessary to commission a report on the importance of site investigation (Site Investigation Steering Group 1993[1]). This report again emphasised the importance of using existing information at the desk study phase.

So, existing information is widely regarded as important but what do we mean by data and are these data available and useable? Data, themselves, are of little value or use without ‘context.’ What users need is information, which is data in context. For example, knowing, in three dimensions, the location of the top of a site investigation borehole (the ‘x, y, z coordinates’) would seem to be essential if the information from the borehole is to be of value. Yet, sometimes, perhaps in the interests of speed and economy, boreholes might be located either using a local grid referencing system or in relation to local landmarks. This method of locating the borehole sites might be

[1] The Group was reconvened towards the end of 2004.

adequate for the duration of the investigation and probably the subsequent construction phase. However, someone wishing to reuse the data later will only be able to do so if the national grid coordinates of the origin of the local grid have been recorded or if the local landmarks to which the site investigation was referenced remain and can be identified.

Similarly, elevation is an important parameter that needs to be known if correlations between boreholes are to have any meaning. This is, potentially, a more expensive parameter to obtain accurately than the (x, y) coordinates because a levelling survey to the nearest benchmark might be required. Alternatively, the elevation might be determined to about the nearest metre using global positioning systems (GPS) or digital elevation models (DEM). However, even if the elevation has been determined instrumentally, this does not mean that uncertainty has been removed. For example, it is sometimes found that when the elevation of a borehole is plotted against the current ground surface the borehole is located either below or above that surface. This results from either the removal of ground or the placing of fill after the investigation. However, the user of the data is left with a degree of uncertainty as to the accuracy of the stated elevation.

The second change in information management has been the rapid development of computer technology and associated software. This enables the more efficient storage and management of larger quantities of information. We can also process, analyse and synthesise more information, more quickly than was possible before the development of personal computers. Information technology developments over the last twenty years have seen large improvements in the sophistication of database design and the amounts of data that can be held. The development of geographical information systems (GIS) has enabled spatial information sets to be combined and compared and new information sets to be derived. Increasingly sophisticated computer programmes have been written for modelling of processes such as groundwater flow and the failure of slopes. More recently, developments have taken place to produce improved software for the three dimensional modelling and visualisation of the shallow subsurface (for example, Sobisch and Bombien 2003)

It has always been recognised that site investigation involves the development of a simplified three-dimensional model of the site. However, as has been indicated above, this was often created after the ground investigation, rather than before or during it. The idea that a site investigation should be designed on the basis of a conceptual ground model was subsequently developed by Fookes (1997) and Fookes et al. (2000). They argued that from a knowledge of the geological and geomorphological environment of a site, it was possible to create a conceptual model that was indicative of the likely ground conditions and which could then be tested by the ground investigation. Fookes et al. (2000) suggested that the conceptual model created should be based around one (or more) of seventeen generic geological models dealing with the bedrock geology and eight covering superficial deposits and landforms. The advantage of this approach is that it can be applied in almost every location on earth based upon our understanding of how the near-surface has evolved due to ancient and modern processes.

However, is this the best that we can do? Will the quality of site investigation only be improved by a better understanding of the processes that have shaped the Earth to better help us predict the likely ground conditions? Or, can we begin to use the information that we have started to collect and store to produce better models based upon it?

NATIONAL GEOLOGICAL DATABASES

Traditionally, the main role of Geological Surveys has been to collect geological information on a national basis, to store and manage it, to analyse and synthesise it and to provide the results to the user community to a high and consistent standard. In the beginning, very little information was available so Geological Surveys went out in the field and collected it, providing the results of their work as maps, sections, memoirs, and reports. This activity was paid for by the State because, while the benefit for the nation, as a whole, was high (as shown by various cost benefit analyses, for example, De Mulder [1988, 1989], Bernknopf et al. [1993], Bhagwat and Berg [1992], Roger Tym and Partners [2003]) no individual user group gained enough benefit to justify commissioning the work as a commercial proposition. This was because the systematic collection of data on the ground is generally labour intensive and time consuming, and hence expensive. As the State paid almost all of the cost, the outputs were usually made available at only the cost of reproduction and distribution.

While the mapping of a country was in progress, government did not usually challenge the continuation of a Survey, though it is interesting to note that the Soil Survey of England and Wales was incorporated into the then National Soil Resources Institute (NSRI) in 1987 part way through its programme of mapping the country pedologically at a scale of 1:50 000. As a result, national systematic soil survey in England, Wales and Scotland had effectively ceased to function by 1987 (Jarvis 1999). Soil map coverage remains incomplete at 1:50 000 scale, though complete coverage exists at smaller scales. Problems arose for Geological Surveys in two ways. First, governments might seek to close down a Survey if it was perceived that mapping was complete. In the United Kingdom this first happened in

1900 when the Wharton Committee was set up to examine the Survey's role, including its potential termination. This review was triggered because the Survey had largely completed the initial task of geologically mapping Ireland, Scotland, Wales and England at a scale of one inch to the mile (1:63 360), begun in 1835 (Bailey 1952). The Survey survived this examination, which was not repeated until the UK government's Prior Options reviews of the early-mid 1990's. This threat is of little consequence to the users, in the short term, as long as they believe that they have the information that they need and that coverage of the country is complete, of an acceptable standard and reasonably consistent.

The second problem was that governments realised that information can be financially valuable and, as a result, expected Surveys to earn a greater return on their costs. This creates tensions. The United States Geological Survey generally does not charge for data. However, the British Geological Survey and some other European Surveys do. The UK Government endorsed this policy in responding to the recommendations of the 2003 Royal Commission on Environmental Pollution. The Royal Commission had recommended that:

- Data which have been gathered in the public name and for the public good should be available electronically at no cost for public use (Recommendation 12).
- Government should adjust the financial model for public bodies holding and developing essential data sets (such as the Natural Environment Research Council [NERC] and the Ordnance Survey [OS]), replacing income from sales of environmental information with direct grants. A market element should be retained by relating the level of grant to the public use made of a body's data sets (Recommendation 13).

- Relevant public sector bodies would be under a statutory obligation to give free access to their information (Recommendation 14).

In response, the UK Government agreed that access to public *registers* (metadata bases) or lists of environmental information should be free of charge but that the NERC and OS should have financial models in which the public and private sectors pay for the information that they use. This policy has the effect of relating the funding of such organisations to the public use made of their data sets. It was argued that this promotes the efficient use of resources by providing users with the incentive to identify their priority requirements and the supplying bodies to respond with value for money services. Thus, provision for public authorities to make environmental information available at a reasonable charge, where appropriate, was considered to be in the interests of fair competition. Where information was made available on a commercial basis, and where this was necessary to guarantee the continued collecting and publishing of such information, a market-based charge was considered to be reasonable. Also, the approach is endorsed by EC Directive 2003/4/EC. Charges for digital data include three elements: a licence administration charge, a charge for preparing and delivering the data, and a charge for use of the data. Where data belonging to other organisations are provided (with permission) (for example, most borehole logs) there will be no data use charge.

In the UK, the activities of the Geological Survey are little influenced by legislation. Survey geologists have the legal right to access private land (following certain procedures) but this right very rarely needs to be enforced. The Mining Industry Act (1926) (as extended by the Petroleum [Production] Act [1934] and updated by the Science and Technology Act [1965]) requires those that sink mineral boreholes or shafts deeper than 30 m (100 feet) to lodge the logs with the Survey (and allow inspection of cores). Similarly, the Water Act (1945) covers wells and boreholes for water extraction deeper than 15 m. However, these Acts also are very rarely enforced. As the legislation concerned with the lodgement of borehole logs was introduced prior to, or shortly after, the Second World War[2], it was not applied to site investigation boreholes, presumably because it was believed that there were very few of these and that, as most site investigation boreholes are quite shallow (less than 30 m), the information that they could provide was of little relevance at the time. As a result, there is no legal obligation for the logs of site investigation boreholes and trial pits to be provided to the Geological Survey. In other countries this may not be the case; for example, in Finland the Helsinki City Authority requires site investigation information to be lodged with it at the planning stage. This is used to improve the three dimensional model of the geotechnical conditions beneath the city, the latest version of which can be obtained by enquirers at a nominal cost (Paul and Chow 1999). Few other City Authorities around the world seem to have followed this example, though some, such as Glasgow in the UK, have built up substantial holdings of site investigation reports on a voluntary basis.

In the past, geologists logged major excavations for roads and railways, and borehole logs were provided by owners to assist with mapping. There were few tensions in this process as no payments were made or expected. Matters changed in Britain when the Geological Survey became required to earn a proportion of its income from ‘commissioned research’ following the Rothschild review of 1972. Government Departments commissioned a wide range of applied research, much of it in urban areas. Whereas in the past geologists had collected a few site investigation borehole logs, they now set about semi-systematic collection from local

[2] Registering of all records of borings and well-sinkings began in 1895

authorities, utility and transportation organisations and geotechnical consultants. The data were catalogued and stored. Owners usually provided the data free while the Geological Survey made a small charge for copies of non-confidential borehole logs to users. This led to a belief that owners were being charged for their own data, regardless of the fact that some organisations handed over all their data to the Survey also passing on the storage and handling costs. Nevertheless, data owners began to realise that data was valuable and that the more data that was held, and the greater its coverage, the more valuable it became. There is little doubt that an absence of legislation covering the national archiving of site investigation data and the financially-motivated reluctance of some data holders to share their data for the greater good, combined with a belief that the Geological Survey is in competition with consultants, has held back the development and interpretation of national databases of geological information. While the lack of availability of suitable, easy to use computer software has been the main constraint on new developments in the use of information from the shallow subsurface, the process has been prolonged by the time taken to acquire data, and validate, standardise and digitise it.

As indicated above, for geological and geotechnical data derived from site investigation to be of use beyond the immediate requirements of the project for which it was derived, the data must be accompanied by sufficient additional information so that non-project users can set it in its spatial context. Second, the site investigation data must be produced to recognised national and/or international standards. Engineering geologists have spent much of the last forty years establishing such standards for the description and classification of rocks and soils. Third, the data should be transferred in digital form using a common electronic data exchange standard. Such a standard was developed over a decade ago in the UK by the

Association of Geotechnical and Geoenvironmental Specialists (now in its third edition, Anon. 1999c). At the current time, the British Geological Survey receives around 10 site investigation reports a month using the format compared with around 150 in conventional paper format. Fourth, the data must be passed to an organisation, or organisations, charged with the maintenance of the data. As indicated above, there is no legislation to ensure this happens with regard to site investigation data. Perhaps the time has come when this should be changed. Fifth, the data must be stored and managed at a location that allows access according to a set of clear and acceptable conditions (for example with regard to copyright, confidentiality and cost). This is becoming less significant as the capability to provide data over the web increases. Sixth, the data must be catalogued, stored/databased, managed and made available to users by a data management organisation. Index data about the data (metadata) must be provided. Culshaw et al. (2005) described metadata as “a method of describing a data item, dataset or group of related datasets so that potential users can determine if they are fit for the intended use.” Because site investigation information is highly variable in terms of the purpose for which the data was collected, the quality of the data itself, the amount of and type of data in any particular report and the changing standards and codes of practice that might apply to the data, this variability needs to be documented by the metadata so that the limitations and constraints are adequately understood by users. National and international standards have been developed for metadata (for example, Anon. 2003). These define the ways in which any spatially located information should be documented in metadata. Figure 2 shows the metadata provided for the deep mine coal data held by the British Geological Survey’s National Geological Records Centre. Information on the source and nature of the data is given.

In the case of geotechnical databases this involves inputting data obtained from site investigations (little arrives at the British Geological Survey in digital form, as indicated above), checking it and managing the resulting database. Whilst the British Geological Survey does manage a geotechnical database containing data on over 250 000 samples from Britain, nothing has been published about the database because until adequate geographical coverage has been achieved, potential users are likely to be put off if they repeatedly find their location of interest has little data for it in the database. Elsewhere, geotechnical databases are occasionally described in the literature. Lundin et al. (1973) discussed the setting up of a Swedish geotechnical database, Wood et al. (1982) and Day et al. (1983) described a pilot databasing study based on records from the Thames Estuary, England, and Lovell and Lo (1983), López Palancar and Garcia Yagüe (1986), Hartevelt (1987), Ishii et al. (1992) and Howland (1992) described databases for Indiana State, USA, Madrid, Spain, the Netherlands, Tokyo, Japan and London’s docklands respectively.

In many countries, the recipient of such data is the Geological Survey or a related, state owned data management organisation (as was the case in much of eastern Europe during the communist era). It is conceivable that such data could be stored and managed by a private company, particularly if set up by, and on behalf of, the national geotechnical industry. However, in all likelihood, such a company would end up being pushed to become financially self-supporting from data licensing and product sales and this might constrain the amount of investment that could be put into the development of storage facilities, improved access and product development. Such data management companies do already operate effectively in the UK and elsewhere, but they are mainly interested in digital data and in serving mass, rather than specialist, markets.

However, despite these tensions, attitudes appear to be changing and there is an acceptance that the managed storage of site investigation data in one place is in the interest of users and providers. The result of this is that the density of coverage of site investigation data for many urban areas is just about sufficient to allow the production of attributed three dimensional models of the shallow subsurface that should enhance and change the way site investigation in these areas is carried out.

THE 3D SPATIAL GEOLOGICAL MODEL

The geological map is a two dimensional representation of a three dimensional object – the ground. As such, it is a form of geological model. The use of the term 'map' to describe this model confuses it with different types of map such as topographical or hydrographical ones that provide only a representation of a surface. This difference is fundamental. The makers of topographical maps are able to observe almost 100% of what they record, whereas geologists might see less than 1%. The geological map is, therefore, an interpretation.

The first modern geological maps (using stratigraphical principles) were produced by William Smith in Britain, by Cuvier and Brongiart in France, and by Werner in Germany. Smith was able to trace sequences of rocks because he recognised groups of fossils that characterised rocks of a particular age. In 1799 he produced a small geological map of the area around Bath based on the relative age of the strata (the stratigraphic succession) (Figure 3). It was the first map of this type and it used a topographical map as its base, a principle that has continued to the present. Smith was only concerned with the practical applications of his newly discovered approach and he struggled to write down descriptions of his work.

Following the publication of William Smith's geological map of southern Britain in 1815 and a description of it a year later (Smith 1816), the Geological Survey of Great Britain was formed in 1835. The Ordnance Survey (then the Ordnance Trigonometrical Survey) had been formed in 1791 to produce topographic maps of Britain and (subsequently) Ireland. When Major General Thomas Colby took over as Superintendent of the Ordnance Survey in 1820, he intended that the topographic maps should serve as the base for geological survey. Captain J Pringle was asked to form a geological branch in Ireland in 1827 but the work lapsed when it became clear that the surveyors were not adequately qualified to supply the geological information. Partly at the suggestion of Sir Roderick Murchison (the President of the Geological Society), a geologist, Henry De la Beche, was recruited to the Ordnance Survey and in 1835 the Geological Ordnance Survey was formed. Richard Griffith, a Fellow of the Geological Society, took over the work in Ireland and in 1845 the Geological Survey of Great Britain and Ireland was formed as an independent organisation (Owen and Pilbeam 1992).

It is interesting to note that in his Presidential Address of 1836 to the Geological Society, Charles Lyell described how the Survey came about and noted that in a report prepared by himself, William Buckland and Adam Sedgwick they stated that it was "… fully our opinion as to the great advantages which must accrue from such an undertaking not only as calculated to promote geological science, which would alone be sufficient object, but also as a work of great practical utility, bearing on agriculture, mining, road-making, the formation of canals and railroads and other branches of national industry." (Bailey 1962). In other words, the Geological Survey was seen as having a strong practical emphasis in which engineering geology played a large part.

In passing, it is worth noting that the French Geological Survey had similar practical origins and may have preceded the Survey in the United Kingdom (the latter is often claimed to be the first in the world). Between about 1825 and 1841 engineers of the Corps Royal des Mines produced a geological map of France at a scale of 1:500 000 (Eyles 1950). Though the French Geological Survey (Service de la Carte Geologique detaillee de la France) was not inaugurated until 1868, it could be argued that because the earlier map was produced by public servants at the expense of the government, this constituted, in effect, the first geological survey.

And so, in Britain, in Ireland, in France and elsewhere, geological surveying began. By the First World War, some eighty years later, Britain and Ireland had been mapped at 1:63 360/1:50 000 scale. However, it was realised from the beginning that the information that was being presented was of a three-dimensional ground model. The problem was how to visualise it. Geological maps were accompanied by vertical and horizontal sections. However, these were quite hard for non-geologists to understand and so solid geological models were also constructed and displayed in the Museum of Practical Geology in London (incorporated into a predecessor of the British Geological Survey but now part of the Natural History Museum). Amongst the earliest three-dimensional, solid geological models produced were those of Thomas Sopwith who reproduced twelve bedrock geological situations in wood (Turner and Dearman 1979). Sopwith demonstrated these models at the Institution of Civil Engineers in 1841. In museums small-scale dioramas included horizontal geological sections.

A geological map is not a piece of paper

Crucial to the development of geological mapping has been the medium on which the geological interpretation is portrayed or visualised. From the publication of William Smith's first geological maps until the 1980's, all but the simplest maps could only be visualised on paper or film, though experiments took place earlier into digitally producing geological maps (Rhind 1971) and some forms of digital geological contouring (for example, Coe and Cratchley 1979). Turner (1991) described the application of 3D geoscientific mapping and modelling to hydrogeological studies, while Turner (2003) discussed the historical development of 3D digital geological models. The application of 3D modelling to offshore aggregate assessment in Hong Kong was described by Orlić and Rösingh (1995). Not surprisingly, the information technology revolution has had as big an effect on the development of geological maps as on other aspects of life.

A map consists of *points*, *lines* and *polygons*. Modern computer software allows these to be held digitally. Consequently, all aspects of a geological map can be held in digital form. In addition to the points, lines and polygons, the software also allows the holding of other information such as text, data tables, photographs, diagrams etc., which can be 'attached' to a point, line or polygon. This additional information can be called-up when the digital geological map is used. On a paper-based map this additional information is better known as the 'key' or 'legend.' However, the amount of additional information that can be provided is limited by the area of paper available to print the information. With a digital map, the amount of additional information that can be included is limited mainly by the time taken to input and check the data and the capacity of the computer hardware and software to store and process it.

This ability to hold additional information in a digital map system opens up new possibilities. A digital map that is simply a display on a computer screen of what could also be presented on paper does not represent much of an advance. As described earlier, the map is an interpretation of the three-dimensional geology and, as such, is a synthesis of a lot of different data types. Sometimes a paper-based map will include a cross section of the geology, which is an interpretation of the geology on a vertical plane. Because of the lack of space, only a few sections can be printed on paper and these sections may not be in the places of interest to the map reader. If the computer-based map simply reproduces these cross sections on a screen little has been added. However, the ability to hold additional information allows the possibility of producing a cross section in any chosen direction. By adding information from boreholes, for example, cross sections that link these boreholes together can be created. In most of the major urban areas of the UK thousands of boreholes have been sunk in the last fifty years. The British Geological Survey holds the logs of around 1 million of these boreholes. Consequently, there is a huge resource of information that can be used, provided that the resources to digitise and check it are available.

A further advantage of the digital geological map is that it can be updated regularly. Paper-based maps, if updated, can only be made available by reprinting. This is expensive and also makes the existing unsold maps redundant. However, it is likely that many decades will pass between updates. For some remote areas, the current map may be up to 150 years old! With the digital map this situation changes. The map can be updated every day and when a user requires a copy they can have the latest version. Also, the user is no longer restricted to receiving a map of a rectangular area. Any outline can be specified, such as a local authority boundary.

Applied geological mapping and the use of geographical information systems (GIS)

In the late 1970s a programme of applied geological mapping was begun by the then Department of the Environment (UK). The key aim of the mapping was to provide appropriate geological information to land use planners (Brook and Marker 1987). It was envisaged that a series of map outputs would be produced; these would be of three types: factual maps, derived maps and synthesised (or summary) maps. The full range of applied maps produced for England and Wales was described by Smith and Ellison (1999) but additional studies were also carried out in Scotland (Culshaw et al. 1990, McMillan and Browne 1987). The early map outputs were all in paper form (for example, Deeside, North Wales [Culshaw 2004]). In the 1990's, with the development of more sophisticated geographical information systems (GIS), the maps were produced digitally and some of the derived maps were produced directly from combinations of other, factual maps. The first applied geological mapping project covered Bristol and the last (in 1996) the Bradford Metropolitan area (Waters et al. 1996).

The penultimate project covered the Wigan Metropolitan Borough (Forster et al. 1995, 2004). A technical report described the geological data collected, discussed the implications of the geological conditions for the area and presented the information in a comprehensive and structured format. This report was supplemented by a database that indexed the various relevant sources of geological data for Wigan. Nine factual and derived maps accompanied this report. The content of these maps indicates how the requirement of geological maps has changed in the last twenty years. Two of them are consistent with the traditional style of litho-stratigraphic maps. These maps, showing the bedrock (solid) geology and the superficial (drift) geology, underpin the other maps, forming the basis for the derivation of many of them. In other words, many of the other maps use some, or all, of the linework from the stratigraphical maps but then describe the different areas enclosed by the lines (polygons) in ways that are appropriate to the theme being covered.

The themes covered by the nine maps are indicated in Table 1, together with an explanation of the nature of the theme and the intended users. The themes covered indicate the nature of the geological issues that are important in Wigan. Elsewhere, other issues might be more important and so, alternative or additional maps might be produced. For example, in Bradford, where similar work was carried out (Waters et al., 1996) landslides are a potential problem. As a consequence, mapping focussed on this hazard and the number of known landslides increased from around twenty to over two hundred. A map showing the extent of landsliding in relation to the steepness of the ground was included as one of the thematic maps.

The second report provided a guide to the ground conditions in Wigan for non-geological users, mainly land use planners. This report was written largely by planners, rather than geologists. It provided an analysis of ground conditions in the context of the planning and economic factors that operate in the Wigan area. This analysis considered particularly:

- the extent of derelict land;
- the means of, and proposals for, remediation of such land;
- the impact of adverse ground conditions on development costs;
- the relationship between ground conditions, economic development policies and potential grant aid.

The second report was accompanied by a synthesised map that showed the key geological factors relevant to planning and development. These factors were:

- abandoned shallow mineworkings;
- the potential for contamination of land by past and present industry, including landfill sites;
- the potential for groundwater contamination;
- mineral resources;
- major faults that might act as pathways for the transmission of gases and liquids.

Though the maps produced for Wigan and Bradford were produced digitally, thus enabling the map area to be cut to the local authority boundary, they were not 3D maps. Such derived and synthesised geological maps, produced in a GIS environment, can be regarded as the final and most sophisticated form of the 2D map that can trace its UK origins back to William Smith’s 1799 map of Bath (Figure 3).

Superficial deposits thickness model of Great Britain

While engineering geologists deal with all types of rock and soil, the bulk of engineering activity is concerned with the shallow subsurface and, consequently, there is an increased emphasis, in many parts of the world, on Quaternary materials. Therefore, because of the importance of defining the base of the Quaternary (geological rockhead in the UK) a model of the thickness of Quaternary (superficial) deposits represents an apparently simple starting point for the development of 3D models of the shallow subsurface.

Most models of superficial deposits are interpreted manually at a large (site) scale. The availability of a 1:50 000 scale digital geological map of Britain (DigMapGB50) (Jackson and Green 2003) and a borehole database containing over one million digitised borehole logs has enabled geologists to produce a national superficial deposits thickness model. More than 600 000 of the borehole logs were used to make the model. Normally, the first step would involve identifying the depth of the base of the superficial deposits on each borehole log. However, with so many boreholes to be used this was not practical. Instead, the superficial deposits thickness was modelled mathematically directly from the borehole record and the resulting interpretation was then ‘cleaned,’ first statistically and then manually.

One of the difficulties in creating such a spatial model is that data density varies between urban to rural areas. While in the urban areas interpretation at a scale of between 1:10 000 and 1:50 000 would be possible, in rural areas 1:50 000 would be the largest practicable scale. Thus the national model was created at the smaller scale. The country was divided into 50 x 50 km squares and for each square an interpolated grid of deposit thickness was created using a 50 m cell size and the ‘natural neighbour’ interpolation method. This method weights the influence of a data point in comparison to the nearest adjacent data points by the area of land nearest to it (Lawley and Booth 2004). The method is appropriate for clustered data sets (for example, boreholes) and the modelled surface tries to honour most of the available data points. The method does tend to produce so-called ‘bullseye’ features, normally considered undesireable, but this was helpful in identifying both anomalous data points and points where the ‘bullseye’ might actually represent reality (for example, a sinkhole).

Figure 4(a and b) shows the model at small scale for the whole of Britain and data modelled at 1:50 000 scale (though not reproduced at that scale). The small-scale map clearly identifies the thick superficial deposits in parts of the Central Valley of Scotland, in Lancashire and Cheshire, in Yorkshire, in Lincolnshire and Cambridgeshire and in East Anglia. Upland areas and parts of south west England are not well represented because of the small number of borehole logs resulting in a low data density. Figure 4b shows variation in the thickness of Superficial Deposits in London along the River Thames. The model shows the probable effects of scouring along parts of the river channel.

Future developments will involve modelling of the geological rockhead surface and then ‘subtracting’ the elevation of that from a model of the ground surface to produce the superficial deposits thickness. For engineering geologists and geotechnical engineers, the superficial thickness model has considerable use, for example in anticipating foundation and excavation conditions and predicting groundwater flow. However, it needs to be complimented by a model that can predict the depth to engineering rockhead. This is more difficult because the transition to engineering rock is unpredictable because of weathering effects. Northmore (pers. comm. 2003) suggested that the depth at which drilling changed from light cable percussion to rotary methods *might* be one indicator but this has not been tested and, in any case, the amount of data available is likely to be limited except in some areas. The increased use of rotary coring methods in glacial tills, for example, makes this suggestion problematical.

3D spatial modelling of the shallow subsurface

In the UK and many other countries, 2D geological maps have presented the distribution of geological units at the land surface and also at geological rockhead. Bedrock (formerly 'Solid') and Superficial (formerly 'Drift') versions of maps only delineate the full extent of the uppermost unit in each of the two layers. With the advances in computing power and technology over the last twenty years, and the availability of increasingly precise and sophisticated digital terrain models (DTM) it is now possible to begin to realise a whole new concept for national geological mapping that, in its way, is as revolutionary as the geological maps produced by William Smith and others nearly 200 years ago. The result will be the systematic 3D geological map.

The key to these advances is the development of software that allows the geologist to construct 3D geological maps easily and flexibly, in ways that replicate geologists' traditional map-making processes. While the production of 3D geological maps is not restricted to any particular brand of 3D GIS software, the characteristics of a particular software tool called GSI3D (Geological Surveying and Investigation in 3 Dimensions) is described here because it has been used extensively, and successfully, at the British Geological Survey by the author's colleagues. For example, the Lynx Geoscience Modelling System (Anon. 1997) was used by Houlding (1994) and by Ozmutlu and Hack (2003) (see below). The GSI3D software is currently intended for use in the near-surface environment (approximately the uppermost 100 m) and cannot deal with heavily faulted and overthrown strata and intrusive bodies. Consequently, it is most suited to environments that are dominated by sedimentary geology, particularly involving thicknesses of Quaternary (including anthropogenic) deposits. However, it is likely that some of the limitations of the software will be reduced with time.

GSI3D was developed principally by Hans-Georg Sobisch at the Soil and Geological Survey of Lower Saxony and at the University of Cologne (Hinze et al. 1999, Sobisch 2000, Sobisch and Bombien 2003). The software can utilise the same data that geologists have always used to produce geological maps, for example:

- boreholes coded lithologically and interpreted stratigraphically;
- 2D geological maps;
- topographic maps and DTMs;
- cross-sections;
- contoured maps of buried surfaces;
- geophysical data;
- geochemical distributions;
- hydrogeological data;
- geotechnical data;

The modelling is based around the creation of a series of intersecting user-defined cross-sections. Figure 5 shows and example from central Manchester and Salford. Also, the geologist must interpret the entire ‘stacking’ order of all deposits in a study area in a so-called Generalised Vertical Section (GVS). An example of such a GVS for the Ipswich area of England is shown in Figure 6. In Quaternary deposits that underlie many urban areas, this is less easy than it seems at first. If every lithological unit encountered by each borehole was separately identified it would probably be impossible to produce any model at all, given the discontinuous nature and limited extent of many lithological units in Quaternary environments. Consequently, geological judgement must be exercised to determine those geological units that are both significant (for a variety of purposes) and can be correlated. Therefore, before the 3D volume model can be computed the geologist must complete the correlation of all units, create all the boundaries of the geological units at the surface and at depth, and define the local stratigraphy. This model is intended to be dynamic so that when new information is obtained new cross sections and envelopes can be iterated and, if necessary, new stratigraphical units can be introduced.

Many conventional 2D lithostratigraphical geological maps are created by walking over the ground, recording information from outcrops, extrapolating between outcrops using surface morphological features observed either on the ground or on remotely sensed images and adding any borehole/ground investigation information. This approach allows maps to be continuous from rural areas, where there is more outcrop and surface features are visible, to urban areas where there may be fewer outcrops and surface features but considerably more borehole/ground investigation data. However, for 3D geological mapping, the amount of subsurface data available for rural areas is likely to be considerably less than for urban areas and, therefore, 3D models at different resolutions, scales and, hence, detail will have to be produced. It is suggested that, broadly, three types of model can be considered – overview, systematic and detailed (Table 2).

The procedure for producing a 3D model can be summarised as follows:

- Borehole log data are stratigraphically and lithologically coded; only the deepest of multiple, closely-spaced and equally reliable boreholes need coding. Borehole selection should be independent of any pre-conceived geological model but quality and reliability criteria may be applied (for example, in terms of locational data [x, y, z coordinate]).

- A DTM of appropriate resolution is loaded.
- The surface geological map at appropriate scale is loaded.
- Boreholes to make a cross-section are selected.
- Starting with the shallowest, geologically realistic lines are drawn (digitised) to connect the geological units (they do not need to be straight between boreholes). The process is illustrated in Figure 7
- A series of regularly spaced cross-sections is created. The spacing of these should be as indicated in Table 2, depending upon the type of 3D model being constructed. If possible, major cross-sections should intersect structures and valleys at approximately right angles, with minor cross-sections being used to cover local variations and anomalies and incorporate linear bodies not adequately included by the major cross-sections.
- Once a series of sub-parallel cross-sections have been constructed, a second series is produced roughly at right angles to the first to produce a 'fence' diagram (Figure 8). The positions of geological boundaries at cross-section intersections are checked and modified as necessary.
- The surfaces that define the top of each geological unit are then created from the surface geological map and the fence diagram by either working outwards from the surface outcrop to include areas buried by other units, or by taking the likely maximum extent of the unit and trimming back and editing the surface based on the cross-sections and borehole data.
- The surfaces are then spatially combined to produce the 3D geological model stack. In this process, elevation (z) values are attributed to each surface by reference to the DTM.

- The model can be checked for mis-correlations by creating a rectangular grid across the whole area, manually viewing the ‘synthetic’ cross-sections and correcting as necessary.

Outputs from the 3D modelling include:

- A fully attributed Generalised Vertical Section (GVS). This forms the basis for engineering geological, hydrogeological and mineral potential classifications (Figure 6).
- Contoured or gridded surfaces of tops, bases, thicknesses and volumes of single or combined geological units (including artificial ground). Figure 9 shows the thickness of overburden and the thickness of the exploitable Kesgrave Sand and Gravel from Sudbury in East Anglia.
- Horizontal slice maps at any depth and vertical cross-sections in any orientation.
- Maps for tunnels or pipelines along the proposed design route.

3D mapping in Salford/Manchester

Salford and Manchester are adjoining cities in north west England (Figure 10). Figure 11a shows the bedrock geology of the central area of the cities of Salford and Manchester with the artificial deposits (made ground, fill, etc.) and superficial deposits stipped off. Figures 11b and c show the superficial deposits and the artificial deposits respectively. The map covers 75 km^2 and was originally created at a scale of 1:10 000. The predominatly urbanized area has a long history of intense industrialization, founded on coal mining, locomotive engineering and the textile industry (including bleaching and dyeing of cotton). These activities have left a legacy of contaminated land, groundwater pollution and extensive artificial deposits in a densely populated area. The area includes Trafford Park (in the west), the largest industrial estate in Europe, Manchester city centre (still being redeveloped following the 1996 terrorist attack) and east Manchester, an area undergoing urban renewal using public and private investment and including the sites developed for the 2002 Commonwealth Games (Carroll 2000). The former Manchester Ship Canal docklands in Salford has also been extensively redeveloped.

Geologically, Salford and Manchester straddle the southern part of the South Lancashire Coalfield and the north-eastern part of the Permo-Triassic Cheshire Basin (Figure 11a). Bedrock exposure is poor throughout the area due to an extensive, and often thick, cover of superficial deposits. The oldest exposed rocks are of Westphalian (late Carboniferous) age (c. 305-298 Ma) and are coal-bearing. The coal was worked until the late 1970's. The Coal Measures are overlain by a sequence of red beds (Etruria Formation) and grey measures (Halesowen Formation) forming part of the Warwickshire Group. These Permo-Triassic rocks (c. 298-205 Ma) underlie much of the central, eastern and southern parts of Manchester. This sandstone-dominated sequence, up to 620 m thick, forms the most important groundwater aquifer in north-west England. The geological evolution of the area has been described by Plant et al. (1999) and Kirby et al. (2000).

Extensive spreads of superficial deposits cover much of the area (Figure 11b). These consist of glacial deposits (presumed to be mainly of late Devensian age, c. 20 000 to 14 468 BP), post glacial deposits associated with the development of the River Irwell, and anthropogenic (artificial) deposits. The glacial deposits are dominated by till deposited from ice streams moving across the area from the north-west and west (Worsley 1968). The till is accompanied, on the lower ground west of the Pennines, by sequences of outwash sediments forming multi-layered complexes sometimes over 40 m thick. Morainic ice ridges are presumed to be ice-contact in origin, possibly representing standstill positions of the retreating ice. During this phase large volumes of meltwater deposited sand and gravel in ice-contact and proglacial settings. Transient glacial lakes also formed and silts and laminated clays were deposited in them. These are widely distributed, though rarely at outcrop. Regrowth of snow fields c. 11 – 10 000 BP provided meltwaters that were channelled down the proto-River Irwell and its tributaries, to deposit 'flood gravels' across much of the area. Post-glacial Holocene deposits consist of river terrace deposits and alluvium, mainly confined to modern river valleys. There is a small deposit of lowland peat in Trafford Park, in the west.

Artificial deposits (Figure 11c) have been proved in over 75% of the 3000+ boreholes examined in the area. The deposits often have no well-defined landform and boundaries are ill-defined or gradational. Three broad categories of 'deposit' were recognised (one represents material removed, rather than deposited) following the approach of Rosenbaum et al. (2003):

- Made ground (material placed on the pre-existing land surface)
- Worked ground (excavations in the pre-existing land surface)
- Infilled ground (wholly or partially backfilled worked ground)

A Quaternary 3D spatial model for the area was constructed using the methodology described above. Once borehole and other data have been collected and databased, the most important task is to establish the stratigraphy to be used for the area. This is important because it determines the order in which surfaces are stacked and intersected in the model. Traditionally, this stratigraphy is established during field-based mapping; this relies heavily on the recognition and interpretation of landforms. However, this essentially 2D based stratigraphy may not be appropriate for a 3D model, depending upon the complexity of the geology, borehole coverage, scale of interrogation and proposed usage. For the Salford/Manchester area the 2D map stratigraphy was adopted with some minor additions, despite the complexity and discontinuous nature of some of the litho-stratigraphic units. The modelled units are listed in Table 3. Figure 12 shows the spatial relationships between the units schematically. A series of cross sections were constructed to form the model as shown in Figure 5.

The lowest surface within the model is geological rockhead (the base of the superficial Quaternary deposits). The surface is well constrained along transport corridors and in major redevelopment areas, but less so in older residential areas, for example in the east, where borehole densities are lower. A significant feature of the surface is the presence of deeply eroded depressions which are thought to form part of north-westerly trending buried channels formed by over-deepening during the last Glaciation by sub-glacial meltwaters flowing under hydrostatic pressure (Johnson 1985). The glaciolacustrine deposits can be traced over an area of several square kilometres to the west and south of Trafford Park in the west of the area. The deposits sit on till and are around 5 m thick. The inferred minimum altitude of the lake surface at the time of deposition is 24 m above Ordnance Datum.

With regard to the artificial deposits, two aims of the modelling process were to provide estimates of their thickness and, where possible, to identify their composition. Figure 13 shows the variation in thickness of artificial ground. However, the 3D model allows some of these variations to be depicted more clearly. For example, Figure 14 shows the former (infilled course of the River Irwell in relation to the Manchester Ship Canal. Mapping of surface deposits only allows the broad classification of variability indicated above (Figure 11c). However, by identifying geographical areas, or 'domains,' where similar historical land use processes have operated, greater delineation of variation can be achieved. This is similar to the approach used by, for example, McMillan et al. (2000) for sub-dividing natural Quaternary deposits. By dividing the two cities into zones, where anthropogenic processes are known to have operated, assumptions about composition, geometry and thickness of the artificial deposits can be made. To establish these zones, it was necessary to understand the historical urban development and industrial archaeology. For example, it was common practice to tip colliery waste and domestic ash into river valleys, hence raising the level of the valley floors. Figure 15 shows nine areas with significant and identifiable types of artificial ground.

The 3D spatial geological model can be interrogated using simple tools available in the software to produce:

- Synthetic logs and cross-sections at user-defined locations;
- Contoured surfaces;
- Isopachytes of single or combined units;
- Domain maps;
- Sub- and supracrop maps.

Elements of the model can also be exported in standard *asci* format to other software packages, such as ARC8 or GoCaD, for futher processing and visualisation. In this way, models of Quaternary deposits produced in one software package can be combined with bedrock models developed in another.

The 3D model was used to examine potential groundwater-surface water interactions as part of a broader, regional groundwater study of the Manchester and Cheshire aquifer being undertaken by the Environment Agency. The model provided information on the geometry, composition and spatial distribution of the main superficial deposits. The approach adopted was first to construct a hydrogeological domains map (Figure 16) and then to create a series of client selected cross-sections from the 3D model that identified potential pathways for groundwater movement through the superficial and artificial deposits (an example is shown in Figure 17). A suite of land-use maps to identify the locations of potentially contaminative activities was also created by mapping areas of potentially contaminative land use (based on Anon. 1991) as interpreted from maps dated 1890, 1920 and 1950 (Figure 18a) and the present day (Figure 18b).

Finally a domain-based aquifer vulnerability model was constructed. In England and Wales, Groundwater vulnerability has been estimated on the basis of:

- The attenuating characteristics of the soil;
- The presence and nature of any superficial deposits;
- The nature of bedrock strata;
- The hydrogeological characterisitics of strata in the unsaturated zone.

For the Salford/Manchester area the methodology was adapted further by taking into account the spatial distribution of the main superficial deposits, their interconnectivity and inferred permeability. The resolution of the model enables it to be used to support broad land-use planning decisions but it would need to be used in conjunction with additional sub-surface investigation for dealing with site specific contaminant issues.

The model needs further development because it does not take into account the effects of (pedological) soil cover (in particular, its geochemistry) or the thickness of the unsaturated zone. To properly determine the variation in thickness of the unsaturated zone requires monitoring of groundwater levels over a significant period of time. For many applications, such an approach would be expensive and impractical because of time constraints. However, site investigation borehole logs frequently record first water strike. Data were extracted from almost 1600 borehole logs and sorted to remove obvious outliers, including null values and positive values (above the ground surface) (where artesian conditions were interpreted as unlikely) and values showing very large changes over very short distances. Data collected prior to 1980 were also excluded because of known fluctuations caused by over-abstraction and changing water levels in the 1970's and 80's. Just over 1000 first water strike values remained of which about 90% were between 2 and 6 m below the ground surface. It might be expected that the shallow water table surface would be a subdued representation of the ground surface (Salama et al. 1996). However, in practice, this is not so (Figure 19). The correlation between first strike depth and ground elevation is very poor. This may be due to poor data quality but is probably also related to the complexity of the superficial geology in terms of lithology, thickness and permeability. Nevertheless, the use of first water strike data, which is widely available from borehole logs, may offer an albeit crude means of assessing the thickness of the unsaturated zone provided that the input data are carefully assessed and screened.

A further application of the 3D model is as a contribution to the design of sustainable urban drainage systems (SUDS). SUDS is an alternative approach to conventional drainage systems, which attempts to replicate, as far as possible, the natural drainage pattern and relies on attenuation, treatment and infiltration techniques to deal with surface run-off (Anon. 2001). The applicability of the SUDS techniques to a particular geological situation can be assessed by reference to the 3D model. Information critical to the assessment includes:

- Slope angle;
- Permeability of the near-surface deposits;
- Thickness of the unsaturated zone.

By combining this information as a simple tri-category map, areas more suited to infiltration techniques can be identified. The model can be made more robust by the addition of information on the potential for contamination and surface sealing (for example, whether the ground surface is tarmaced or concreted over). Figure 20 shows a SUDS suitability map for Salford/Manchester. It will be noted that the different suitability classes are related to land parcel boundaries rather than geological ones.

3D mapping in Swansea/Port Talbot

A study was carried out in part of the Swansea/Port Talbot area of South Wales (Figure 10) to investigate how risks associated with contaminant source areas and surface and groundwater pathways might be modelled on a regional basis using 3D geological spatial models. Past industrial activity, including a well-documented history of metalliferous smelting, has produced land that is contaminated variously and which, because of the local geology and geomorphology, has the potential for contaminant migration. The main study area covered some 100 km^2 in the local authority areas of Swansea City and County and Neath-Port Talbot. Urban development in the area began in about the 12^{th} Century, following occupation by the Normans. However, it was with the extraction and export of coal in the 18^{th} Century that major expansion and industrialisation took place. The coal was also used for smelting of imported metal ores.

Geologically, the area is entirely underlain by bedrock of Westphalian age comprising the South Wales Coal Measures Group and Pennant Sandstone and Grovesend Formations of the Warwickshire Group (Figure 21). The South Wales Coal Measures Group is dominantly soft and argillaceous with mudstone, siltstone, subordinate sandstone and many coal seams. The overlying Pennant Sandstone Formation consists mainly of thick, relatively hard sandstone with subordinate mudstone and coal seams. The uppermost Grovesend Formation is predominantly mudstone. The bedrock is overlain by thick superficial deposits (Figure 22). On the coastal plain these consist of Beach and Tidal Flat deposits, Blown Sand and Peat; the main, glacially incised palaeovalleys of the rivers Tawe and Neath are filled by thick deposits of alluvium, glaciofluvial deposits, glacial till and peat. Interfluve areas have a relatively thin cover of complex glacial deposits. Artificial deposits are common and extensive in the main urban areas, including the coastal plain and the river valleys. These deposits have been mapped using the classification described above.

Superficial and artificial deposits were modelled in 3D using the approach described above (Figure 23). The model was the applied to investigate whether an existing 2D, GIS-based model for the assessment and ranking of potentially contaminated sites could be improved by the inclusion of 3D information. The 2D scheme assigns scores based on the source-pathway-receptor linkage concept. The scoring of the groundwater pathway includes a superficial deposits parameter and scores are assigned based on the interrogation of 2D geological data relating to the presence of superficial deposits with low, moderate or high permeability values, or their absence.

The incorporation of 3D geological information could potentially improve the scoring criteria by taking into account the type and thickness of superficial material at depth.

Uncertainty

The traditional 2D geological map contains a limited amount of information on the uncertainty associated with the content of the map. For example, geological boundaries might be presented as continuous lines where the boundaries had been observed in the field or as pecked lines where they had not. However, this gives little indication of the degree of uncertainty (whether the position of the line is accurate to the nearest 10, 100, or even 1000 m). Names of the geological mappers might be included on the map legend; this allows subjective judgements to be made about map quality if the map user has access to information on the geologist’s mapping ability. As geological maps were not changed for decades (or, sometimes, even centuries) there was plenty of time for users to come to understand the adequacy of the map through trial and error usage. As long as geological maps were used mainly by other geologists, the uncertainty associated with the map probably did not matter very much because all geologists were trained in geological map-making techniques and, so, intuitively, knew the likely uncertainties associated with maps from different geological domains.

Now that geological maps have a much wider range of users, and digital techniques allow maps to be updated on an almost daily basis, there is a need for ‘uncertainty’ to be more clearly expressed. Evans (2003) identified two areas of uncertainty:

- that associated with the data (natural variability) and measurements themselves (sampling and measurement error) and,

- the uncertainties of the modelling process (including the assumptions and simplifications made).

He also stated that “3D models and visualisations should be able to provide tools for exploring uncertainty, and to assist in finding it, understanding it, mapping it and visualising it. ….. Another approach is to employ visualisation, expressing the uncertainty as a ‘fogged’ display ….. analogous to the way a geologist would use a dotted line on a map rather than a solid boundary to represent the uncertainty of location.”

There are three broad methods for estimating uncertainty:

- Analytical approach, which uses rigorous statistical theory to propagate combined uncertainties through the mathematical functions that use the measured inputs to produce the modelled outputs. Some of the simpler statistical methods for estimating the variability of geotechnical property data are discussed below.
- Computationally intensive approach, which requires that the model is calculated a number of times; each time a small change is made to the input parameters (representative of the natural uncertainty of that parameter). The result of each run of the model is stored and, with the use of suitable strategies for the choice of input parameter changes, the distribution of results for the repetitions will be representative of the uncertainty in the model. These methods are complex and require considerable computing power and currently have little application to 3D geological spatial models and geotechnical data.

- Measurement of uncertainty on subjective and semi-quantitative data. Geological interpretation is an example of subjective information. Borehole logs and geological maps produced by different geologists will be different according to their experience and background; data from these sources is then digitised and can end up as an input to a 3D geological spatial model. The size of these differences may vary, resulting in different effects on the final model. The problem, then, is to identify which interpretation is most 'correct' and how to calculate the uncertainty associated with the interpretation process. Organisations will set out to minimise these differences, for example by the use of standard methods of description and classification (for example, Anon. 1970, 1972, 1981b, 1995, 1999b) and by training, but measures of the uncertainties are still needed. Fuzzy logic (Zadeh 1965) and Bayesian statistics have been used to describe imprecise or vague information.

However, in trying to quantify uncertainty, it is necessary first to identify the causes of uncertainty and secondly the relationships between the causes. This can be done by using a cause and effect diagram known as an 'Ishikawa' (after its inventor) or 'fishbone' diagram (Kindlarski 1984). The first step is to identify the specific problem of interest arising from a complex process. With regard to 3D geological modelling of the shallow sub-surface, the problem (or effect) is the lack of certainty in the model. The main causes of this lack of certainty are identified and for each of these main causes a series of sub-causes are identified hierarchically. The fishbone diagram is built up from the effect (lack of certainty in the model), which forms the backbone and the causes that branch off the backbone as shown in Figure 24. The branches can have branches of their own which represent smaller and smaller sub-causes.

The cause and effect diagram is best derived by team members working together or brainstorming. This approach makes the team members think laterally about the uncertainties that may be inherent in their area of responsibility; it brings to their attention the sources of inaccuracy inherited from other areas of the modelling process; it demonstrates how the causes can interact or influence each other. (Figure 25) shows a cause and effect diagram for the uncertainties in modelling a 3D surface from limited point depth (borehole) data.

Having identified the causes of uncertainty, it is then necessary to quantify it in a way that can be simply understood and applied by users. For a geological surface produced by gridded interpolation of borehole data, one method for estimating the uncertainty produced by the gridding procedure is to resample the (borehole) data used to interpolate a gridded surface many times (known as ‘bootstrap’ resampling), each time interpolating a new surface, and measuring the standard deviation at each gridded point resulting from the interpolations. Figure 26 shows an interpolated surface obtained by gridding the available borehole data. Figure 27 shows the predicted uncertainty using resampling methods. Other methods of measuring uncertainty would need to be applied to the other causes of uncertainty identified in the cause and effect diagram, hence building up an understanding of the significance of each of the causes contributing to uncertainty. Further research is needed to develop means of presenting and visualising overall uncertainty (and its variability in different parts of a 3D geological spatial model).

GEOTECHNICAL PROPERTY ATTRIBUTION

While the realistic portrayal of geological surfaces in three dimensions is becoming easier, it remains difficult to attribute the geological volumes defined by the surfaces with geotechnical property data meaningfully. All interpretative and many factual site investigation reports will attempt to summarise the geotechnical properties of the geological formations encountered during the investigation. The simplest way of doing this is to give ranges for the values of each parameter measured. Sometimes, the data are subsequently presented in research papers that become widely used (for example, Cripps and Taylor (1981) for British mudrocks; Bell and Culshaw (1993) for Triassic sandstones). Whilst such an approach is factual, it can give little indication of whether the values presented are *representative* of the geological formation, even at the site level. Sometimes, the ranges presented cover depth intervals over which changes in some properties might be expected. As a result, engineering geologists and geotechnical engineers have developed other ways to indicate the variation in geotechnical properties. These approaches can be divided into those that seek to summarise the variability of a geotechnical parameter statistically for the whole of a specified engineering geological unit and those that provide a visualisation of the variability of the parameter within the engineering geological unit in either 2 or 3D.

Statistical analysis of geotechnical property variability

The analysis and synthesis of values of a particular geotechnical parameter involves the use of ‘batches’ of data (the data population). The number of values in a batch might range from one to several thousands but, typically, might be in the tens or less often the hundreds. The range and variability within a batch of data can be attributed to the combined effect of several factors:

- Inherent soil/rock variability. The in situ composition and state of soils and rocks is the net result of a great number of processes, including the supply of source material, the environment of deposition, consolidation, lithifaction, stress and temperature regimes, groundwater movement and composition, weathering and erosion and others, which will all, to a greater or lesser extent, vary in time and space. As a result, soils and rocks will vary in composition, structure and fabric, and thereby in geotechnical properties, on all scales from microscopic to regional, even within a given geological unit.

- Sampling and handling. Soils are particularly vulnerable. The procedures for sampling, packaging and transporting samples from the in situ location to the laboratory inevitably will induce changes in the soil. Whilst some changes could be purely random in nature, others will not be. For example, stress relief will be greater for those samples from greater depths. As most soils have a high degree of saturation, changes of moisture content will tend to be those of reduction. Sample size may contribute to variability caused by handling.
- Laboratory testing. Testing procedures, both in the field and laboratory, are subject to many human influences that can introduce both systematic and random errors. For many simple, index tests, repeatability is often only moderate. Where testing is destructive it becomes even more difficult to establish accuracy or detect errors.
- Data transfer. Even when using digital data transfer formats, the numeric data derived from a test will have to be transcribed several times before it enters the database. At each stage errors will be introduced.
- Geological unit definition and data allocation. For databasing and analysis, test results are usually ‘allocated’ to an engineering geological unit (which

may correspond to all, or part, of a geological member or formation). Errors will arise in identifying the correct unit. Borehole logs might be inaccurate or imprecise and even interpretation by an experienced geologist may not ensure correct allocation. Where doubts remain, data should be excluded.

While the variability that should be analysed is solely that caused by soil/rock variability (the 'true' variability), 'contamination' by errors caused by the other factors is probable. It is difficult to imagine many other types of data for which the statisticians term 'dirty' could be more appropriate!

Statistical methods for geotechnical data

The overall objective in statistically analysing a batch of data from a geotechnical database is to predict the properties of each engineering geological unit, in statistical terms, to a quantifiable degree of confidence. Inherent in the data are several aspects that can inhibit this broad objective and must be taken into account:

- Spatial distribution of the data. To predict a parameter for a whole engineering geological unit within a defined area would require a statistically valid distribution of the sample locations. In urban areas, if the data comes from a large enough number of site investigations, this ideal may be approached. However, in more rural areas, where data comes from separated sites or from linear engineering activities such as roads or railways, this will rarely be the case. Therefore, each analysis or data summary must be assessed for its applicability throughout the geographical area or engineering geological unit. This will usually be done subjectively using expert judgement.

- Validity of engineering geological units. Some of these units may be well-defined, distinctive and spatially consistent geological formations. However, others, of necessity, may be more variable (for example, artificial deposits, some glacial deposits) and, ideally, subdivided themselves. It cannot be assumed that an engineering geological unit necessarily possesses sufficient consistency to constitute a 'population' in the statistical sense. Hence, the statistical approach used should avoid any prior assumption that the data values fall within a mathematically definable distribution.
- Data accuracy. As the data are likely to be highly variable in accuracy (see above), and may contain gross errors, the statistical method used should, as far as possible, accommodate these defects.

The numerical distribution of a parameter, based on a large number of samples, is often represented as a frequency distribution curve. The horizontal axis gives the measurement scale for the given parameter and the vertical axis gives the frequency of occurrence. Typically, the curve is bell-shaped, with the greatest concentration of data in the central area and decreasing amounts laterally to each tail. Such curves may be symmetrical or skewed to one side, peaked or flat, regular or irregular in form. There are two conventional means of describing or summarising a frequency distribution numerically: parametrically and non-parametrically.

Parametric statistics

The parametric approach is to measure several essentially separate attributes or parameters of the whole distribution of the data. First, the centre or 'location' of the distribution is determined by the arithmetic mean; second, the spread or dispersion, is determined by the standard deviation and third and fourth (and much less frequently), the skewness and the kurtosis are derived (the latter being essentially a measure of data in the tails, not the peak). In each case, all the data values contribute to the given parameter, according to the square of their distance from the mean for the standard deviation, to the cube for the skewness and the fourth power for the kurtosis.

The problem with this approach is that the statistics are concerned with the situation where data variation can be regarded as purely random and that variations will generally follow a Gaussian distribution. Most data sets will, in fact, not follow this distribution, commonly having larger tails than predicted. The approach is not appropriate for geotechnical data because it assumes that all the data values for a parameter are ‘good’ and of equal validity (when in reality, data may be of variable quality), that the variations between the values are truly random (they are not, as they are geologically controlled) and that a single ’true’ value exists to be predicted.

Non-parametric statistics

An alternative approach is to dispense with the concept of parameters (mean, standard deviation) and use order or rank statistics instead (hence the term ‘non-parametric’). The data values are first rearranged into ascending numerical order. The order statistics are then the numerical data values at given levels in this ascending order. So, the 0.1 order statistic or 10^{th} percentile or lower decile is the data value one-tenth up the data sequence. The 0.5 order statistic or 50^{th} percentile is more commonly known as the median. The advantage of this form of statistics is that they are valid whatever the nature of the underlying data distribution; for example, there are always an equal number of data values above and below the median. The information provided by these statistics is always clear and unambiguous but, necessarily, simple.

Robust statistics

Parametric and non-parametric statistics both depend on all the data values being ‘good’ and equally reliable, which is rarely the case, in reality, with geotechnical data. Robust statistics provide a flexible approach or attitude to the data, rather than any specific set of mathematical rules. First, it attempts to allow for the fact that most, if not all, real data sets do contain a proportion of poor or bad data values. This is particularly true with computerised databases containing large volumes of data that would be uneconomic to validate rigorously. Secondly, it recognises that virtually all data sets do have some underlying structure, placing it as intermediate between parametric and non-parametric statistics. Robust statistics are usually used with exploratory data analysis techniques on the grounds that the data should be examined before the most appropriate statistics can be selected.

Exploratory data analysis

The objective of an exploratory analysis of the distribution of a geotechnical data set is to reveal both the general and detailed structure of the data, ultimately with a view to ‘cleaning’ the data if necessary. To achieve this, a graphical approach is required that reveals such features as the shape, spread and symmetry of the data and the presence of gaps or concentrations. Histograms are a well-known type of representation of data distribution but a good histogram can be hard to produce, mainly because of the difficulty in selecting the class interval. An alternative method, the ‘stem and leaf’ display, was devised by Hoaglin et al. (1983). For a given data set, values (say of plastic limit) are split into two parts at a consistent point with respect to the decimal point. This split is usually located such that either one or two of the leading digits are separated from the remainder to form the stem while the trailing digits form the leaf. So, for a plastic limit value of 12 (%), ‘1’ would form the stem and ‘2’ would become leaf value. For dry density data, 1.13 (Mg/m^3) might be shown with ‘11’ as the stem and ‘3’ as the leaf. Alternatively, 1.13 could be shown with ‘1’ as the stem and ‘1’ as the leaf (the ‘3’ would be ignored). The problem here is that in the former case there might be too many stems and not enough leafs while in the latter there might be too few stems and too many leaves. In these situations two lines can be used for each stem with leaf values of 0-4 allocated to the first line and values of 5-9 to the second line. Further subdivision allows five lines per stem with lines containing leaf values of 0-1, 2-3, 4-5, 6-7 and 8-9 respectively. Any further trailing digits would be ignored. An example of two stem and leaf plots are shown in Figure 28 for dry density and plastic limit data for Mercia Mudstone samples from the Coventry area. The output visually resembles a histogram with the length of each line proportional to the number of leaf values. The display produces information that can be also deduced from a histogram such as:

- The symmetry of the data
- The spread of the data
- The isolation of a few values from the main body of the data
- Local concentrations within the data
- Gaps in the data

In addition, patterns and peculiarities in the digits in a line can be seen, for example, if ‘0’s predominate it might infer that part of the raw data had been rounded off more than the rest. Also, as the display is composed of actual data values, it is easier to trace particular values of interest back to the individual raw data. Compared with a histogram, there are no problems or doubts with values at, or close to, class limits and the automatic selection of the stems and leaves ensures that a tolerable display will be produced.

One of the drawbacks of stem-and-leaf diagrams (and, indeed histograms) is that whilst they demonstrate the general structure of the data, and at least some of the anomalies within it, visually they are little more than statements of the obvious. By removing the bell shape of such diagrams other aspects of distribution will become more apparent. This can be achieved by presenting the data as a ‘normal’ probability plot. The x-axis is scaled to the data units, whilst the y-axis shows cumulative percentages of the data. The result is that a Gaussian or ‘normal’ frequency distribution will be portrayed not as a bell-shape but as a straight line. However, probability plots of geotechnical data will most commonly depart from a straight line, having single or multi-curved (eg ‘S’) shapes (Figure 29). A somewhat irregular or ‘noisy’ plot may be encountered, particularly where the data batch is of limited size (Figure 30). As a result of the normal probability scale used on the y-axis, these plots tend to concentrate data points at the centre with greater separation towards the tails, hence making the tails appear more irregular. Nevertheless, they should follow a pattern consistent with the main bulk of the plot. Where points do not follow this pattern either existing as outliers or following a pattern but at variance with the majority of the data (Figure 31), then an error might be expected. In this case, the inconsistency might represent a mis-coding of the original data either in terms of the engineering geological unit or the geotechnical property.

Graphical summarisation

As indicated above, summarisation of distributed data can be achieved by presenting some measure of the centre of the data and some measure of their spread or dispersion. Mean and standard deviation are only adequate where the data distribution is Gaussian. As most geotechnical data do not show a Gaussian distribution (see above) the data are better summarised by the median and the interquartile range (IQR), that is the range, or spread, between the lower and upper quartiles – the central half of the distribution. The 'box and whisker' plot can be used to display the summarisation. Figure 32 is a simple plot for liquid limit values for clay bands from the Coventry Sandstone. The ends of the box are drawn at the lower and upper quartiles with the internal division at the median value. The 'whiskers' are drawn from the ends of the box to the lowest and highest data values that are not outliers (extreme values that are represented by crosses beyond the 'whisker' ends). The plot can be modified by adding a 'notch' in the box at the position of the median, which indicates the extent to which the total population distribution can be inferred from the actual data distribution. The width of the notch is usually calculated such that there is a minimum 95% probability that the population median will lie within the limits of the notch.

With such a plot it is possible to quickly grasp the major aspects of a distribution at a glance. The centre of the distribution is shown by the median crossbar within the box. The interquartile range is shown by the length of the box and the 'whiskers' illustrate the tail lengths of the distribution. However, this plot gives no information between the quartiles and the ends of the 'whiskers.' To do this, the box plot can be extended by calculating a number of percentiles, not just the quartiles, such as 1, 2, 5, 10, 25 (quartile), 50 (median), 75 (quartile), 90, 95, and 98. The additional percentages are used to define a series of subsidiary boxes to either side of the central box (Figure 33). The heights of the various boxes are scaled in proportion to the square root of the number of samples ‘contained’ in each box.

Typically, most actual data batches will be too small to calculate the outer percentiles. Therefore, to ensure that the plot is reasonably meaningful, it is necessary to limit the number of subsidiary boxes with regard to the size of the data set. It is suggested that the outermost box at each end should contain a minimum of three values and that at least two further values should fall beyond this box. Table 5 indicates the number of outer boxes that should be plotted in relation to the number of data points. Figure 34 shows extended (but un-notched) box and whisker plots for SPT ‘N’ and undrained cohesion values for various engineering geological units found in the Wrexham area of North Wales.

Summary

- It is almost inevitable that ‘batches’ of geotechnical data will be ‘dirty’ in a statistical sense. There are many potential sources of error in the numerical values, the spatial distribution of the data is usually poor, and the allocation to engineering geological units cannot be achieved with consistent reliability.
- For data of this nature, it is much more appropriate to take a ‘robust’ rather than classical approach to statistics. By placing emphasis on the structure exhibited by the bulk of the data, a higher level of confidence can be placed in the reliability of the resultant statistics.
- Graphical, rather than purely numerical displays are much to be preferred, both for analysis of the data and its summarisation.

- Histograms generally should be avoided, as great care is required in their formulation. The stem-and-leaf display is more reliable where a bar display is required in data analysis.
- The most valuable tool for data analysis is the probability plot. It will reveal the structure and coherence of a data batch and provide a basis for identifying possibly erroneous data values.
- The classical parametric statistics, such as the mean and standard deviation, should be avoided as a means of summarising a distribution. They place undue weight on the tail values and can be seriously misleading where the distribution is non-Gaussian. The range is a particularly poor statistic, as it takes account of only the most extreme values and generally will increase with the size of the batch.
- For a numerical summary, it is preferable to use a selection of percentiles, including the median and quartiles. These are highly resistant to erroneous values in the data batch.
- The extended box plot provides a fuller and more informative summary of a distribution. This graphical display will emphasise the essential structure within a distribution and the significant differences between distributions. It also indicates the degree of confidence that may be placed in the summary. To fully utilise the 'robust' approach, the required percentiles for a box plot should be abstracted from a manually smoothed probability plot.

Geostatistical analysis

Geostatistics is a branch of applied statistics developed by Krige (1951) because of the inadequacy of techniques for the estimation of ore grade being applied in South

African goldfields. It was formalised by Matheron (1963). Geostatistics have been used extensively in mineral exploration and geochemistry to determine the variability of element concentrations during mineral exploration. However, more recently, the principles have been applied to a variety of areas in geology and other scientific disciplines.

Giles (1994) provided a straight-forward summary of how geostatistical techniques are used. The process involves two main stages: the determination of the spatial correlation between the observed sample points and the interpolation of these onto a regular grid that can then be contoured. He also pointed out that another advantage of the interpolation stage is that it produces an error value for every estimated point. These errors can also be contoured to show areas with greater or lesser degrees of interpolated reliability.

One unique aspect of geostatistics is the use of regionalized variables. These are variables that fall between random variables and completely deterministic variables. Regionalized variables describe phenomena with geographical distribution (e.g. elevation of ground surface). The phenomena exhibit spatial continuity. However, it is not always possible to sample every location. Therefore, unknown values must be estimated from data taken at specific locations that can be sampled. The size, shape, orientation, and spatial arrangement of the sample locations influence the capability to predict the unknown samples. If any of these characteristics change, then the unknown values will change. The sampling and estimation of regionalized variables are carried out so that a pattern of variation in a particular phenomenon can be presented as, for example, a contour map for a geographical region.

Geostatistics have been little used for the modelling of geotechnical data. One reason is that sufficient quantities of adequately spaced data are rarely available (ground investigation programmes are not designed, or funded, with this application in mind). Secondly, the data may lack spatial continuity; in effect, all the data points may not belong to the same data set. For example, if the geology changes from clay to sand, density values will belong to two quite separate data sets that cannot be geostatistically modelled as a single set.

Nathanail and Rosenbaum (1994) geostatistically modelled some of the geotechnical properties of the Triassic Mercia Mudstone at a former steelworks blast furnace site at Redcar in north east England using the ‘conditional simulation’ method (Journel 1974). This method models the spatial variation of the parameter being investigated while remaining true to the measured control points. Nathanail and Rosenbaum assessed the variability in the elevation of, and depth to, rockhead (because the foundation would be piled to engineering rockhead) based on data from 51 boreholes. The modelling identified a number of areas where the required condition (rockhead elevation greater than –15 m above Ordnance Datum) was met. Hence, they claimed that the technique could be applied to estimate the range in value and spatial distribution across a construction site. Ozmutlu and Hack (2003) used geostatistics to model the distribution of cone resistance (CPT) values as part of research to model the variation of settlement over the whole of the modelled soil volume using attributed 10 m x10 m x 1 m volume cells (see below).

Visualisation of geotechnical property variability

While the statistical methods discussed above provide a valid means of summarising the variation of geotechnical data for defined geological units, they give no help in understanding how a given geotechnical property might vary spatially within that unit. Depth and ‘horizontal’ surface plots have been used to try to illustrate this variation.

The depth profile

One of the simplest ways of illustrating the variation of geotechnical properties is by the use of multiple borehole depth profiles. In this approach, depth profiles from a number of boreholes might be plotted on the same axes to show the total variability of a geotechnical parameter. Gostelow and Browne (1986) plotted variability in SPT ‘N’ values for the upper estuary area of the Firth of Forth near Edinburgh in Scotland (Figure 35a). The histograms show that the data does not have a Gaussian distribution and so the summary statistics used may be inappropriate (see above). Also, while the depth plots do allow variation in SPT ‘N’ values within individual boreholes to be compared, they give little indication of any spatial variation except between two geographical areas (Falkirk and north of Linlithgow). Similarly, SPT ‘N’ values plotted against depth for the Upper Chalk in the area of Ordnance Survey 1:10 000 scale map sheet TQ57NE (to the east of London), show a general increase in ‘N’ value with depth but it is difficult to extract more detail from the plot (Figure 35b).

Voxel attribution

Turner (2003) briefly described how spatially continuously varying values (for example, geotechnical properties) can be displayed by breaking up a geological unit volume into a series of ‘voxels’ or volume elements. However, he pointed out that a volume represented by 100 rows by 100 columns by 100 layers, would require 1 000 000 voxels and might still provide a relatively low-resolution image.

Ozmutlu and Hack (2003) constructed a grid of voxels 10 m by 10 m horizontally and 1 m vertically. They calculated the settlement at the centre of each voxel by attributing each with appropriate data (coefficient of compressibility, initial effective vertical stress and change in vertical effective stress based on cone penetrometer test and geological data). The settlement at any depth can then be calculated by adding the individual displacements for each voxel.

Schade (2004, pers. comm.) suggested that for voxel attribution, the following were needed:

- x, y, z positions for the original data points
- a conceptual model of for the unmeasured data/parameters
- the degree of uncertainty dependent on output scale, parameter and area
- synthetic boreholes and logs with specified parameters
- subsurface/contour maps of specified parameters
- statistical analyses (e.g. degree of variation)

Figure 36 shows an attempt to model SPT ‘N’ value data for the glacial tills of the Salford and Manchester area (described above). This was created using 1564 SPT ‘N’ values from 164 boreholes, which were imported into the 3D geological model of the till and then interpolated (using proprietary software) to produce the 3D model showing the interpreted ‘N’ value model. Much further research is needed to produce a series of workable volume models attributed with geotechnical data and to assess which methods are most appropriate for interpolating the data. However, the key issue is not the merit of any particular software used but how close the model produced is to ‘reality’ (how ‘uncertain’ it is) and whether it is of practical use. Models such as these will need to be tested against additional ‘real’ site investigation data.

GEOLOGICAL PROCESSES AND CHANGE

Geological, climatic, anthropogenic and other processes can act to change the geotechnical conditions in the ground within the life of a building or structure, as well as during its construction. Therefore, it is essential that every site investigation takes these potential changes into account. This can be done in two ways. First, as part of the desk study, a hazard assessment (and, increasingly a risk assessment) will be made. Secondly, if necessary, the hazards may be specifically investigated using intrusive and non-intrusive investigation methods, sampling and testing and quantitative assessment of the ground stability. Engineering geologists and geotechnical engineers have put considerable research effort into improving our understanding of most of the geological processes that affect ground stability (this research has been summarised by several authors, for example, Bell and Culshaw 1998, 2001, 2003a, 2003b, Vaughan 1999). Similarly, numerical methods for analysing stability have become both more sophisticated and easier to use (through the development and availability of personal computer-based, easy to use software, for example, http://www.icivilengineer.com/Software_Guide/Slope_Stability_Analysis/ a web site that lists many slope stability software packages). However, until recently, the amount of information about geohazards available nationally (as opposed to on a site specific basis) has been somewhat limited, making the anticipation of potential geological hazards and risks difficult and largely based on experiential knowledge. In Britain, geohazard information systems are becoming available to meet general and specific user needs. However, the existence of such systems will pose new challenges in terms of the limits to which such information can be put.

Hazard and risk definitions

The definition of hazard and risk is not straightforward despite the efforts of landslide specialists, in particular, over the last twenty years. Amongst many engineering geologists and geotechnical engineers there is agreement that risk is a combination of the probability or frequency of occurrence of a defined hazard and the magnitude, including the seriousness of the consequences. Varnes (1984) description of the total risk in terms of the hazard, the elements at risk and the vulnerability is well known even though it sometimes is not applied. For example, Benson et al. (2003) published a strategy for assessing the “risk” of karst subsidence, which, according to Varnes’ definition, actually assesses the hazard. Similarly, Buttrick et al. (2001) characterised sinkhole-affected ground at Simunye, South Africa, in terms of “inherent risk classes” that equate to hazard classes according to Varnes. Some geohazard specialists still refer to the landslide, sinkhole or mineshaft etc as the ‘hazard’ and the frequency or probability of occurrence as the ‘risk.’ So, even though much has been done to develop geohazard assessment methods, Varnes’ basic definition is still not universally used and accepted by geohazard specialists. Similarly, in comparison to hazard assessment, *risk* assessment methods are still poorly developed in relation to geological hazards (Hearn and Griffiths 2001), though a book on this subject published while this paper was being finalised is a significant step forward (Lee and Jones 2004).

There are a number of possible reasons why there has not been faster application of risk assessment. First, Varnes’ definition of total risk appears to be based on the approach taken by seismologists, in particular, to define hazard, though Varnes (1984) simply states that the approach is based upon the definitions used by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) and the Office of the United Nations Disaster Relief Co-ordinator (UNDRO). The hazard definition requires the determination of the probability of a potentially damaging event occurring in a defined area within a specified time period. However, the difference between earthquakes and most other geological hazards is that the former can be monitored instrumentally, and have been over many decades. This gives a reasonably complete data record, albeit for a limited length of time. Also, because larger earthquakes are felt over regions, they tend to be recorded in historical documents going back over thousands of years. Other hazards, such as sinkholes or landslides tend to be more localised. Consequently, they are less likely to be recorded other than, perhaps, in local newspapers that may have a history going back a few hundred years at best (for example, Culshaw and Bell 1992, Lee 2000).

Second, the recording of still observable geohazards is generally poor. For example, in 1987, a study of published and unpublished literature identified records of approximately 8500 landslides in Britain, the majority of which were portrayed on British Geological Survey maps (Geomorphological Services Ltd. 1987). For the Bradford Metropolitan Borough area approximately 20 landslides were recorded. Subsequent landslide mapping of the area noted 201 landslides (Waters et al. 1996). This, and other subsequent (but as yet unpublished) mapping by the British Geological Survey, suggests that the original database, produced by Geomorphological Services Ltd. for the British Government's Department of the Environment, recorded only around 10% of the number of mappable events. Similarly, in a literature-based study of Great Britain, Applied Geology Ltd. (1993) recorded around 8300 natural cavities of which about 6500 were dissolution features such as sinkholes (the rest were other natural cavities such as sea caves and gulls). Figure 37 shows maps of the Newbury area of Berkshire, UK. Dissolution features from the database of Applied Geology Ltd. (Figure 37a) and from more recent ground-based mapping of the area (Figure 37b) show that the number of features recorded has increased approximately five times. This paucity of data on geohazard events can make the quantitative determination of probability difficult. However, with regard to landslides, Anon. 2000 suggested a that number of alternative methods could be used when historical data is lacking:

- Empirical approaches for ranking potential for instability of different slopes;
- Relationship of rainfall frequency, intensity and duration to landsliding;
- Direct assessment based on judgement;
- Modelling a dominant parameter such as pore water pressure.

Third, the assessment of the elements at risk and vulnerability may require the input of non-geologists/geomorphologists such as economists and social scientists. Not only do these different professionals use different terminology but, also, ways of combining the different forms of data are poorly developed. In relation to this, Varnes' (1984) original definitions of hazard and risk in relation to landslides can confuse as they are expressed in a quasi-mathematical relationship (Total risk [R_s]= Hazard [H] x Elements at risk [E] x Vulnerability [V]) that is difficult to resolve quantitatively.

Fourth, the users of information on geohazards provided by engineering geologists and other geohazard specialists have different requirements. Some of these users need information on risk but others may only want to know whether there is a (geo)hazard threatening them or the property for which they have a financial liability. Examples of different user requirements are discussed below:

- The general public understands the nature of the elements at risk (usually, their house or other property) and wants to know whether their property is threatened by a (geo)hazard and, if so, how severely that property is likely to be affected (the vulnerability).
- Land use planners are concerned mainly with understanding the (geo)hazard. They can then reduce the risk to zero by not allowing any

development in hazardous areas or partially limit the risk by reducing the vulnerability by requiring the developer to protect the development from the (geo)hazard. For example, when permission to build on a river flood plain is requested, depending upon the local regulations, the planner might either refuse permission or require the developer to install flood protection measures.

- Insurers, like householders, understand very well the elements at risk and, based on claims experience, will have a good appreciation of the level of vulnerability. However, they require information on the (geo)hazard both in terms of susceptibility and frequency. This requirement has led to the development of national geohazard information systems based on geological data, such as GHASP (GeoHAzard Susceptibility Package) in the UK (Culshaw 1993, 2003, Culshaw and Kelk 1994), and its successor, GEOSURE, and INSURE (INformation System for Underground Risk Evaluation) a system based on soil map data (Jones et al. 1995).
- With regard to geotechnical engineering, Clayton (2001) identified three types of risk: those arising from problems with the site (the geohazards), those associated with the type of contract chosen, and those associated with the way in which the project is managed. The site investigation is intended to identify the geohazards that pose a risk to the completion of the engineering work to specification, time and budget. Clayton (2001) recommended that risks could be controlled by using systematic risk management techniques including the establishment and maintenance of a risk register. This risk register would be passed through the project as it progressed. He also stressed that risk management must start during pre-project planning which,

for building projects, means before land is purchased. Van Staveren and Peters (2004) emphasised that it was necessary to explicitly allocate responsibility for particular risks between the client and the contractor so that each party has an incentive to manage and reduce the risk. Consequently, the identification of geohazards and the risks that they pose is only a part of the process to reduce the overall risks.

Vulnerability

Heijmans (2001) discussed the concept of vulnerability but pointed out that no universally accepted definition existed. It is clear to anyone who takes note of the popular media that poorer people in less developed countries tend to be more vulnerable to natural disasters; in other words, they suffer more deaths and injuries and greater personal economic loss (in relative terms). A comparison between the effects of the magnitude 6.6 Bam earthquake in Iran on 26 December 2003 and the magnitude 7.1 Loma Prieta earthquake in northern California on 17 October 1989 shows the difference. According to the United States Geological Survey, in the Bam earthquake around 43 000 people may have died (the exact figure may never be known), 30 000 people were injured and 85% of buildings were damaged or destroyed. In northern California in the Loma Prieta earthquake there were 63 deaths and nearly 3800 injuries. The cost of damage to property and infrastructure has been estimated at more than $10bn but the percentage of buildings damaged was somewhat smaller than at Bam. However, the differences in terms of death and injury are startling.

Heijmans (2001) identified three different causes of vulnerability and, consequently, three different strategies for reducing it:

- Natural hazards are the cause and vulnerability results from the size of the hazard and the proximity of people to it. Solutions involve mitigating the hazard through prediction (geological approach), relocation of people (planning approach) and better building design and construction enforced by better building codes (engineering approach).
- Cost is the cause; mitigation is too costly and so not applied. Solutions include insurance, government disaster funds and subsidised personal savings.
- The socio-economic and political situation is the cause; poorer people find it more difficult to respond to, cope with and recover from hazard events. Solutions involve alleviating poverty by changing social and political structures.

Hazard and risk mapping at the site scale

Despite, the potential difficulties discussed above in moving towards better methods of hazard and risk assessment progress has been made. Many of the published methodologies relate to engineering structures. Hearn (1995) proposed a simple but empirical way of getting round the problem that, for many geohazards, probability of occurrence cannot be measured scientifically because of a lack of data.

Similar to Varnes' method, Hearn identified *hazard*, *probability*, *risk value (elements at risk/exposure)* and *vulnerability* as the key components of the *total risk*. He then defined the total risk 'number' for twenty five 'geomorphological units (GU)' in relation to the threat from landsliding to a mine in Papua New Guinea. For each GU he determined the total risk number (Table 6).

Hearn's (1995) method was adapted by Boggett et al. (2000) for a coastal site in NW England affected by landsliding. Hearn had not provided any classification of total risk values obtained by applying the method. Boggett et al. provided the risk classification shown in Table 7, but without providing any guidance on how it should be used as a tool to reduce the risk. Chowdhury and Flentje (2003) recommended that risk assessments should be carried out separately for the probability of loss of life and the value of property loss.

Hearn and Griffiths (2001) listed the seven action stages required to produce a quantitative risk assessment (for landsliding):

1. "Preparation of a landslide location and susceptibility map to identify potential landslide sources.
2. "Estimation of the volumes of potential landslide masses likely to be derived from these sources.
3. "Estimation of the likely areal influence and runout distance of these landslide masses.
4. "Assessment of frequency or return periods of different landslide and runout scenarios.
5. "List of potential consequences and vulnerability of the elements at risk to these landslide and runout scenarios.
6. "Calculation of the economic loss and evaluation of the public safety implications associated with outcomes likely to take place over the lifetime of an existing or proposed development, for example 25 years in the case of a low-cost road, or 100 years in the case of a housing development.

7. “If the risk levels calculated in action 6 are unacceptable, calculation of the cost of mitigation works and decision as to the most appropriate strategy for risk management. In the extreme, this may mean cancellation of the project.”

So far, few case histories have appeared in the engineering geological literature to illustrate the application of this and similar approaches. However, Cruden and Fell (1997) have brought together a useful collection of information on how progress can be made. From a practical point of view, Einstein (1988, 1997) described the various mapping stages that can be carried out:

Level 1:	State of nature maps
Level 2:	Danger maps
Level 3:	Hazard maps
Level 4:	Risk maps
Level 5:	Landslide management maps and procedures.

Wu et al. (1996) equated these levels to the steps in a decision making process:

Step 1:	Characterise site	(Level 1)
Step 2:	Identify failure modes	(Level 2)
Step 3:	Evaluate hazard for each failure mode	(Level 3)
Step 4:	Evaluate consequences for each failure mode	(Level 4)
Step 5:	Evaluate risk for each management option	(Level 4)
Step 6:	Chose management option	(Level 5)

With the publication of the book on landslide risk assessment by Lee and Jones (2004), it is likely that the various risk assessment methods proposed will come into more general use and helpful case histories will become available. This process is being helped by the development of national geohazard databases.

In Italy there is considerable investment in the building of sophisticated landslide databases for each region. The IFFI project (Inventario dei Fenomeni Franosi in Italia) started in the late 1998 and is managed at the national level by the Italian Geological Survey (http://www.apat.gov.it/site/it-IT/Progetti/IFFI/) (Amanti 2004). However, the databases are populated and implemented at the regional level. The number of landslides identified is very large (over 380 000), with many of the regions reporting over 40 000 each. Similarly, Italy is developing a sinkhole database. In Ireland, following the occurrence in the north west of slides and flows in peat in 2003, a landslide database has been designed and is being populated. Similar databases for landslides and karst features are under development in the UK.

Hazard and risk assessment for contaminated land

Considerable research has been carried out to develop risk assessment procedures for contaminated land. In Britain, these have a similar approach to those being developed for the assessment of physical geohazards. For example, in its strategy for the inspection of contaminated land, Wrexham County Borough Council outlines the procedure that it has adopted (Anon. 2002a) based on the national guidelines published by the Department for Environment, Food and Rural Affairs and the Environment Agency (Anon 2002b):

1. Hazard indication: identify the hazards that exist or occur on a site (action 1 from Hearn and Griffiths 2001);

2. Hazard assessment: assessing the degree of hazard through the consideration of plausible hazard/pathway/receptor scenarios (actions 2 to 4 from Hearn and Griffiths 2001);
3. Risk estimation: estimating the likelihood that an adverse effect will result from exposure to the hazard and the nature of the effect (action 5 from Hearn and Griffiths 2001);
4. Risk evaluation: evaluating the significance of estimated risks (action 6 from Hearn and Griffiths 2001);
5. Evaluation and selection of remedial measures (action 7 from Hearn and Griffiths 2001);
6. Implementation of risk management measures (action 7 of Hearn and Griffiths 2001).

The process is based on Part IIA of the Environmental Protection Act (1990) (which applies to England and Wales) in which the presence of a source of contamination, a pathway and a receptor are essential for a risk to be present. Local authorities are required to prioritise land within their areas in terms of risk and initiate action where the risks are high enough. The assessments take place on a site scale.

Hazard and risk assessment at a national scale

In Britain, several systems have been devised to provide hazard assessments for a range of geological hazards nationally. The assumptions made in creating these systems are that the system must have national coverage and that all the significant geohazards must be included. GHASP (see above) was created following the dry period from 1989 to 1991 when insurance losses for ‘subsidence’ damage reached around £500 m per year for each year (based on prices at the time). A system was devised based on the geological map and the postcode system used by the insurance industry to group properties (and based, originally, on post deliverer's rounds of approximately equal numbers of addresses). Digital geological maps were available at a scale of 1:250 000 for the whole of Britain together with some at 1:50 000 scale. Every mapped geological formation was assessed in terms of its susceptibility to a range of geohazards, namely:

- mass movement;
- swell/shrink;
- dissolution;
- compressibility;
- shallow undermining.

Then, for each postcode district (the full postcode is in the form AB1 2AB; a postcode district is defined by AB1 2) each hazard was assessed on a scale from 0 to 1 in 0.1 intervals. Adjustments were made for the likely affect of each hazard relative to the others and for the percentage area it covered within the postcode district. The resulting figures for each geohazard were then summed to give an overall postcode factor. These could then be tabulated for use by insurance companies in determining risk. The postcode factors ranged between 0 and 200 and were placed in a series of classes to enable the postcodes districts to be classified. Maps were produced showing the different hazard classes that applied to each postcode district (Figure 38).

The disadvantage of this approach was that the geohazard rating was an attribution of a postcode district rather than a geological formation. Once the digitisation of geological maps at a scale of 1:50 000 was completed (Jackson and Green 2003), it became possible to produce a national geohazard map (GeoSure) that was independent of postcode areas and based upon the degree susceptibility of each geological formation to each geohazard. Factors such as slope angle (landsliding) or plasticity (swell shrink) could be incorporated into algorithms for the assessment of each geohazard to produce national geohazard susceptibility maps. Figure 39 shows a portion of the map for the site of the landslides that blocked the A85 road in Glen Ogle, west of Perth, Scotland, in August 2004. It can be seen that the locations of the landslides had been classified, before their occurrence, as being in the high hazard category. Because the system is digital, there is the potential to access information for a specific site over the internet. However, as at present, such information may not be free (though any cost is likely to be relatively low, reflecting more that cost of providing, maintaining and improving the service rather than the true value of the data or the market conditions). Different data providers in different countries work to different governmental instructions so the situation is likely to vary. However, the development of common data formats will lead to compatibility between information systems in neighbouring countries.

The provision of information on the effect of geological processes on the ground is at a less advanced level than the 3D spatial model. In the UK, as described above, comprehensive 2D geohazard information is based on information at a scale of 1:50 000 with a resolution of around 50 m. With the digitisation of geological maps at a scale of 1:10 000, and resolution of 10 m, likely in the next decade, the provision of site-relevant 2D information on geohazard susceptibility is likely to occur relatively quickly. However, the incorporation of the effects of geological processes into the 3D spatial model to produce 4D models is still some way off, except in some site-specific situations where considerable amounts of relevant information have been specially collected.

CONCLUDING COMMENTS

Geology has come a long way in the last two decades in terms of the development of both digital (2D) geological maps of a wide range of types and, more recently, 3D spatial modelling of the shallow subsurface. In 1988, the Committee on Geologic Mapping, of the Board of Earth Sciences, of the Commission on Physical Sciences, Mathematics, and Resources, of the National Research Council of the USA attempted to identify future needs for geological mapping (Anon., 1988). In doing so, it carried out a survey of 'users,' of whom, unfortunately, around 85% appeared to be geoscientists, or in closely related professions and two-thirds were involved in resource planning, exploration and development. The biggest request was for the "large-scale, general-purpose color geologic map." With regard to future innovations in geoscience maps, there was a demand for "additional high-quality ground truth data, a ready and inexpensive means for map data manipulation, improved ways to portray map data, and a ready means to determine where data reside and how they can be accessed." However, only 22 respondents out of 1213 (less than 2%) requested "computer/digitally produced maps."

In 20 years computer technology has transformed our ability to construct 3D digital models of the shallow subsurface. These models can be produced combining bedrock, superficial and artificial deposits. Research to attribute them with point physical, mechanical and chemical property values and to summarise the point data across geological units is underway. Integration of groundwater and mineworkings information is being attempted. Our ability to do this results from the archiving of thousands of borehole logs and their associated data. At the national scale, the development of digital geological maps at medium scale for the whole of Britain has allowed us to produce geohazard susceptibility maps that are useful to everyone from the professional engineering geologist carrying out a desk study to the private citizen seeking to understand the hazards that might affect a property that they wish to buy.

These models will transform geological map-making, which Conway Morris (2000) described as geology's most important key episode of the preceding millennium. He suggested that the geological map was more important than, for example, plate tectonics, seismics, the thin section and the use of isotopes. Thus, we are approaching the end of a major era of geological development. William Smith's 2D interpretative geological map is about to be replaced by the interactive, digital 3D model attributed with geotechnical data. As a result, the site investigation practices that have met the needs of engineering geologists and geotechnical engineers for more than 50 years will have to change.

It is suggested that, in future, the first requirement of the ground investigation will be to test the veracity of the 3D engineering geological model. The amount of new subsurface work required will depend upon the amount of information used to build the model in the first place and, in a general sense, on the uncertainty associated with it. The risks associated with different degrees of uncertainty will need to be determined so that judgements can be made. In addition, site investigation practitioners and their clients will have to come to accept that if these uncertainties and associated risks are to be reduced in the future, then they have to play their part in making the models better. This will require site investigation data to be made readily and systematically available to those charged with producing the new models. Unless all those that are involved in the site investigation process, whether as practitioners, clients or information providers, can agree that the exchange of information is central to increased quality and efficiency, we are destined to continue 'probing in the dark.'

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TABLES

Table 1. Content and principal users of thematic geological maps of Wigan (after Forster et al., 1995).

Theme	Content	Examples of users
Bedrock geology	Extent and litho-stratigraphy of bedrock	Geologists and geologically literate professionals
Superficial geology	Extent, thickness and lithostratigraphy of superficial deposits	Geologists and geologically literate professionals
Distribution of pits, boreholes and site investigations	Locations of subsurface boreholes, pits and indirect measurements	Geologists and geologically literate professionals
Hydrogeology	Surface and ground-water features, water abstraction points and aquifers	Planners, water companies, waste disposal companies
Mineral resources	Potential and exploited mineral resources	Planners, mineral companies
Distribution of made and worked ground	Extent and types of made ground, waste materials, landfill and other modified ground	Planners, geotechnical and geoenvironmental engineers
Previous and present industrial uses	Potentially contaminative and general industrial land use, past and present	Planners, developers, financiers geotechnical and geoenvironmental engineers
Engineering geology	Geotechnical characteristics and likely engineering behaviour	Planners, geotechnical and geoenvironmental engineers
Shallow mining	Extent of opencast and subsurface mine workings, mine entries	Planners, developers, geotechnical and geoenvironmental engineers

Table 2. Types of 3D model and their characteristics.

Type of 3D model	Overview	Systematic	Detailed
Cross-section spacing	Several km	0.5-1.5 km	< 500 m
Cross-section length	Tens of km	5-10 km	< 5 km
Density of (coded) boreholes	< 1 per km^2	Commonly 5-20 per km^2	Often hundreds per km^2
Stratigraphical level	Major Groups and Formations only	Formations and Members; big lenses	Members and thin individual beds and lenses; artificial ground
Modelling speed (excluding data preparation)	Up to hundreds of km^2 per day	2-10 km^2 per day	< 2 km^2 per day
Scale	Compatible with 1:625000 and 1:50000 geological linework	Compatible with 1:25000 and 1:10000 geological linework	Compatible with detailed site plans at scales as large as 1:1000
Minimum unit thickness	2 m	1 m	0.1 m
Modelling output	Often only sections and an open fence diagram	Computation of surfaces for export to GIS	Computation of surfaces and lenses for export to GIS
Uses	Education, visualisation and overviews (for example, general catchment characterisation), first-pass assessments	Builds a 3D model stack for interrogation in site selection, route planning, resource assessment, recharge and aquifer studies etc.	Detailed 3D model for analysis of thickness, volumes, flow paths providing bed-by-bed stratigraphy for use in urban planning, site investigation and development

Table 3. Map and model nomenclature used in the 3D model of the shallow subsurface in Salford and Manchester.

	Map Unit	Model Unit	Lithology	Environment (inferred)
HOLOCENE	**Worked Ground**	Worked Ground		Anthropogenic (Artificial deposits)
	Made Ground	Made Ground	Mixed	
	Infilled Ground	Infilled Ground	Mixed	
	Peat (lowland bog)	Peat	Peat	Organic
	Alluvium	Overbank Floodplain Deposits Peat	Silt, clay Peat	Fluvial
		River Channel Deposits	Sand, gravel	Fluvial (may include glaciofluvial element)
	River Terraces: Undivided First Second	River Terrace Deposits Undivided (River Irwell, River Medlock)	Sand, gravel	Fluvial/Ice marginal
PLEISTOCENE (DEVENSIAN)	**Glaciofluvial Sheet Deposits**: Sheet deposits (formerly Late Glacial Flood Gravels	1. Sheet deposits (including Late Glacial Flood Gravels 2. Basal Sand and Gravel	Sand, gravel	High level terrace
	Ice-contact Deposits	1. Buile Hill Deposits 2. Intra-till channel deposits (major) 3. Intra-till lens and sheet deposits (minor)	Loose, fine sand Sand, gravel Sand, gravel	Ice-contact glaciofluvial/ glaciolacustrine Sub/supra glacial drainage

	Glaciolacustrine Deposits	1. Laterally Extensive (km-scale) Deposits 2. Intra-till deposits (restricted distribution) 3. Deformed deposits	Laminated silts	Ice-distal Ice-proximal Ice-contact, ?push moraine
		Moraine complex Till, sand and laminated clay, undivided	Till, sand, gravel	?Push moraine
	Till	Till	Till, interbedded sands, impersistent laminated clays	Lodgment and melt-out tills, undivided
BEDROCK				

Table 4. UK Department of the Environment classification of past potentially contaminative industries (Anon. 1991).

DoE code	Category	Sub-category
C1	Agriculture	Agricultural land
C2	Extractive industry	Extractive industries and mineral processing: coal mines, quarries, brickfields
C3a	Energy industry	Gas works, coke works, coal carbonisation works
C3d/e	Energy industry	Power stations, sub stations
C4b	Production of metals	Metal works: smelting and electroplating
C5b	Production of non-metals and their products	Asbestos manufacture and handling
C6a	Glass making and ceramics	Glass making, potteries, tile works
C7a	Production and use of chemicals	Oil refineries, tar distilleries, asphalt and tarpaulin works
C7b	Production and use of chemicals	Chemical, paint, dye and rubber works
C8a	Engineering and manufacturing processes	Engineering works
C8b	Engineering and manufacturing processes	MoD land, barracks, TA Centres
C9	Food processing industry	
C9b	Food processing industry	Animal and products of processing works, including abattoirs, tanneries and leather goods
C10a	Paper, pulp and printing industry	Paper, pulp and printing works
C11a	Timber and timber products industry	Timber yards and works
C12b/d	Textile industry	Textile industry and dyeing works
C14a	Infrastructure	Docks, dockland, council depots, warehouses and markets
C14c	Infrastructure	Road vehicle maintenance
C14d	Infrastructure	Airports/airfields
C14e	Infrastructure	Railway land: stations, sidings, sheds and marshalling yards
C14o	Infrastructure	Petrol filling stations and bulk storage of oil/petrol products
C15a	Waste disposal	Sewage treatment
C15c	Waste disposal	Waste treatment sites
C16	Miscellaneous	Including unspecified works
C16d	Miscellaneous	Laundries and public baths
C16e	Miscellaneous	Hospitals, cemeteries and workhouses
C17	Vacant land	Including spoil tips and landfill

Table 5. Determination of the number of outer boxes on a box and whisker plot in relation to the number of data points.

Number of data points	**Outer box limits**
10-19	25, 75%
20-59	10, 90%
60-99	5, 95%
100-299	2, 98%
300+	1, 99%

Table 6. Determination of risk resulting from landsliding at a mine site in Papua New Guinea (after Hearn 1995).

Hazard (H)

1 = small soil failure/soil erosion

2 = moderately sized (1000m^3) slope failure or erosion

3 = deep failure (>30m) over large area (>10 000m^2)

4 = major failure of valley side

Probability (P) (chance of occurrence/reoccurrence within mine life)

1 = unlikely

2 = possible

3 = likely

Elements at risk (E)

1 = hard standing, marginal areas not in use

2 = unoccupied buildings, feeder roads, feeder pylons (22kV)

3 = haul road, slurry and water supply pipes, mine supply pylons (132kV)

4 = residential areas/permanently occupied buildings

Vulnerability (V)

1 = little or no effect

2 = nuisance or minor damage

3 = major damage

4 = loss

Total risk number (RN) = H x P x E x V

Table 7. Risk classification for a coastal landslide site in north-west England (after Boggett et al. 2000).

Risk class		Risk Number
V	Highest	>100
IV		60-100
III	Moderate	30-60
II		10-30
I	Lowest	0-10

FIGURES

Figure 1. The engineering geological triangle developed by observation, experience, intuition and synthesis (modified after Knill 2003).

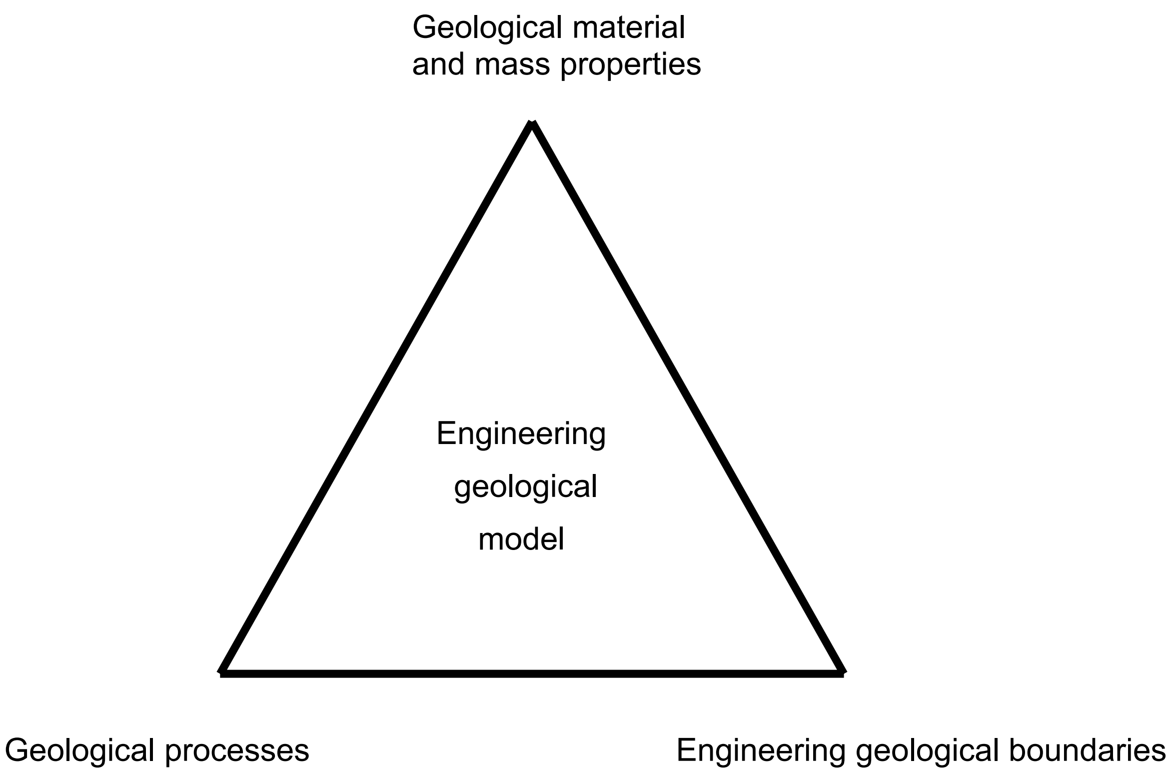


Figure 2. Example of 'discovery metadata' for the Coal Authority's deep coal exploration data (deposited with the British Geological Survey).

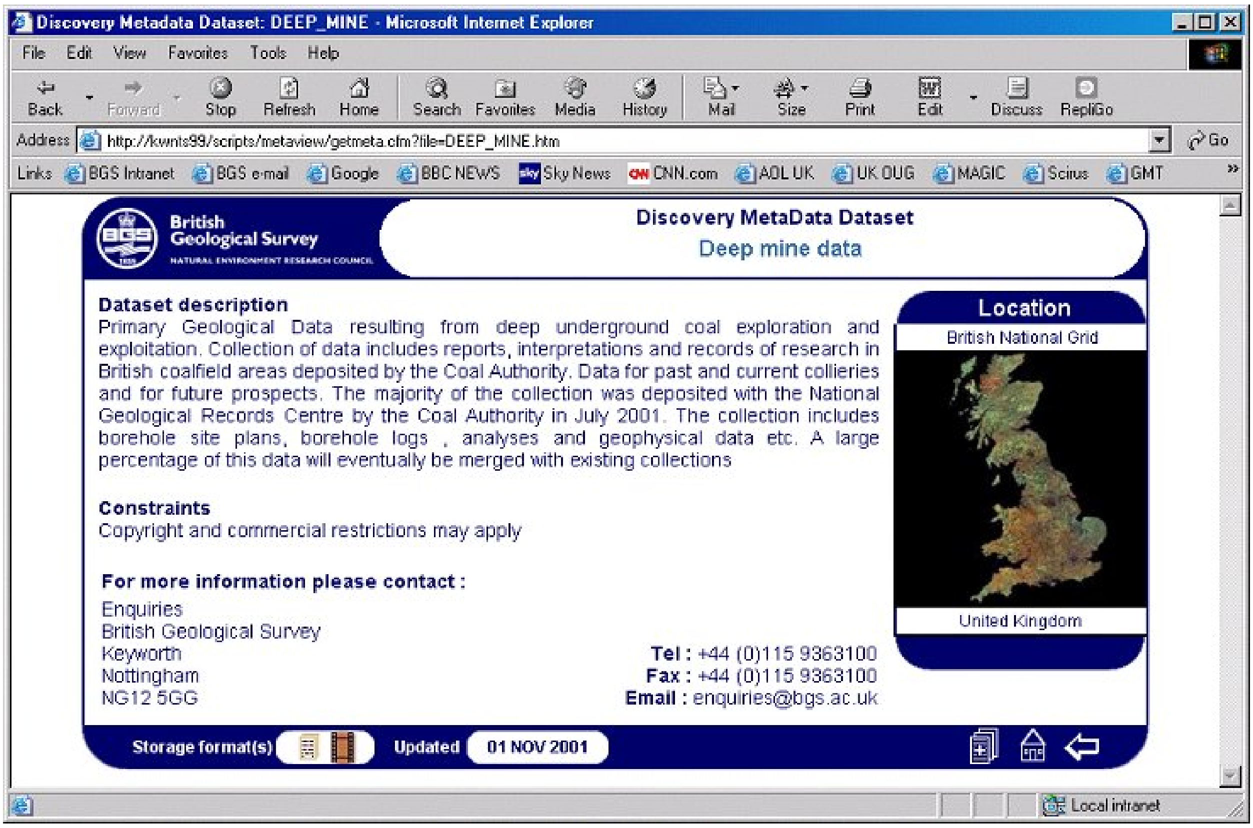


Figure 3. William Smith's 1799 geological map of Bath.

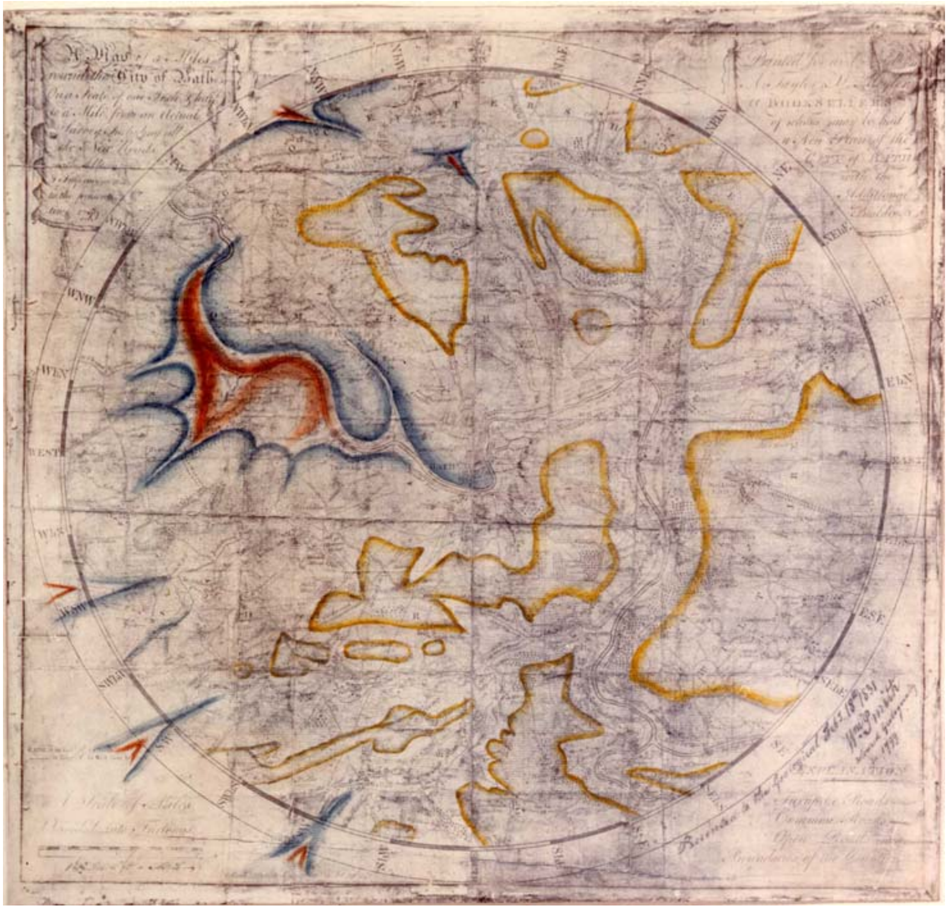


Figure 4a. Reduced scale image of the Superficial Deposit thickness model of Great Britain.

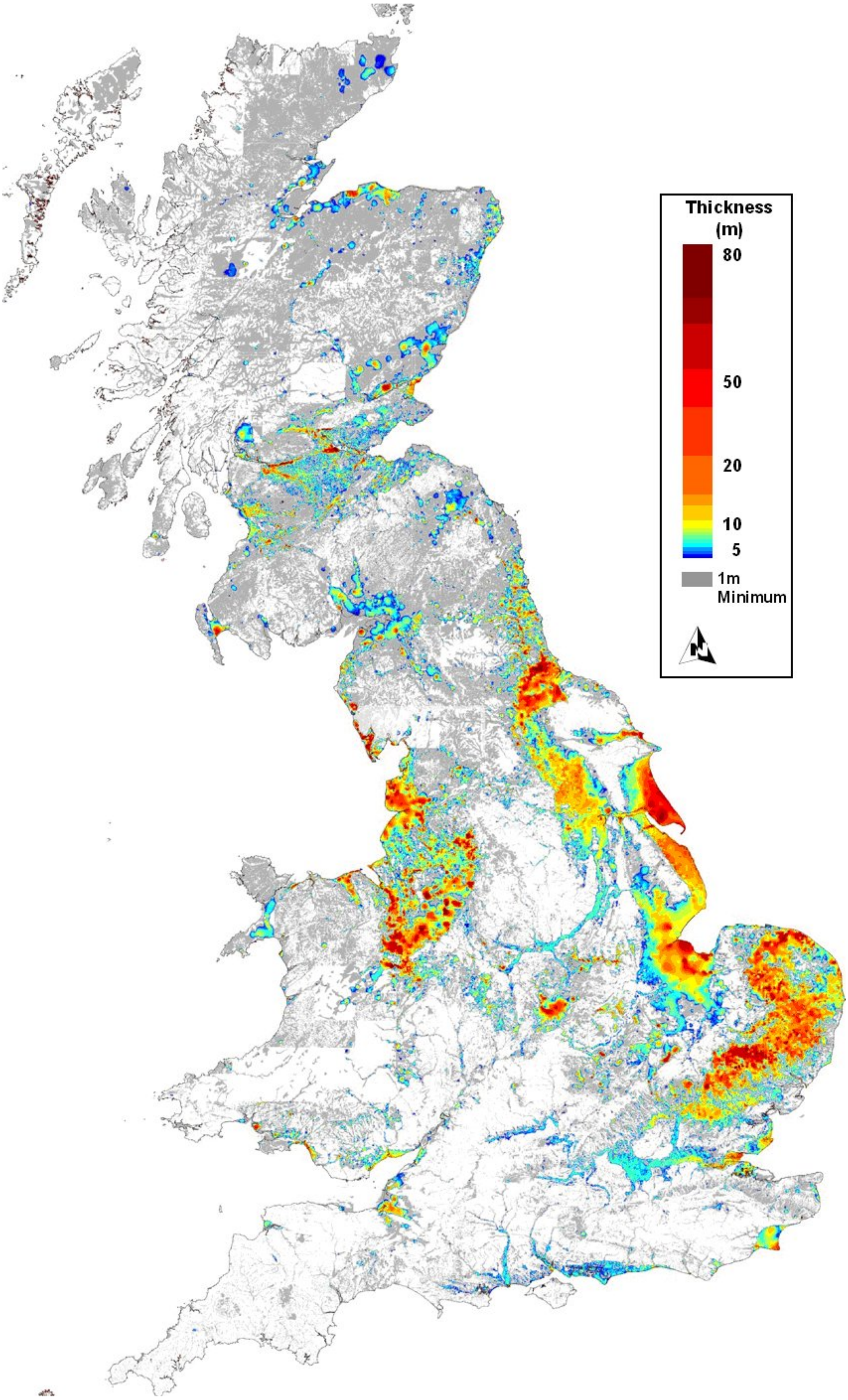


Figure 4b. Superficial Deposit thickness variation across part of the River Thames. Note the thinning (blue) associated with modern scouring along the current river channel.

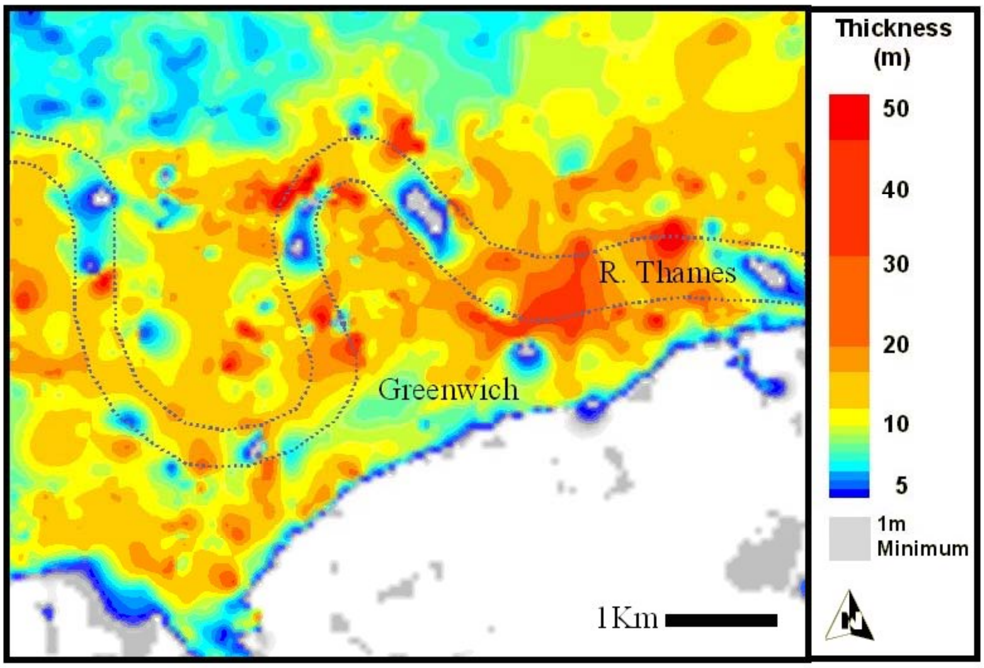


Figure 5. Geological cross sections for part of central Manchester and Salford.

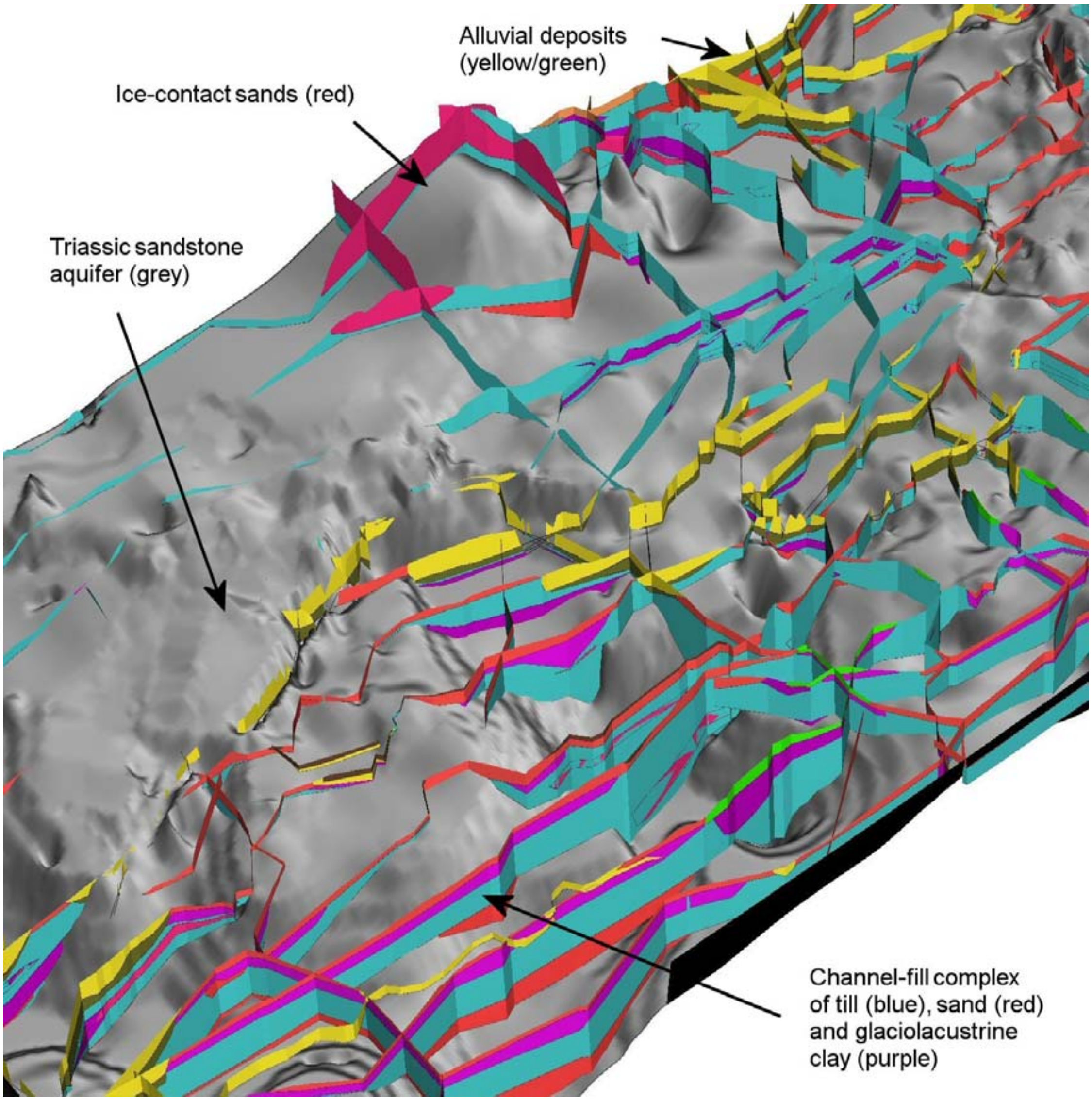


Figure 6. Part of the Generalised Vertical Section (GVS) for the area around Ipswich in southern East Anglia.

model	sequ	LEX	Strat text	Lith	Lith2	Gen	Gen text	Chror	Chron text	Aggpot	Hydr	Colour	Carb	Morpholo
DTM	0	DTM												
bsa	5	BSA	Blown sand	s			Aeolian	1100	Holocene	2	4		0	Dune forn
peat	10	PEAT	Peat	p		Pal	Paludal	1100	Holocene	0	2	black	1	Flat latera
alv	20	ALV	Freshwater Alluv	cz		Flv	Fluvial overbank	1100	Holocene	0	2	grey	1	Floodplair
stob	35	STOB	Storm beach der	lvs			Littoral	1100	Holocene	4	5		0	Beach fac
peat1	40	PEAT	Peat	p		Pal	Paludal	1100	Holocene	0	2	black	1	Flat latera
alv1	50	ALV	Freshwater Alluv	cz		Flv	Fluvial overbank	1100	Holocene	0	2	grey	1	Floodplair
itdu1	60	ITDU	Intertidal Deposit	cz	zs	Int	Intertidal flats	1100	Holocene	0	2	grey	1	Estuarine
lde	65	LDE	Lake Deposits	cz		Lac	Lacustrine	1500	Pleistocene pc	0	2	grey	1	
head	70	HEAD	Head	czsv		Mam	Mass Movement pe	1000	Pleistocene pc	0	2	brown	0	
rtdu	80	RTDU	River terrace De	sv		Flv	Fluvial mainly braic	1300	Pleistocene pc	4	5	yellow bı	0	Terrace
lde1	90	LDE	Lake Deposits	cz		Lac	Lacustrine	1500	Pleistocene pc	0	2	grey	1	
gstc	100	GSTC	Glacial Silt and C	cz		Glac	Lacustrine glacial	1700	Anglian	0	2	grey	1	Channel ir
gsg	120	GSG	Glacial Sand anc	sv		Gflv	Fluvial glacial	1700	Anglian	3	5	brown	3	Remnant
gstc1t	170	LOFT	Lowestoft Till	czsvlb		Glal	Glacial	1700	Anglian	0	2	grey-bla	4	
gstc1	130	GSTC	Glacial Silt and C	cz		Glac	Lacustrine glacial	1700	Anglian	0	2	grey	1	
gsg2	160	GSG	Glacial Sand anc	cz		Gflv	Fluvial glacial	1700	Anglian	3	2	brown	3	
loft	170	LOFT	Lowestoft Till	czsvlb		Glal	Glacial	1700	Anglian	0	2	grey-bla	4	Dissectec
gstcb1	180	GSTC	Glacial Silt and C	cz		Glac	Lacustrine glacial	1700	Anglian	0	2	grey	1	
gsgb1	190	GSG	Glacial Sand anc	sv		Gflv	Fluvial glacial	1700	Anglian	3	5	brown	3	
gsgb2	210	GSG	Glacial Sand anc	sv		Gflv	Fluvial glacial	1700	Anglian	3	5	brown	3	
loftb	215	LOFT	Lowestoft Till bas	czsvlb		Glac	Glacial	1700	Anglian	0	2	grey-bla	4	
gch	217	GCD	Glacial Channel I	sv	cz	Glac	Glacial	1700	Anglian	0	4	grey bro	2	
kes	220	KES	Kesgrave Sand a	sv	cz	Flv	Fluvial braided	1900	Cromerian-Be	4	4	very pale	1	Dissectec
cfc	230	CFC	Chillesford Clay I	cz	sz	Int	High Intertidal mud	2120	Baventian-Pre	0	2	grey	2	
cfb	240	CFB	Chillesford Sand	sz		Int	low Intertidal sandfl	2120	Brammertonia	2	3	yellow bı	2	
rcg	250	RCG	Red Crag Forma	s	sv	Mar	Marine, tide domin	2150	Pre Ludhamiaı	2	4	red brow	3	
ccg	260	CCG	Coralline Crag F	s	sv	Mar	Marine, tide domin	2200	Pliocene	0	4	yellow bı	5	Buried rid
tham	270	THAM	Thames Group	cz	s	Mar	Cyclic shelf	2800	Eocene	0	2	blue-gre	2	
llte	280	LLTE	Lower London Te	cz	s	Pal	Paludal with fluvial	2900	Palaeocene	1	2	grey	1	

regional

Figure 7. Building cross sections – correlation of geological units from the surface geological map (geological boundaries shown by arrows) and borehole logs.

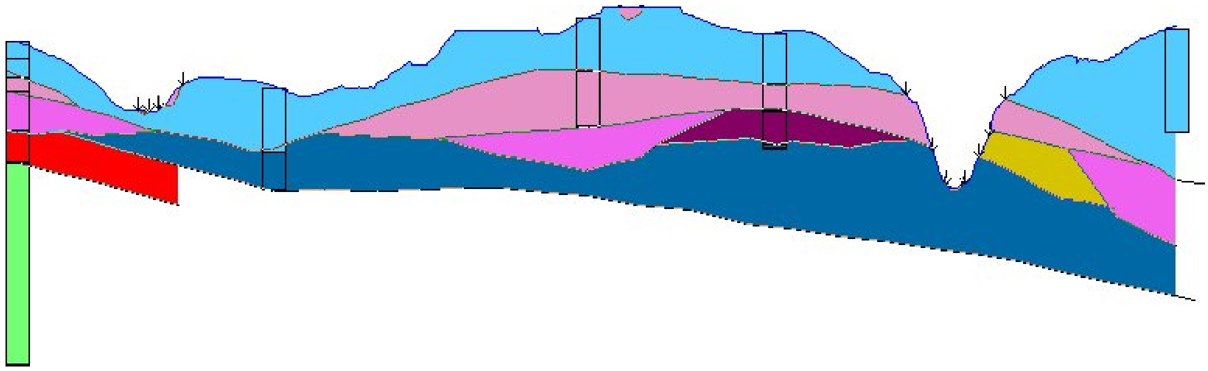


Figure 8. Stylised example of a fence diagram used to develop the 3D model.

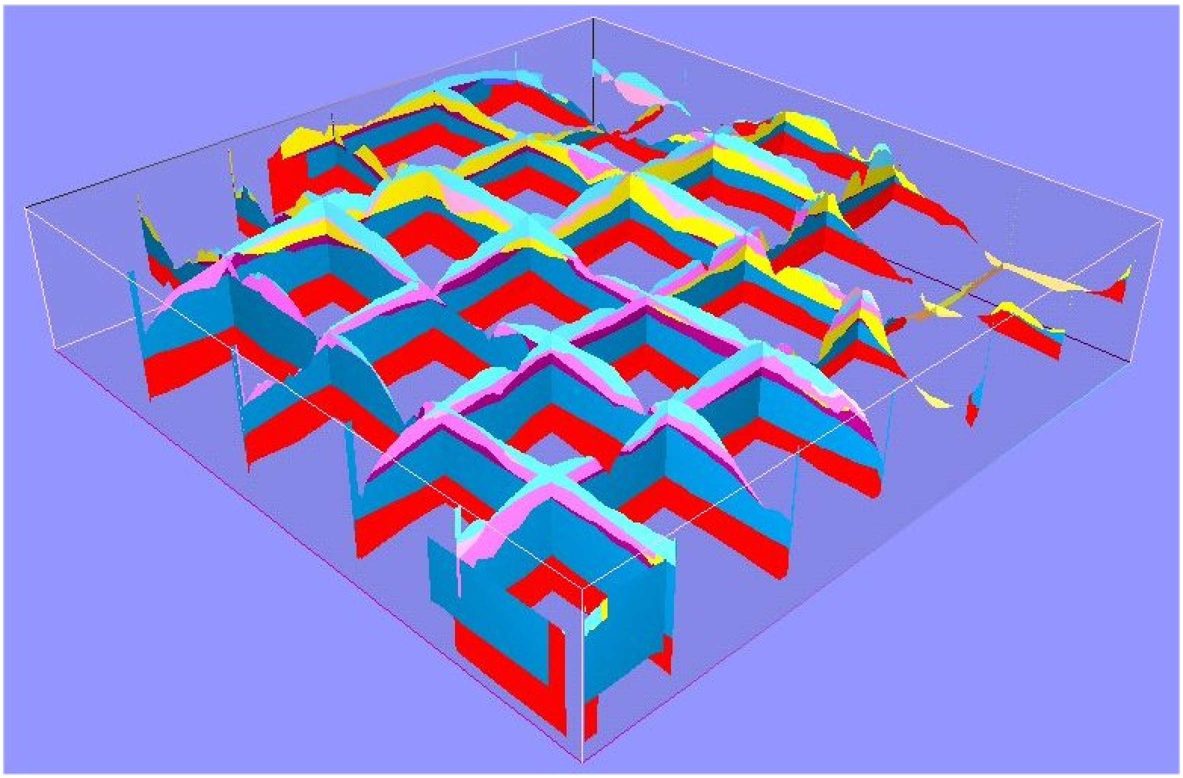


Figure 9. Thickness of the Kesgrave Sand and Gravel (yellow to red) and the non-mineral overburden (blue) in the Sudbury area of southern East Anglia.

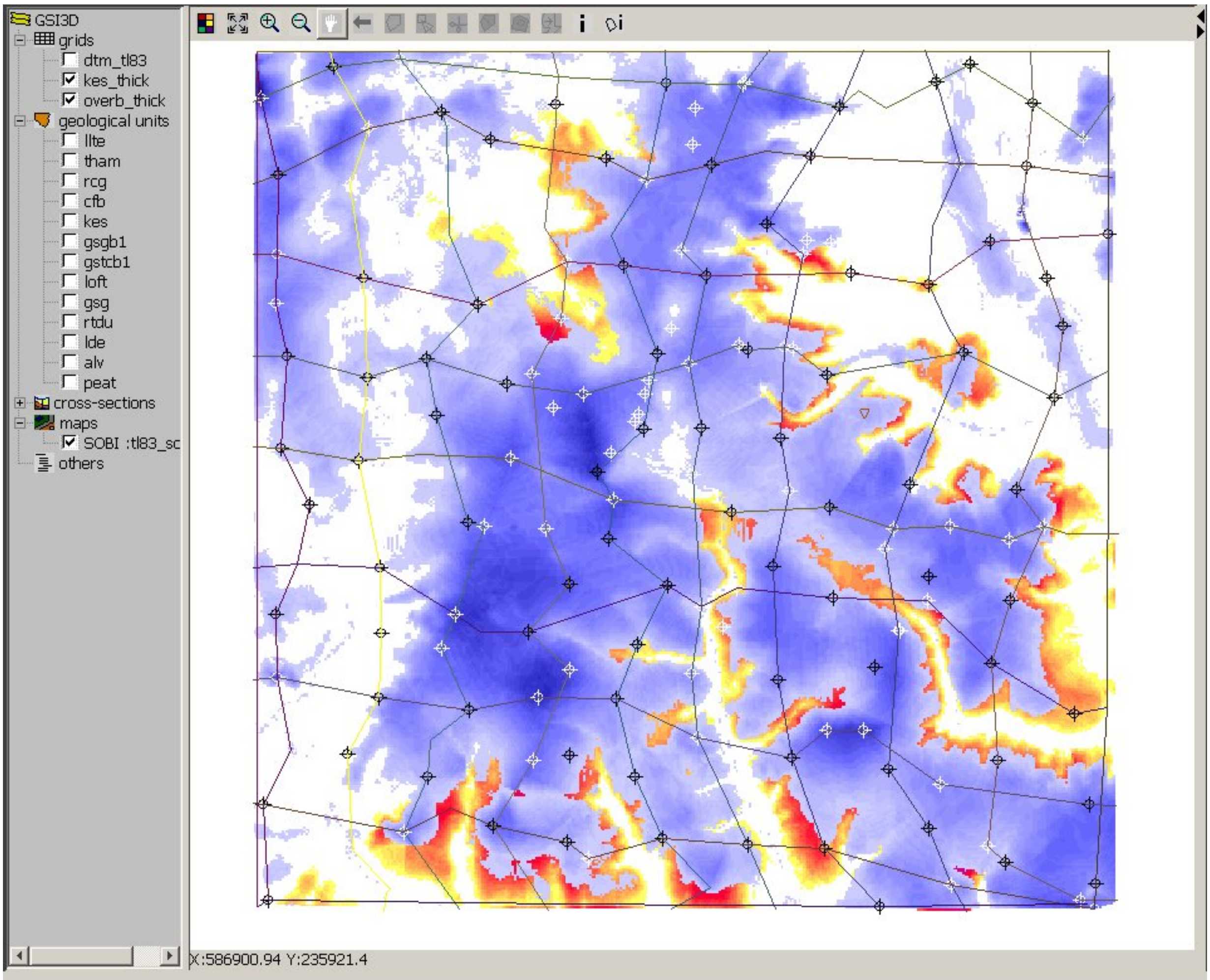


Figure 10. Location of 3D mapping projects discussed in the text.

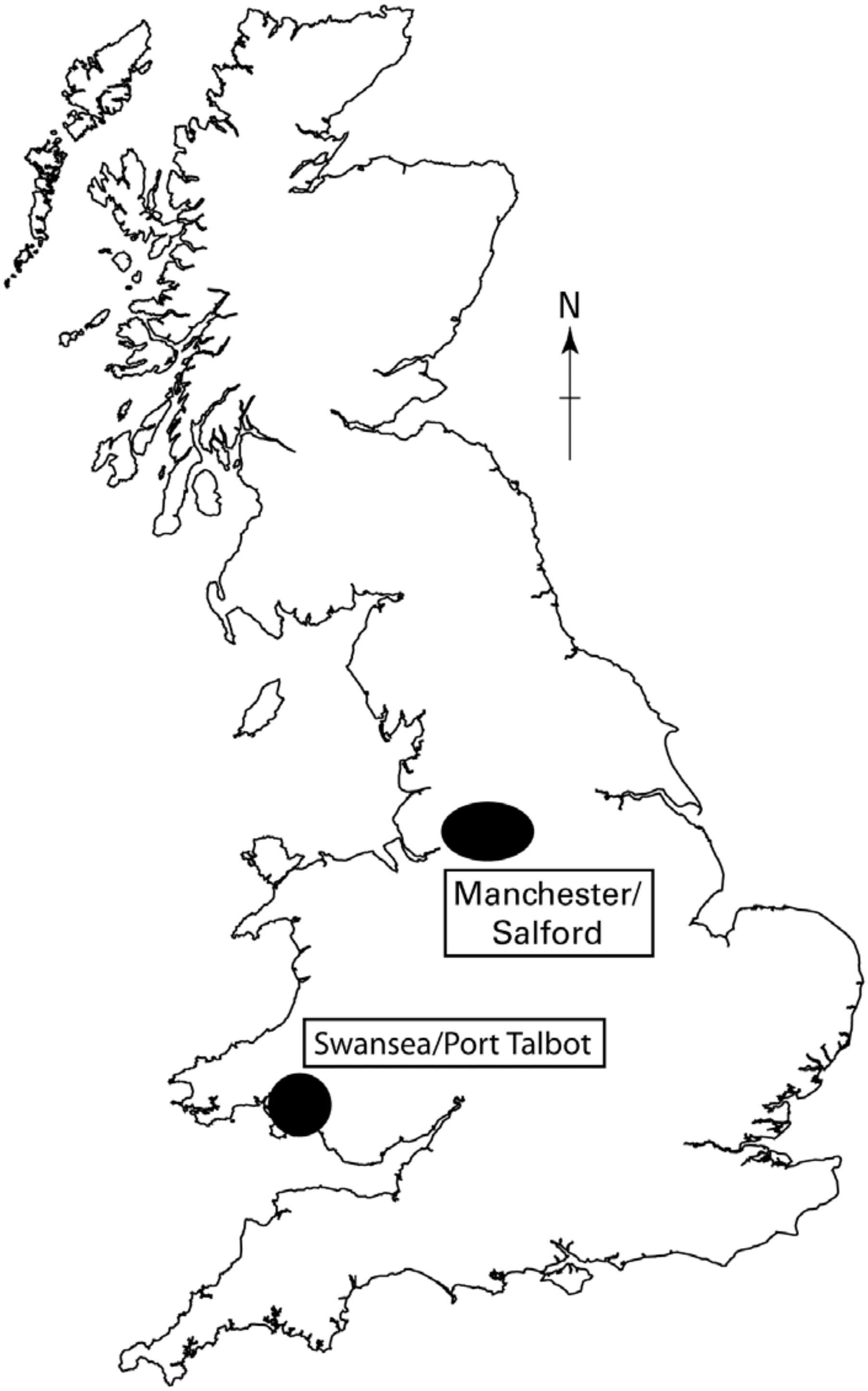
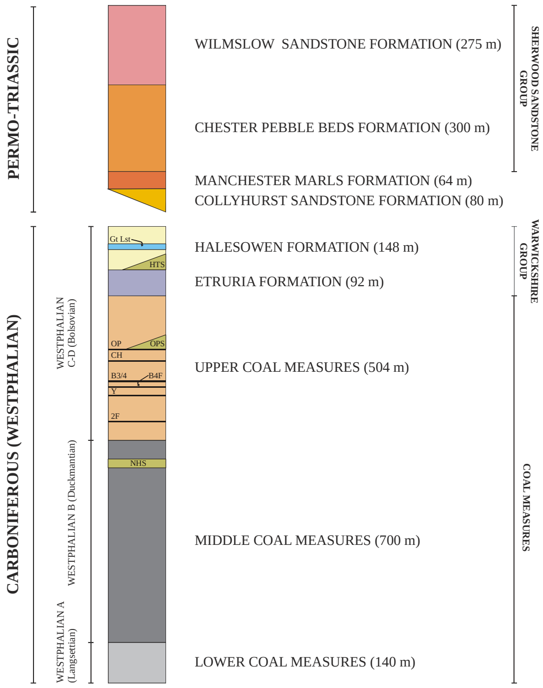


Figure 11a. Bedrock geology beneath central Manchester and Salford.



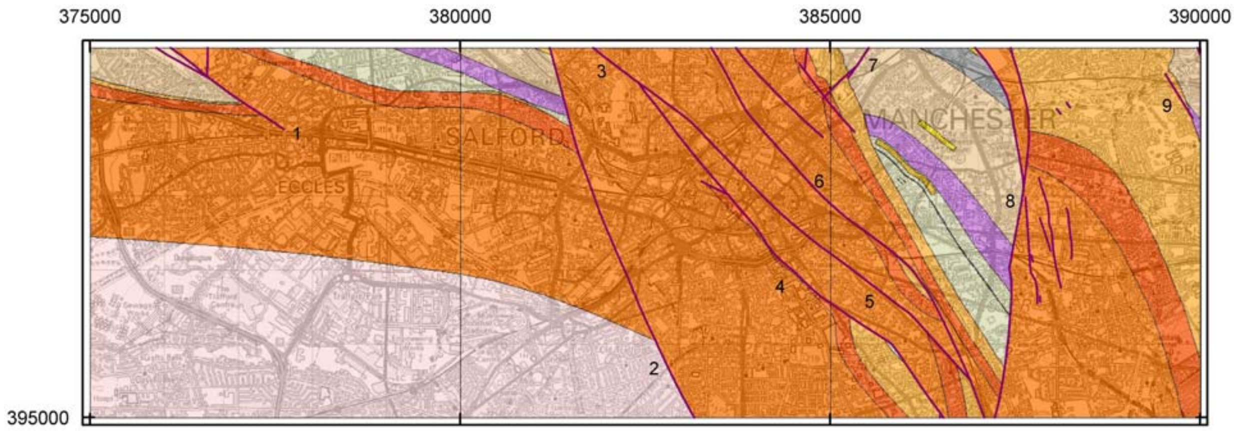


Figure 11b. Superficial geology beneath central Manchester and Salford.

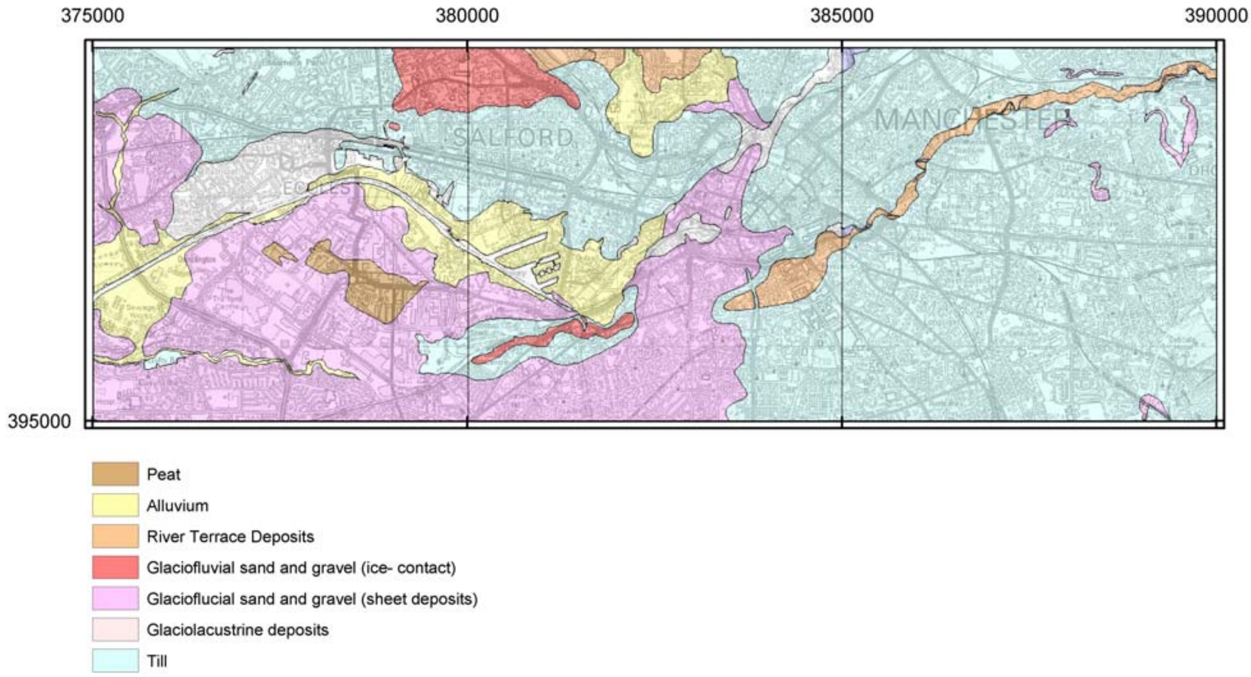


Figure 11c. Artificial deposits beneath central Manchester and Salford.

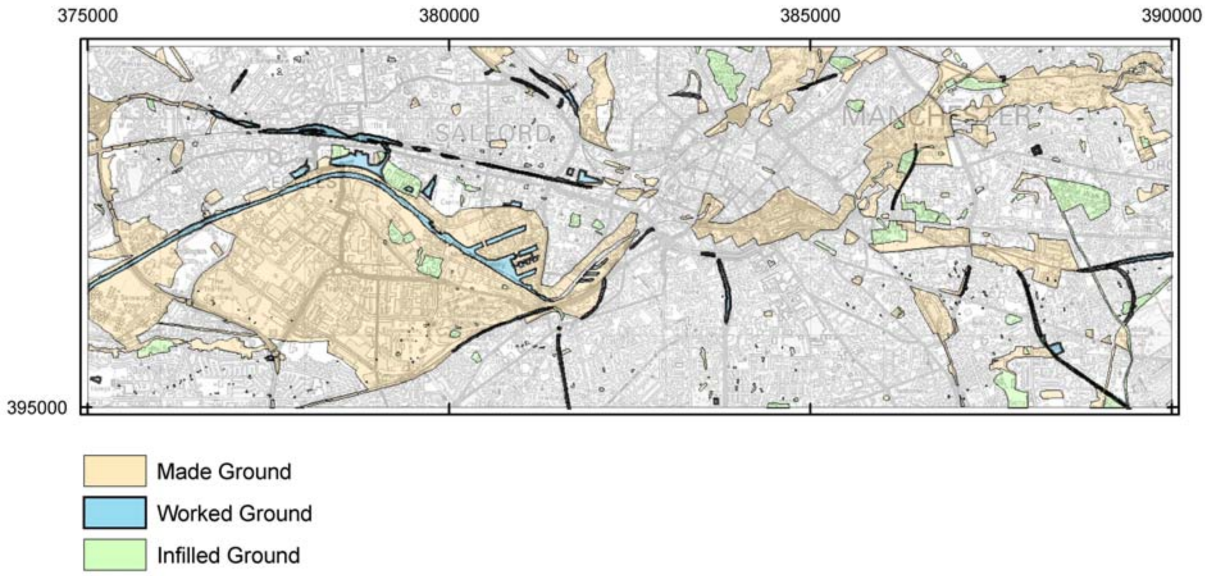


Figure 12. Schematic diagram (with vertical exaggeration) showing relationships between the modelled units for central Manchester and Salford. The unit codes are those used in British Geological Survey databases.

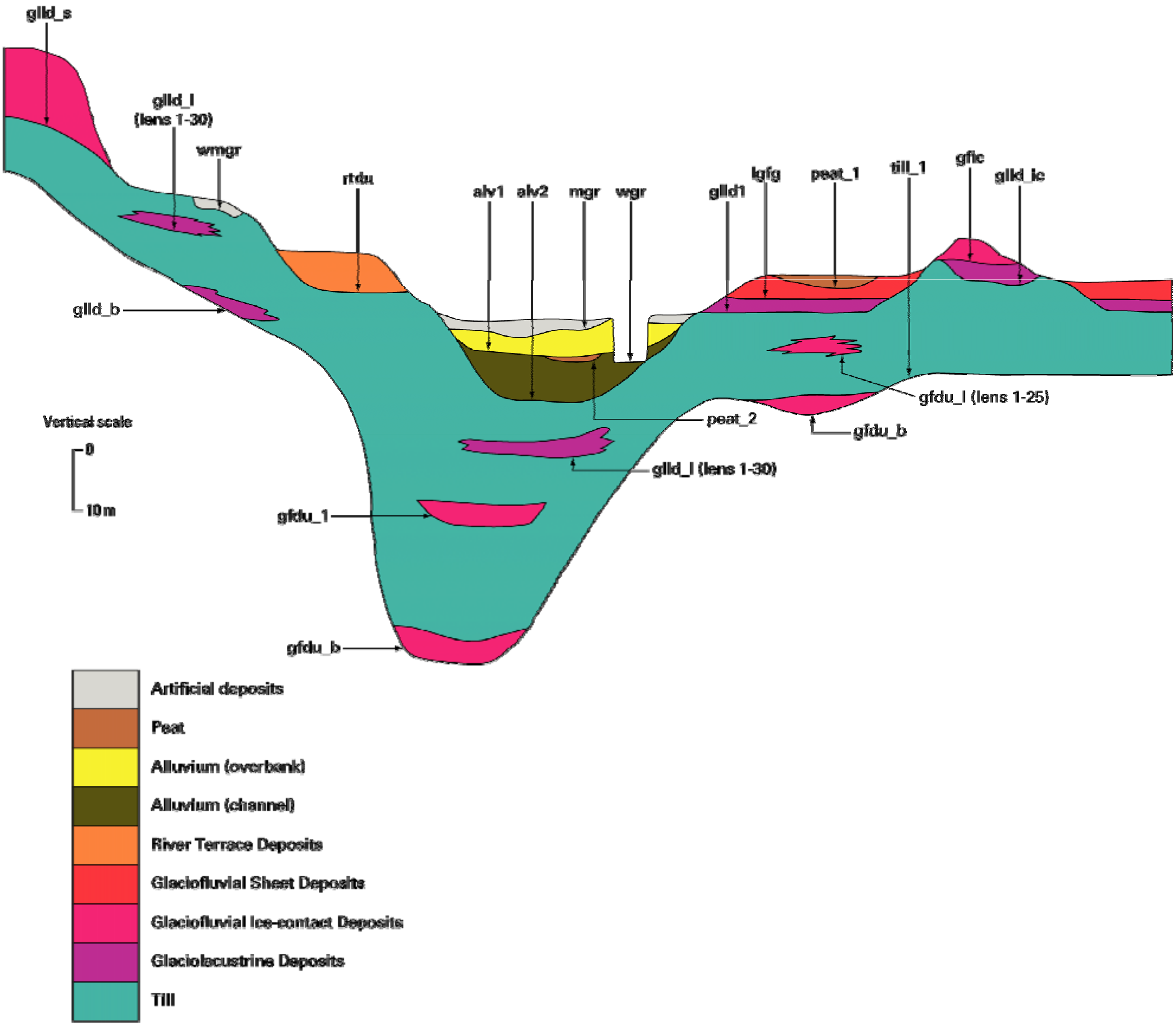


Figure 13. Thickness of artificial deposits (in metres) for central Manchester and Salford.

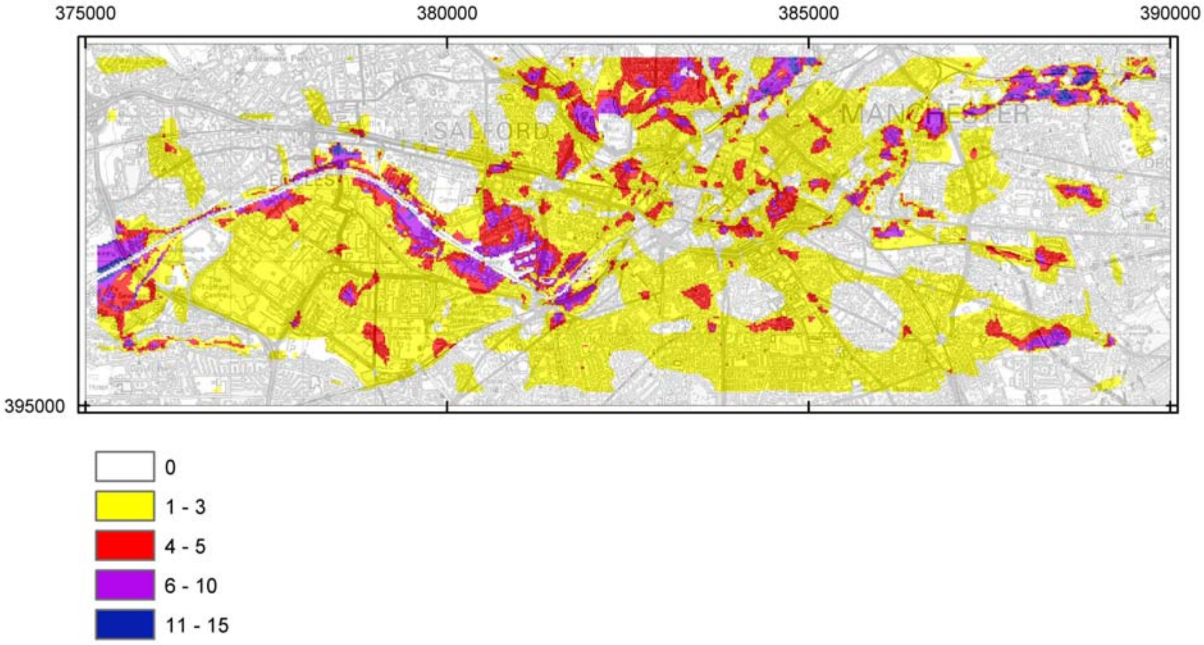


Figure 14. Former course of the River Irwell (orange) in relation to the Manchester Ship Canal (green).

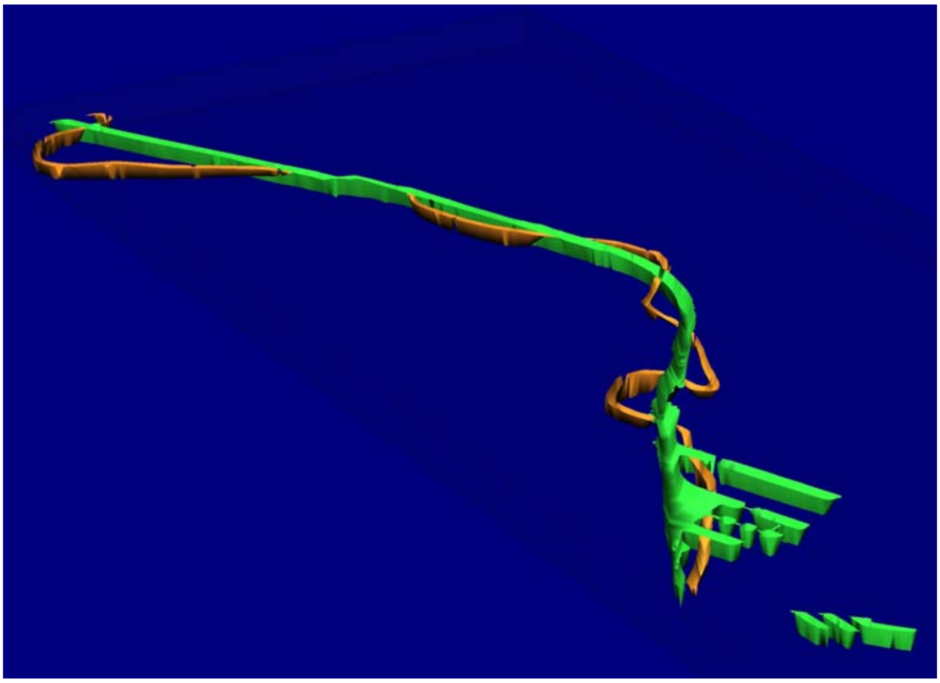


Figure 15. Detailed classification of artificial deposits for central Manchester and Salford.

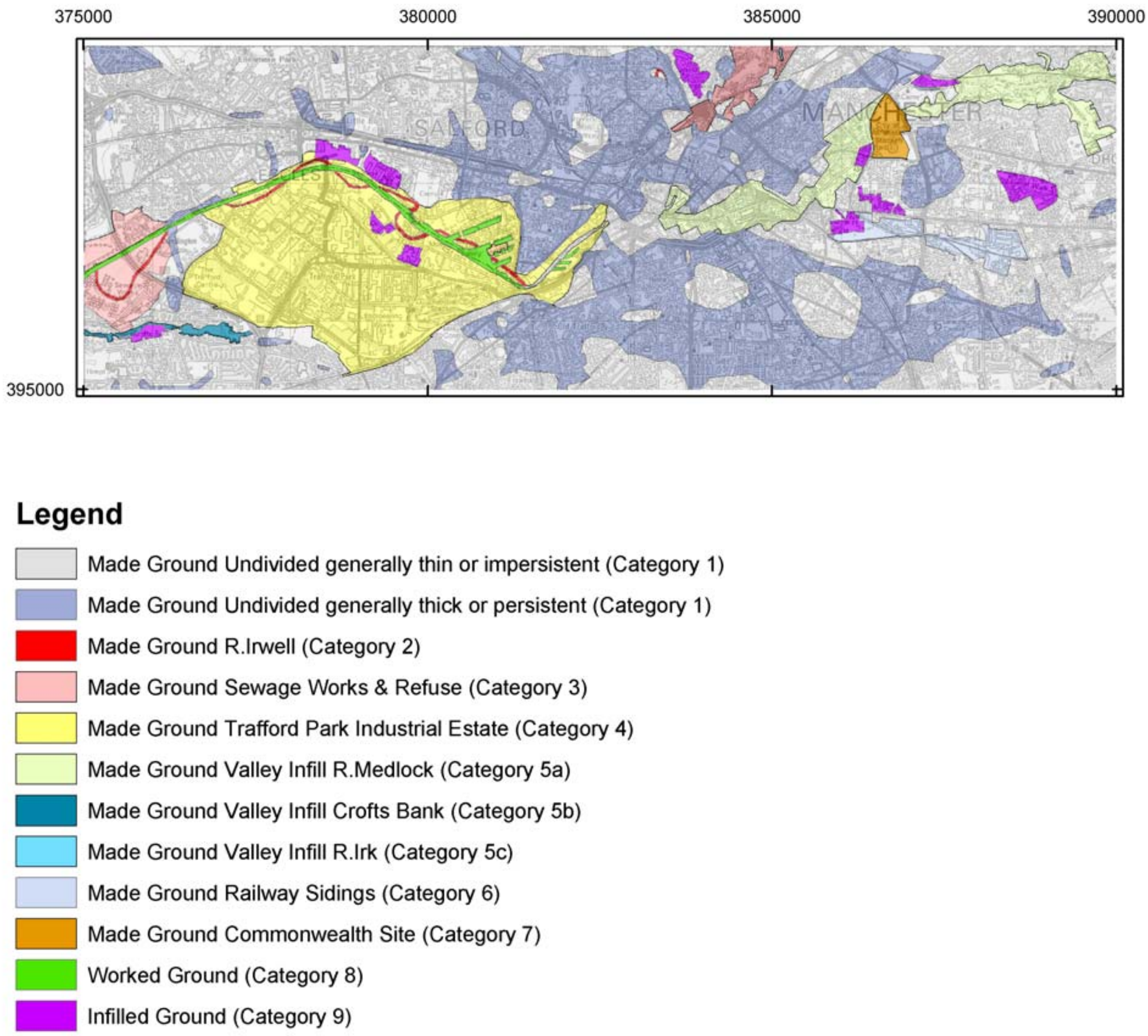


Figure 16. Hydrogeological domains map of central Manchester and Salford. Domain 1 = bedrock outcrop, major aquifer; Domain 2 = permeable superficial deposits in contact with or <5m above major aquifer; Domain 3 = multiple permeable superficial deposits in contact with or <5m above major aquifer; Domain 4 = bedrock outcrop, minor aquifer; Domain 5 = permeable superficial deposits in contact with or <5m above minor aquifer; Domain 6 = multiple permeable superficial deposits in contact with or <5m above minor aquifer; Domain 7 = perched aquifer consisting of permeable superficial deposits; Domain 8 = aquitard of low permeability superficial deposits; Domain 9 = non-aquifer bedrock strata.

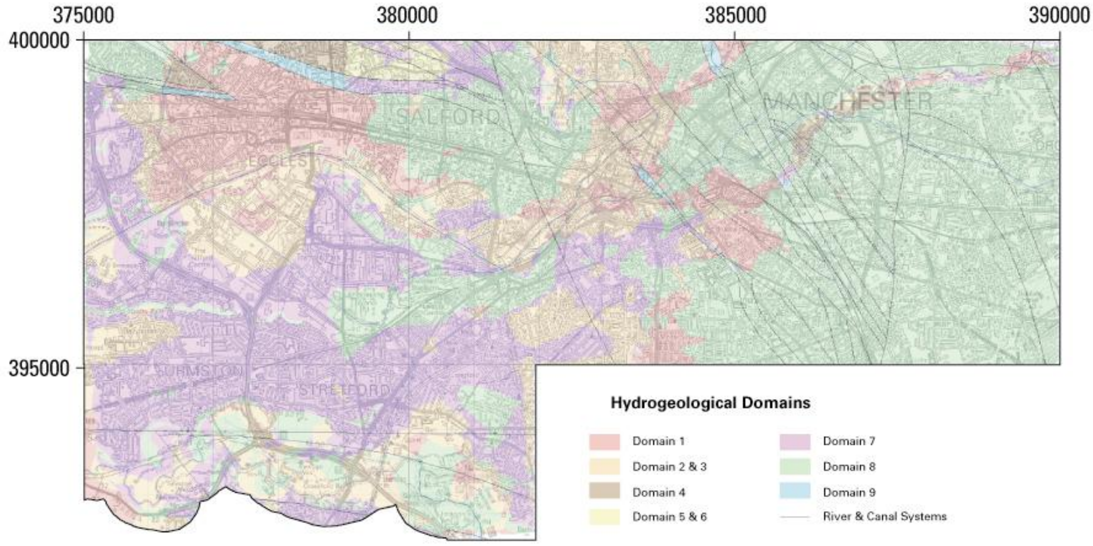


Figure 17. Cross section through Trafford Park, Greater Manchester, showing potential recharge pathways.

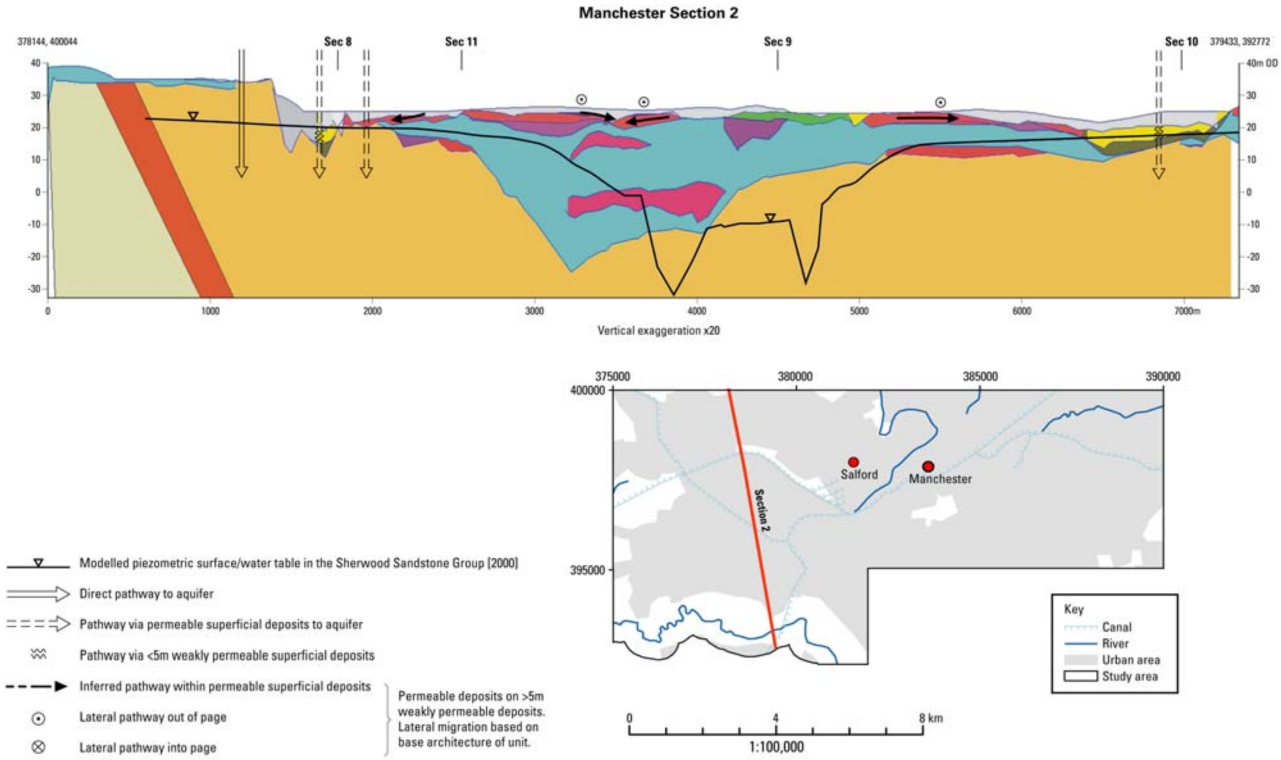
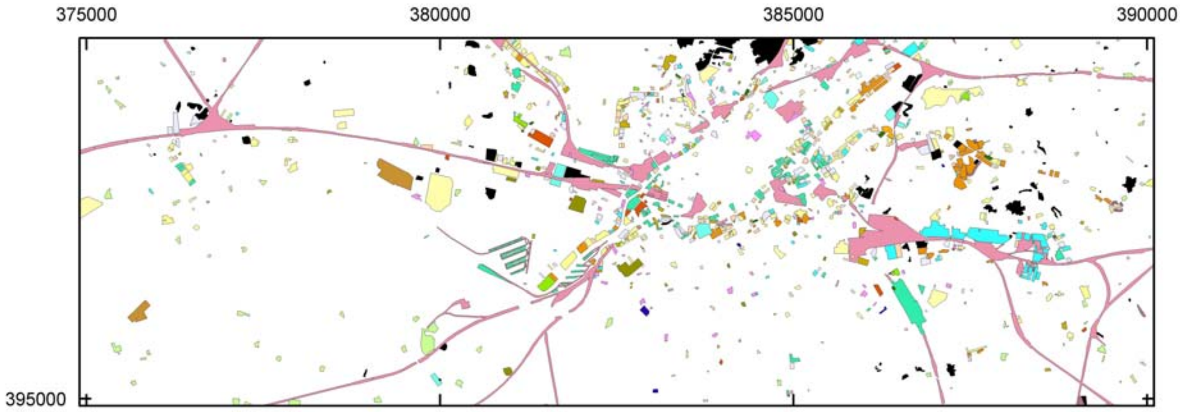
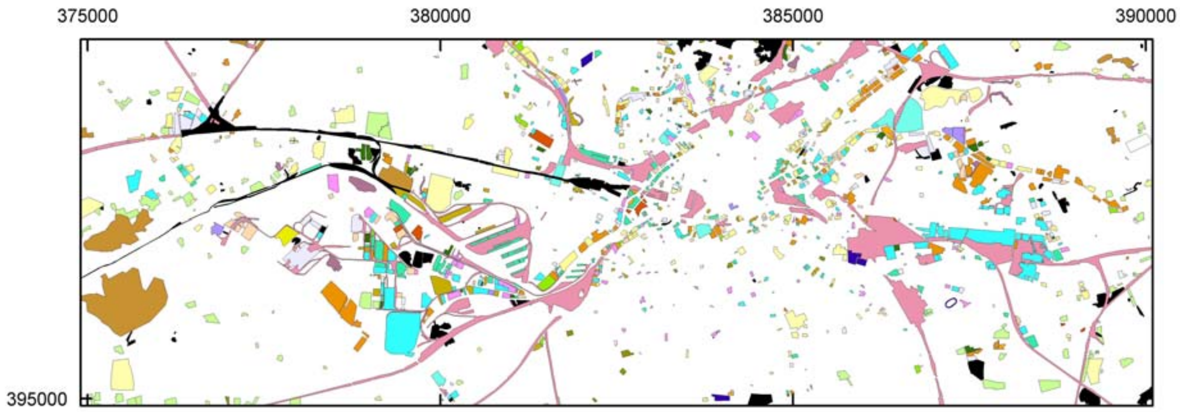


Figure 18a. Past land use for central Manchester and Salford in i) 1890, ii) 1920, iii) 1950. Classification of the UK Department of the Environment has been used (Anon. 1991) (see Table 4).

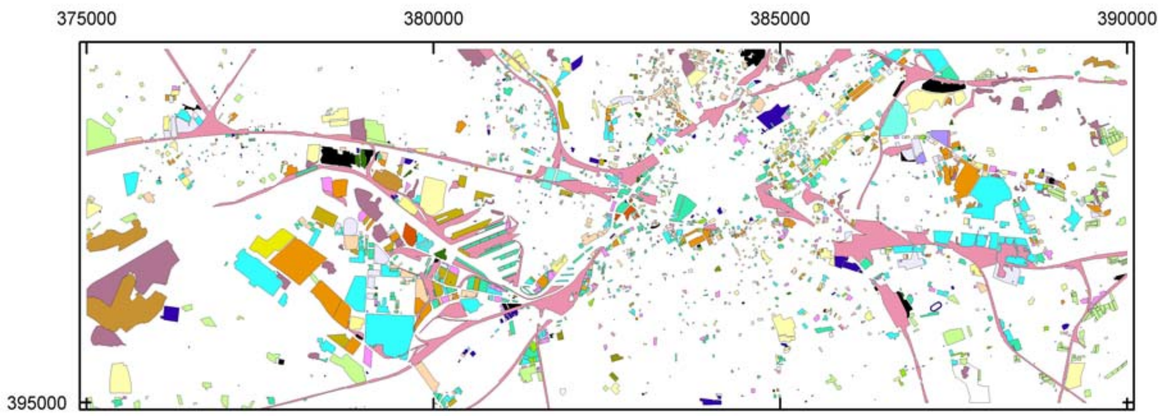
i) 1890



ii) 1920



iii) 1950



Key

C1	C14o	C2	C5b
C10a	C15a	C2-C17	C6a
C11a	C15c	C3a	C7a
C126a	C16	C3d	C7b
C12b/d	C16a	C3d/a	C7d
C14	C16c	C3d/b	C8
C14a	C16d	C3d/c	C8A
C14c	C16e	C3d/e	C8a
C14e	C17	C4b	C8b
			C9
			C9b

Figure 18b. Present day (2004) land use in central Manchester and Salford.

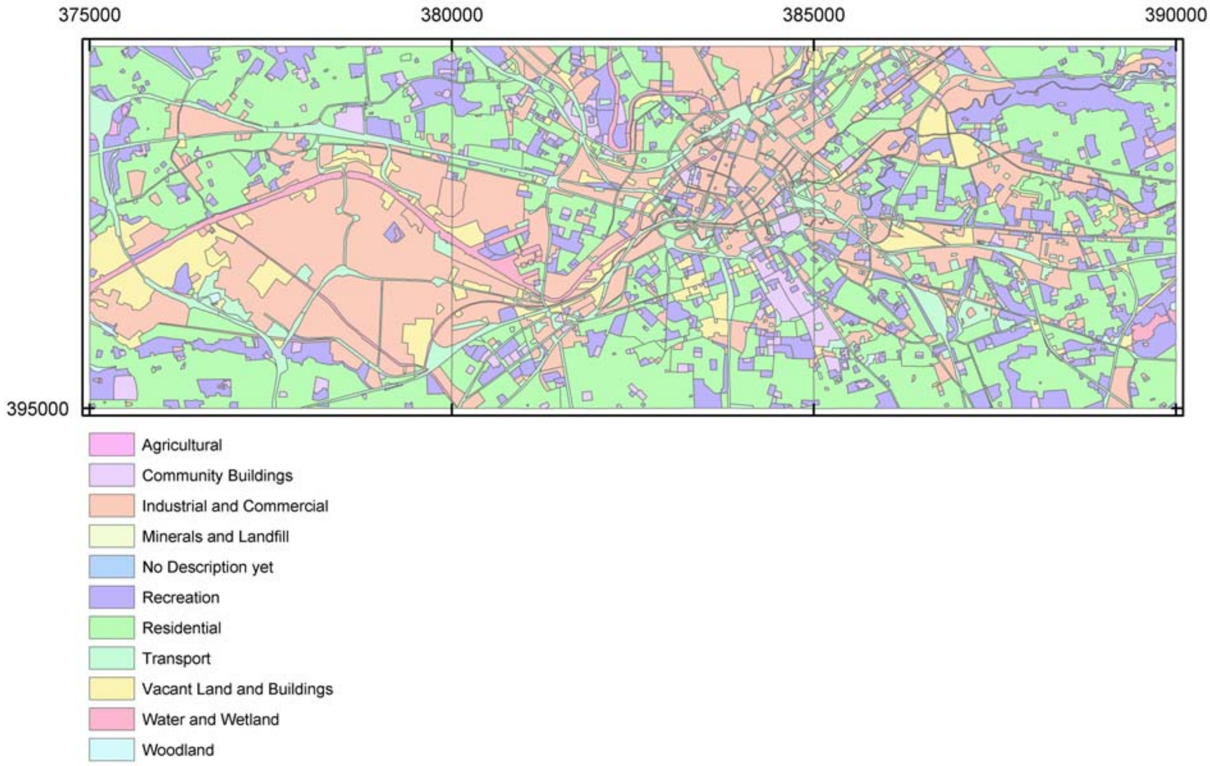


Figure 19. Relationship between topography and first water strike in boreholes in central Manchester and Salford.

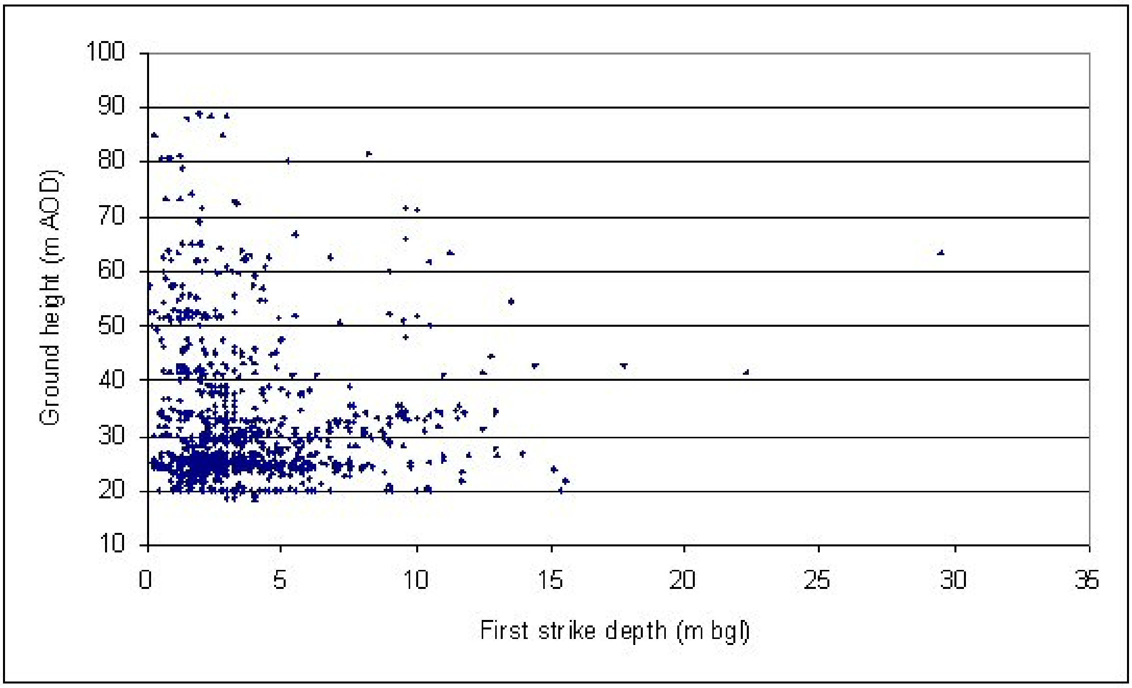


Figure 20. Map of suitability for sustainable urban drainage in central Manchester and Salford. Red = unsuitable; yellow = potentially suitable; green = suitable.

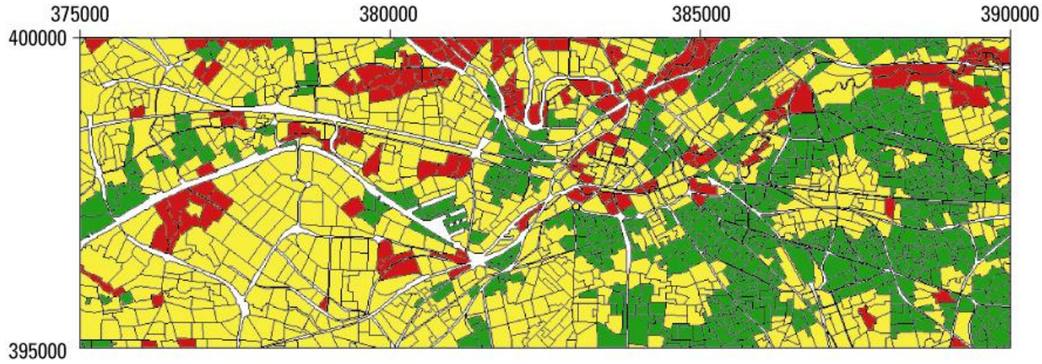
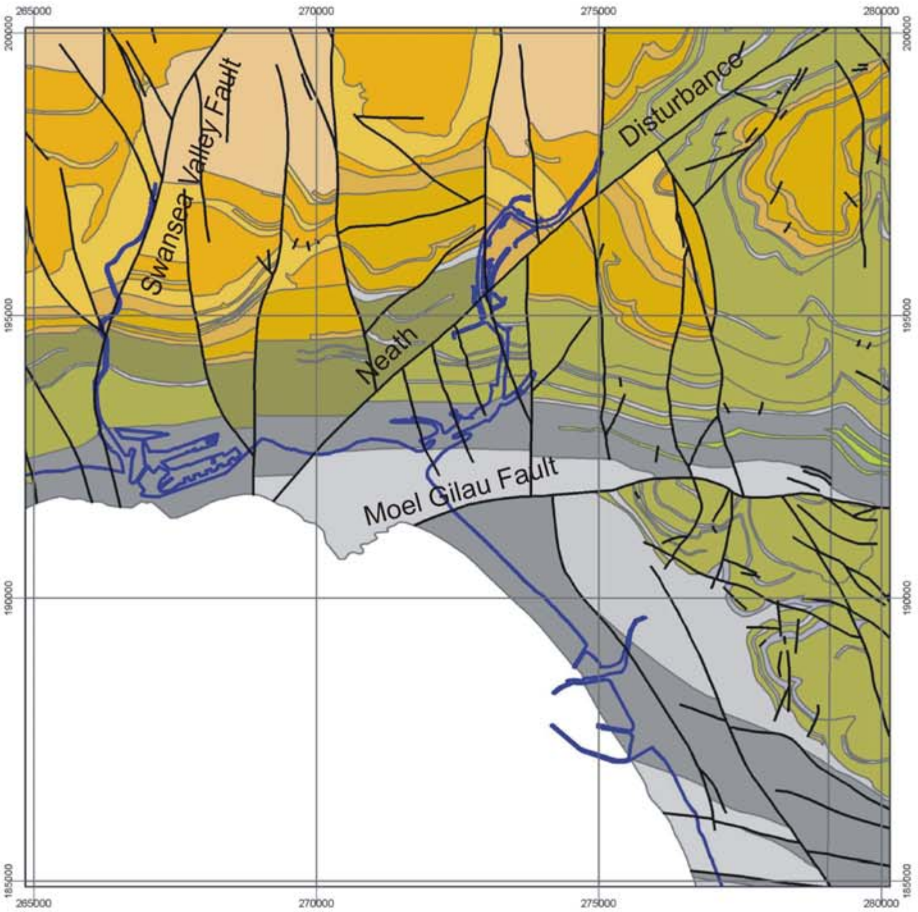


Figure 21. Bedrock geology of the Swansea – Port Talbot area.



Main Lithology	Stratigraphy		
Mudstone	Grovesend Formation	WARWICKSHIRE GROUP	
Sandstone	Pennant Sandstone Formation		
Mudstone			
Sandstone			
Sandstone			
Sandstone			
Mudstone	Middle Coal Measures Formation	SOUTH WALES COAL MEASURES GROUP	
Mudstone	Lower Coal Measures Formation		

Figure 22. Superficial geology of the Swansea – Port Talbot area.

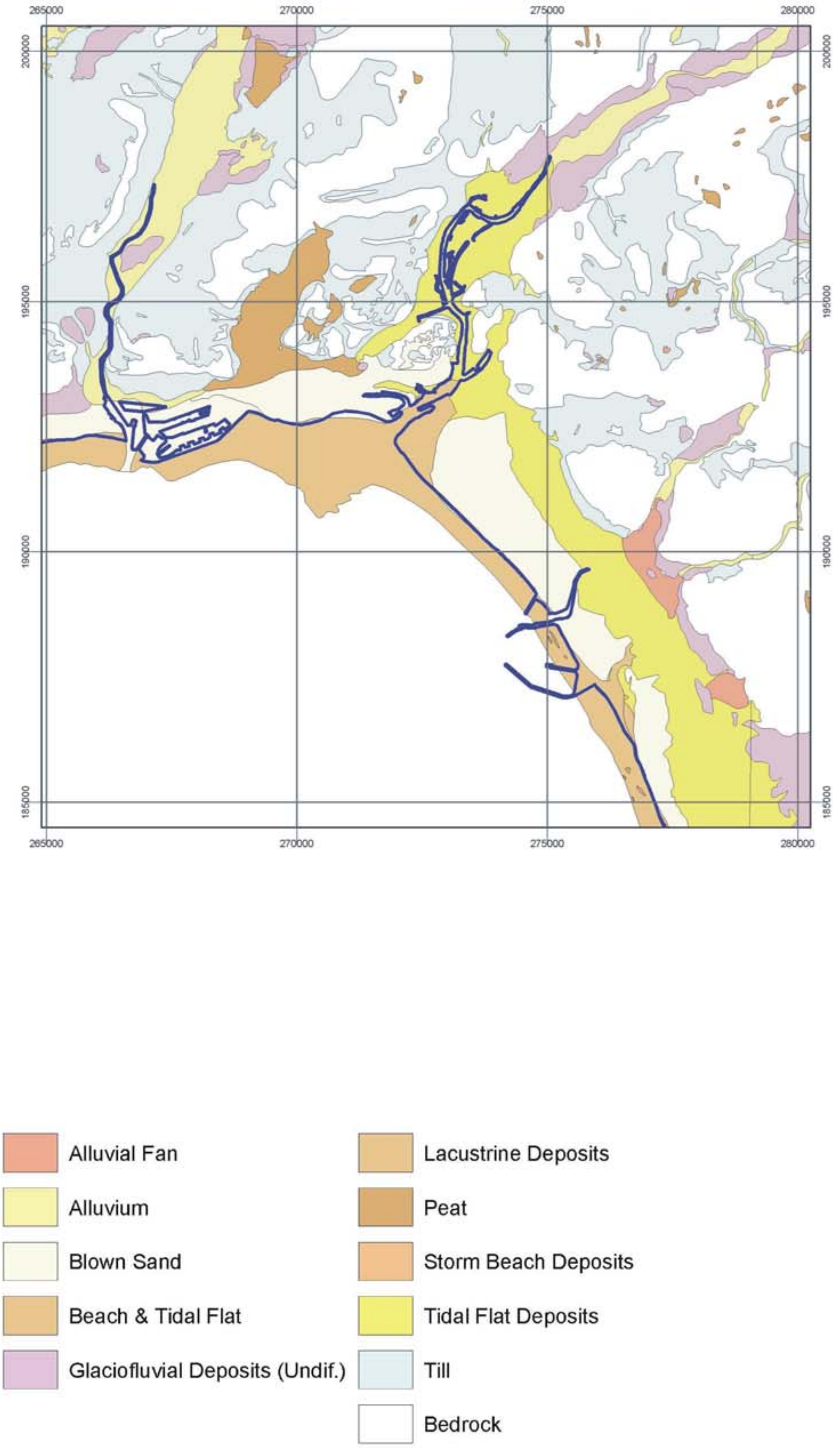


Figure 23. Superficial and artificial deposits draped over the bedrock surface of the Swansea/Port Talbot area (blue = till; pink = glaciofluvial sand and gravel; ochre = beach and tidal flats deposits; brown = peat; yellow = alluvium; dark brown = beach and blown sand; red = artificial deposits; glaciolacustrine deposits are present in the model but are hidden by later ones).

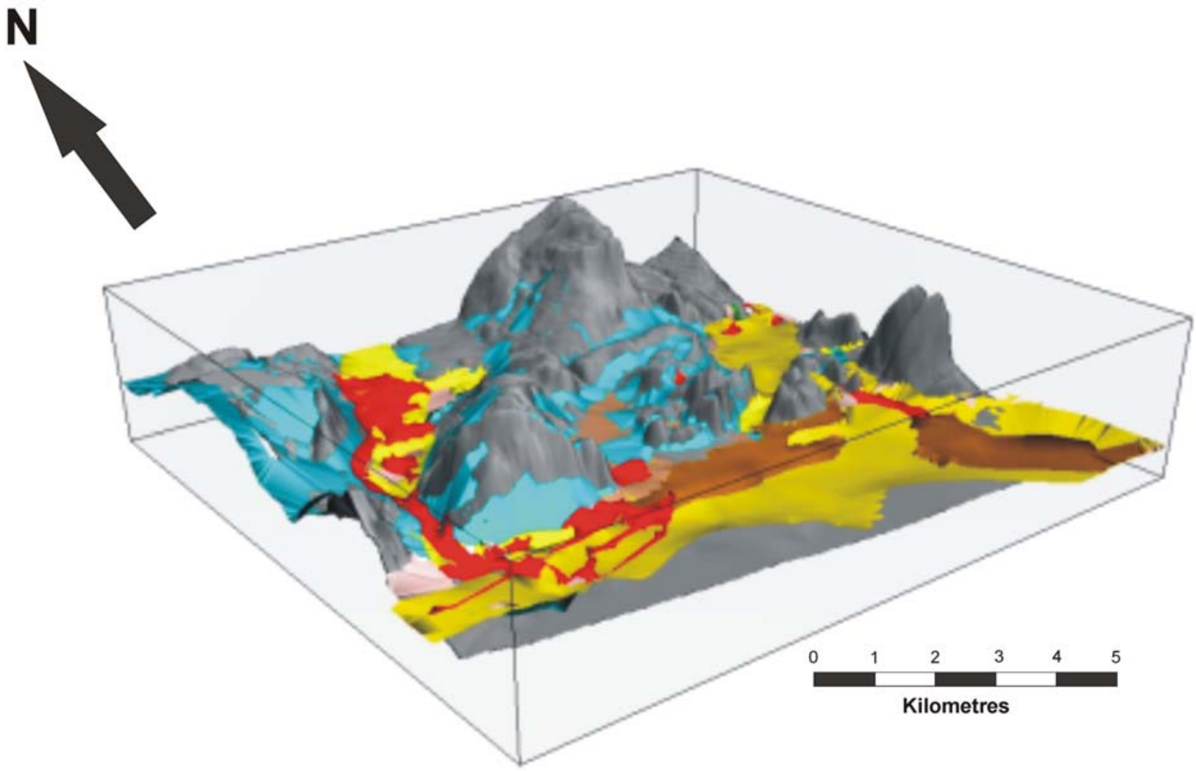


Figure 24. Identification of large-scale causes of a lack of knowledge about the uncertainty present in current 3-D geological models of the shallow subsurface.

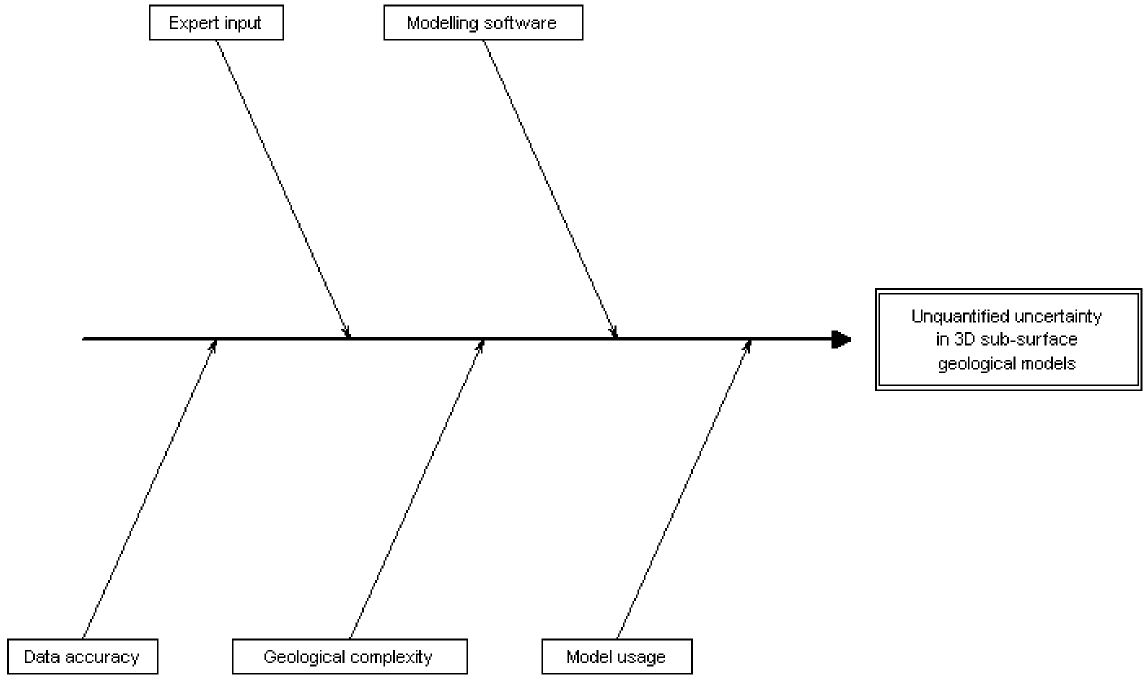


Figure 25. Some basic causes leading to uncertainty in the modelling process.

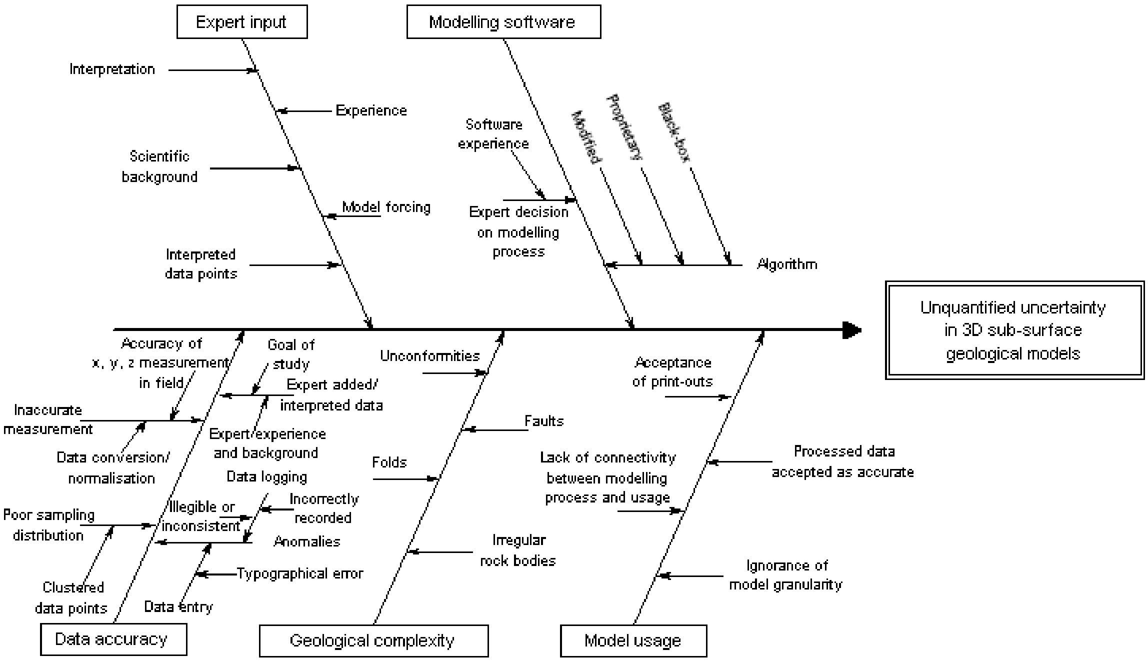


Figure 26. Interpolated surface obtained by gridding of available borehole data. The three axes show spatial x, y, z coordinates for the data points and the surface relative to an arbitrary grid origin at (0, 0, 0)

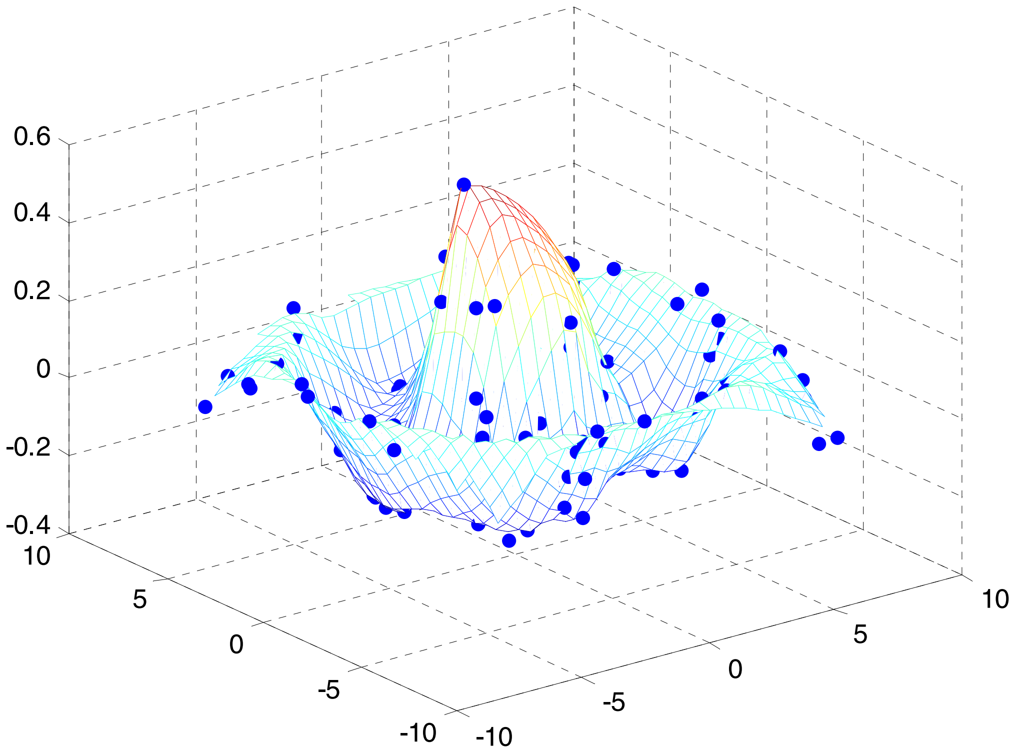


Figure 27. Predicted uncertainty for the data shown in Figure 26 using resampling. The x and y axes show the same spatial coordinates relative to an arbitrary grid origin as in Figure 26. The z axis shows the relative uncertainty in terms of standard deviation.

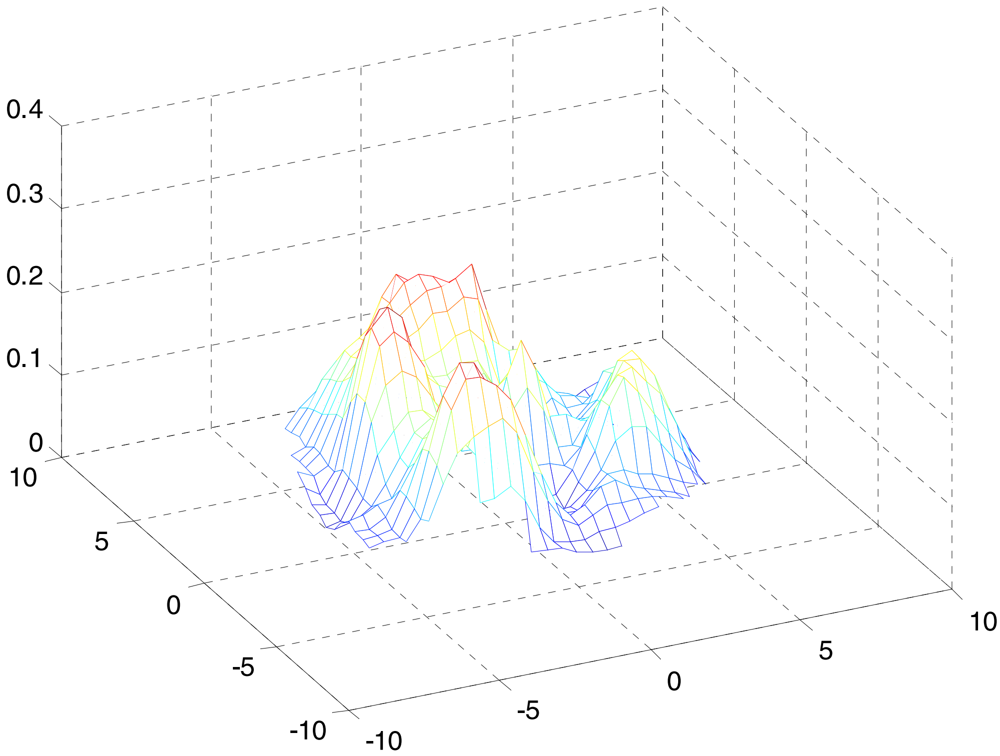


Figure 28. Stem and leaf displays with 1 and 5 lines per stem for a) dry density data and b) plastic limit data for Mercia Mudstone samples from the Coventry area, respectively. In a) the dry density values range from 1.13 Mg/m^3 to 2.10 Mg/m^3. In b) the plastic limit values range from 10% to a high value of 35%.

a) unit = 0.01

```
11 |3                                      ←1.13
12 |8
13 |03569
14 |34779999
15 |011111122222244444555555577777779999
16 |00222222224677777888
17 |0000111223333334667788899
18 |001111111334444445555566799
19 |1222233344445555667
20 |3
21 |0                                      ←2.10
```

b) unit = 1

```
1* |011                                    ←10, 11 and 11
1T|2333
1F|44444444555555555
1S|666666666666666666666667777777777777777777777
1o|8888888888888888888888888899999999999999999999999999
2* |00000000000000000000000011111111111111111111
2T|222222222222222222222333333333333333333333
2F|4444444445555555555
2S|6667777
2o|88899                                   ←28, 28, 28, 29 and 29
HI values|30,30,35
```

T = ‘twos’ and ‘threes’; F = ‘fours’ and ‘fives’; S = ‘sixes’ and ‘ sevens’; o = ‘eights’ and ‘nines’; * = ‘noughts’ and ‘ones’

Figure 29. Stylised examples of non-Gaussian patterns in probability plots. The x-axis is the value of the property (for example, dry density in Mg/m^3 as in Figure 30) and the y-axis is the cumulative percentage; a) is light-tailed, b) is heavy-tailed, c) is left-skewed and d) is right-skewed.

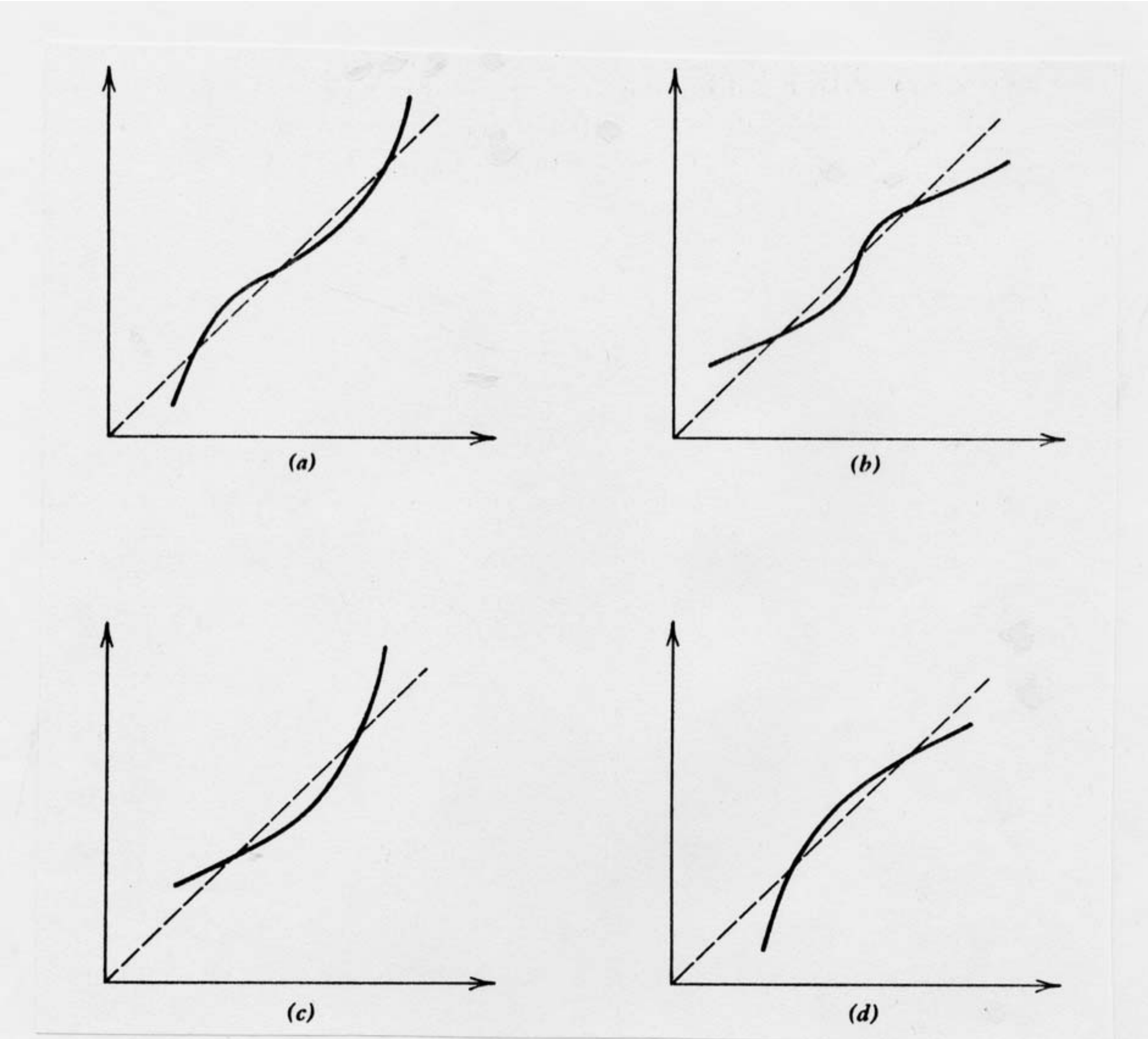


Figure 30. Probability plot with local irregularities for dry density data from the Mercia Mudstone in the Coventry area.

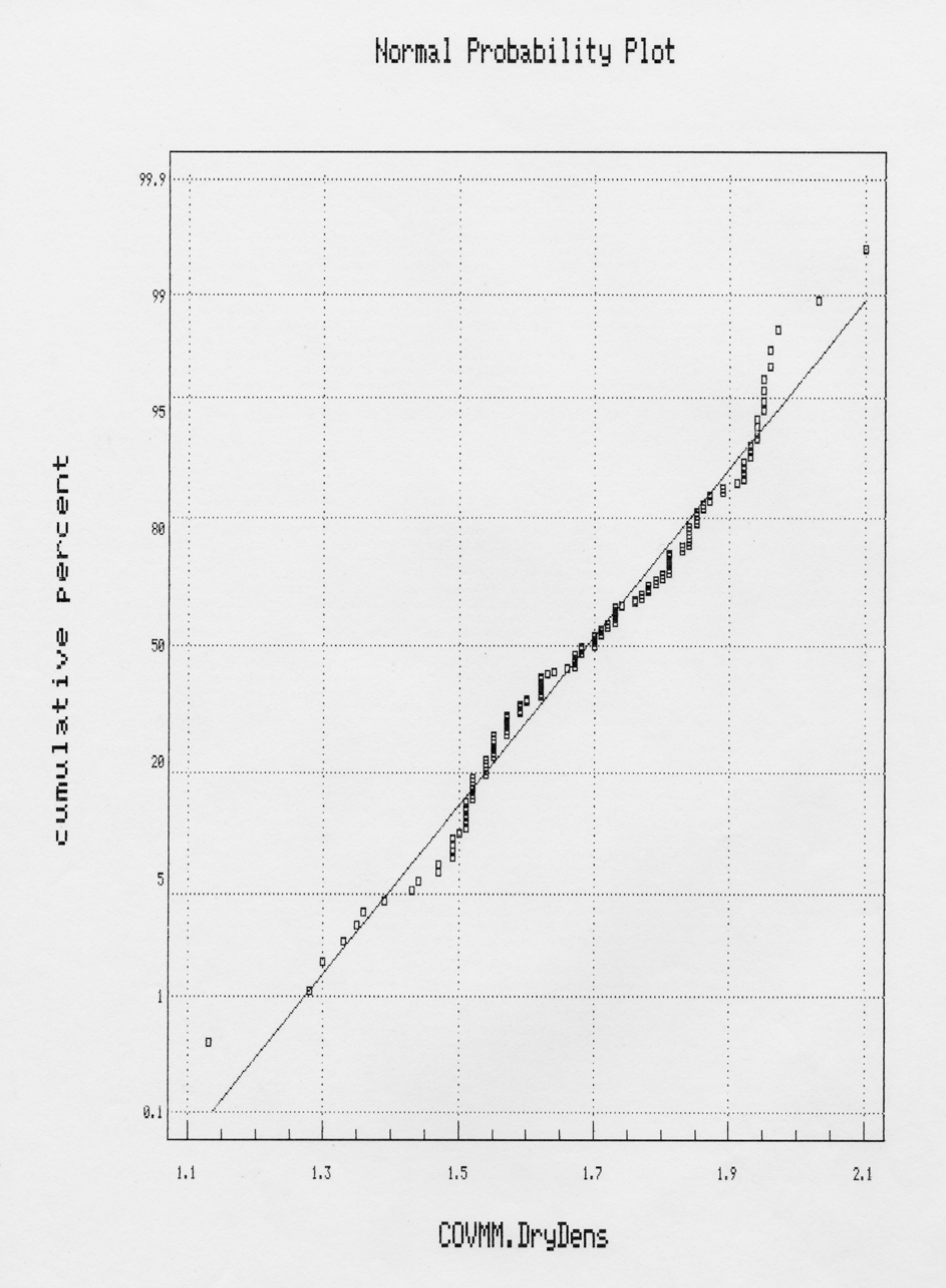


Figure 31. Probability plot showing a distinct distribution of low values for bulk density data from the Quaternary Wolston Clay in the Coventry area.

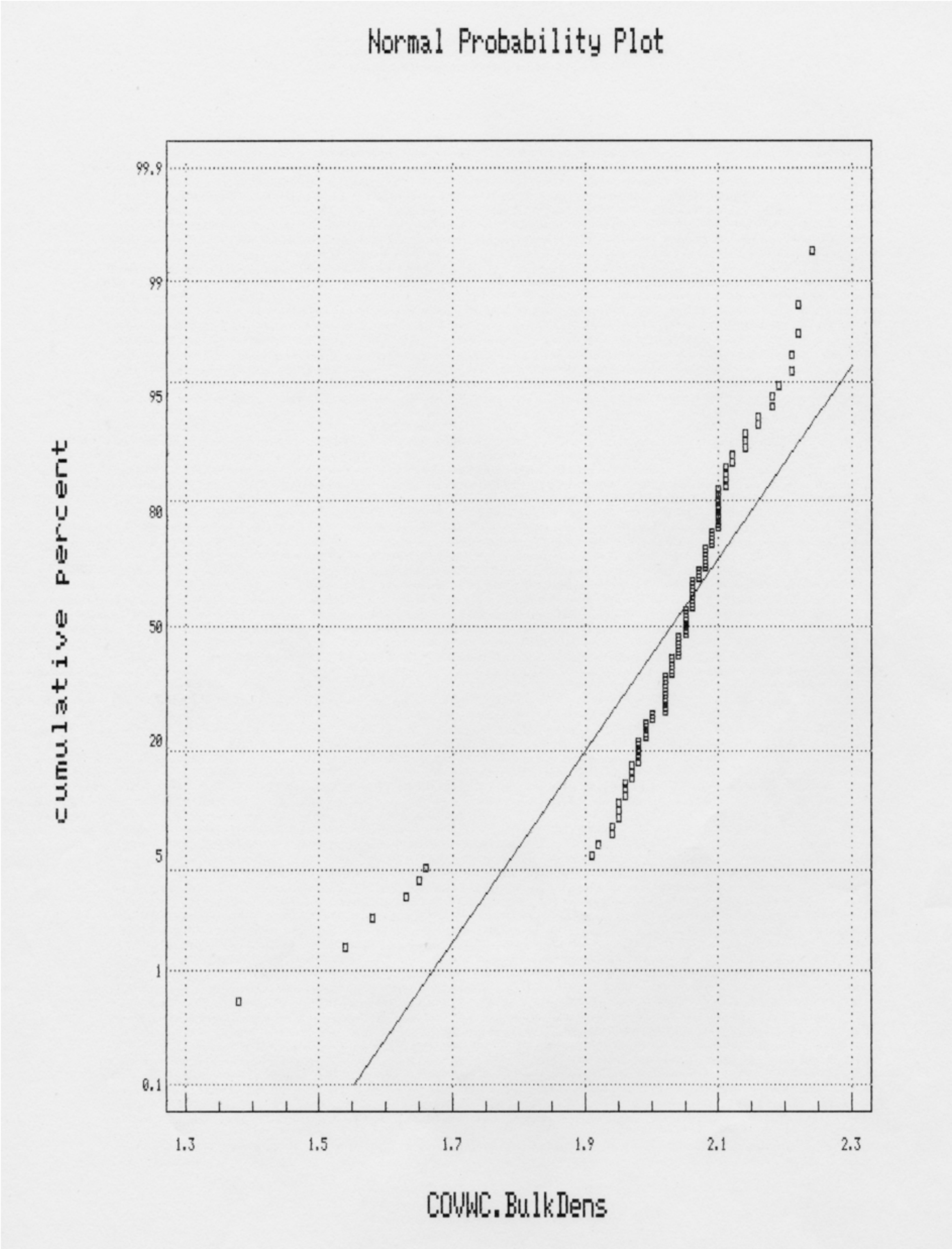


Figure 32. Standard box-and-whisker plot for liquid limit data for clay bands in the Coventry Sandstone from the Coventry area.

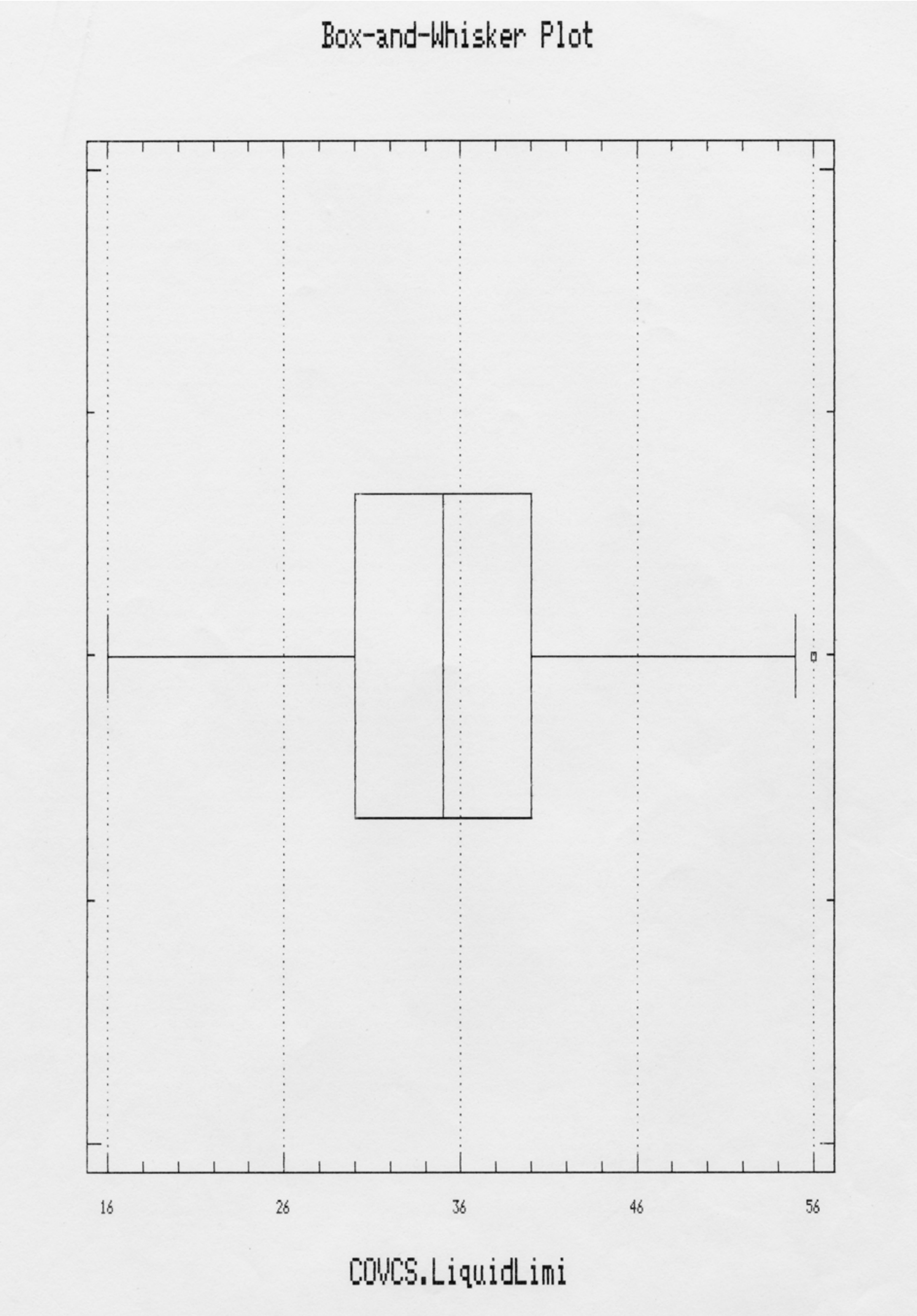


Figure 33. Structure of the extended notched box-plot for a Gaussian distribution.

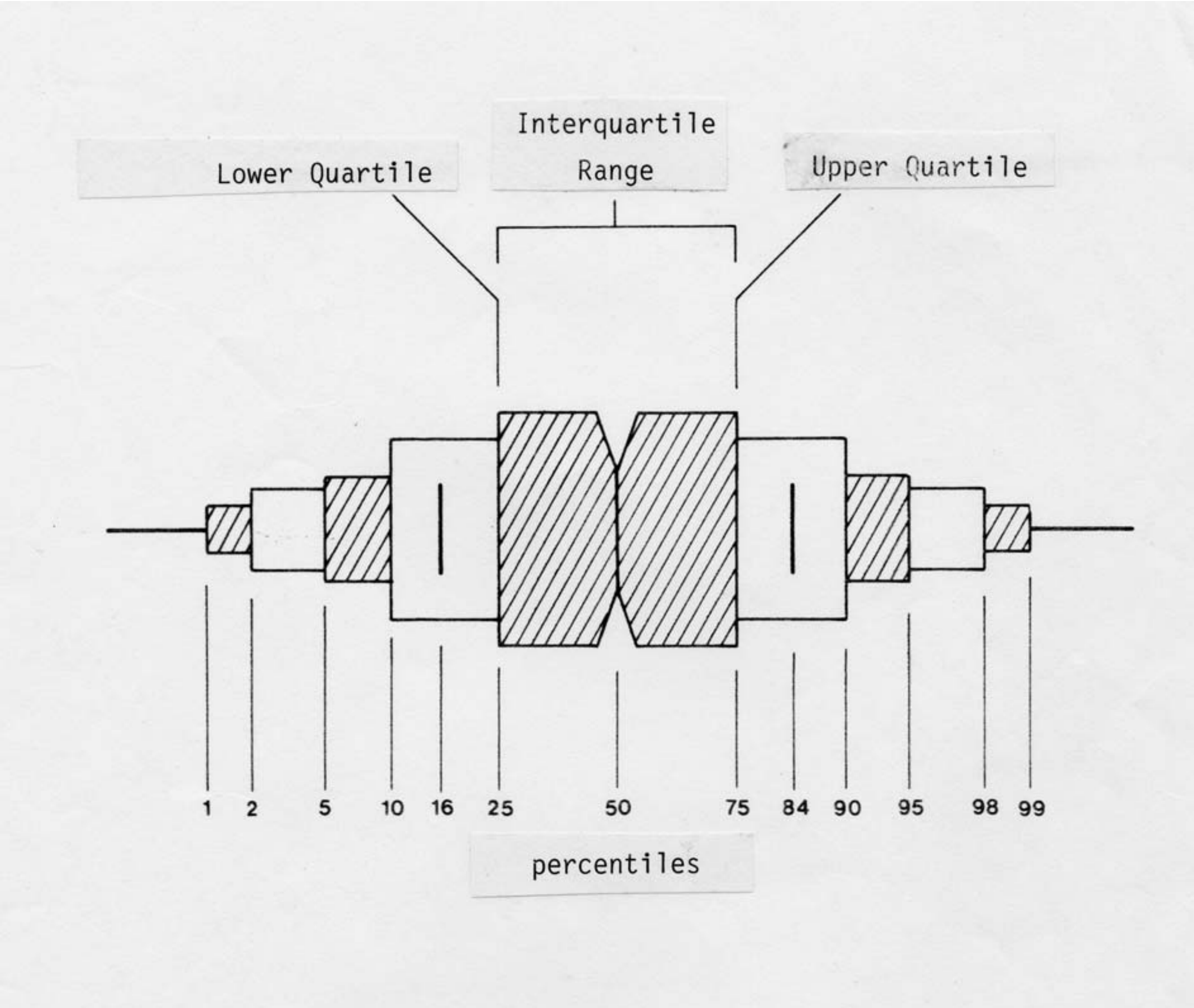


Figure 34. Example of extended box-plots for summarising and comparing geotechnical data (from the Wrexham area of North Wales).

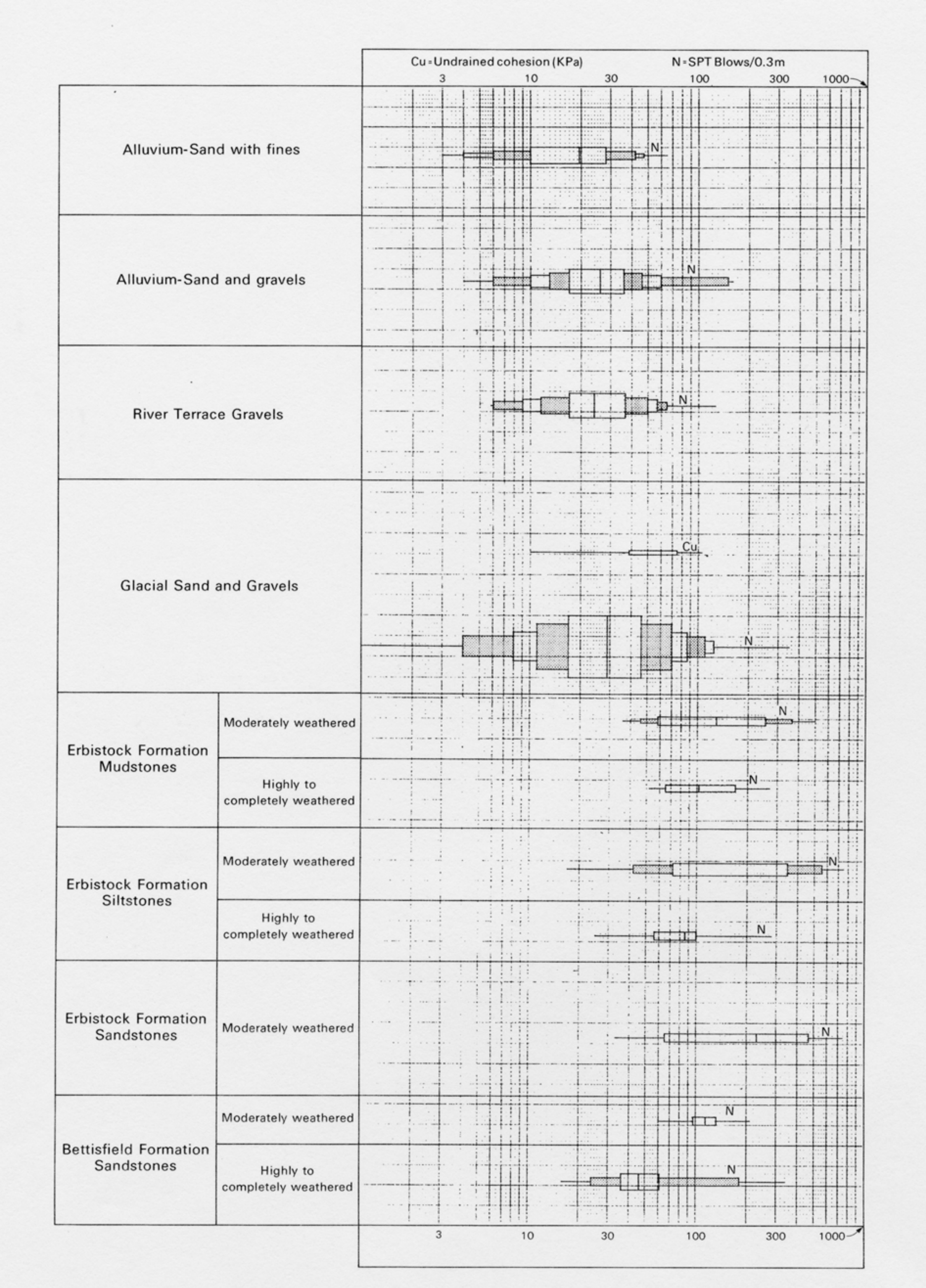


Figure 35a. SPT 'N' value profiles for cohesionless glacial soils from the upper Forth estuary (after Gostelow and Browne, 1986).

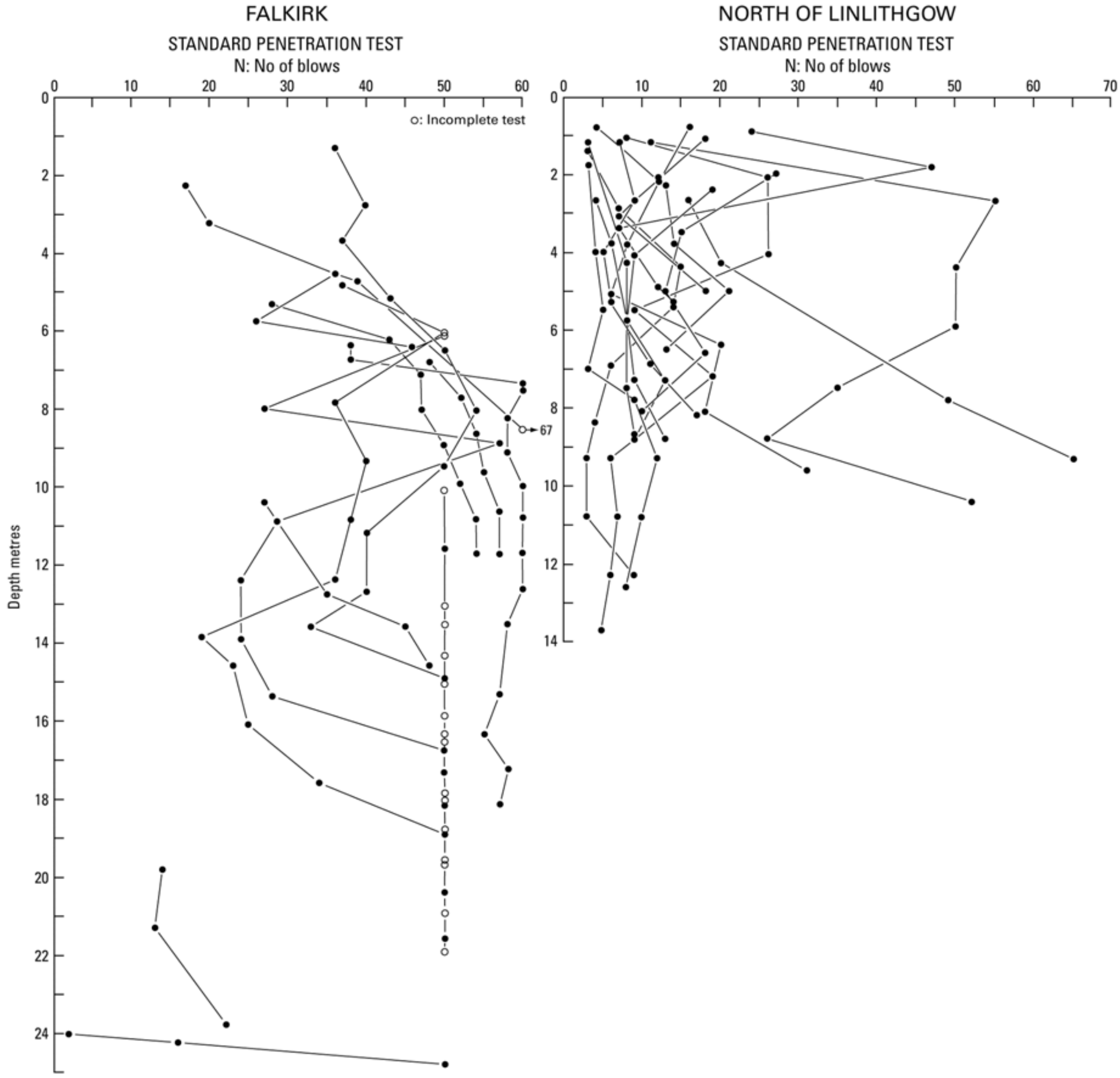


Figure 35b. SPT 'N' value profiles for the Upper Chalk within Ordnance Survey 1:10 000 scale map sheet TQ57NE (Thurrock and Purfleet area, east of London). The concentration of 'N' equal to 100 results from the rounding of higher values.

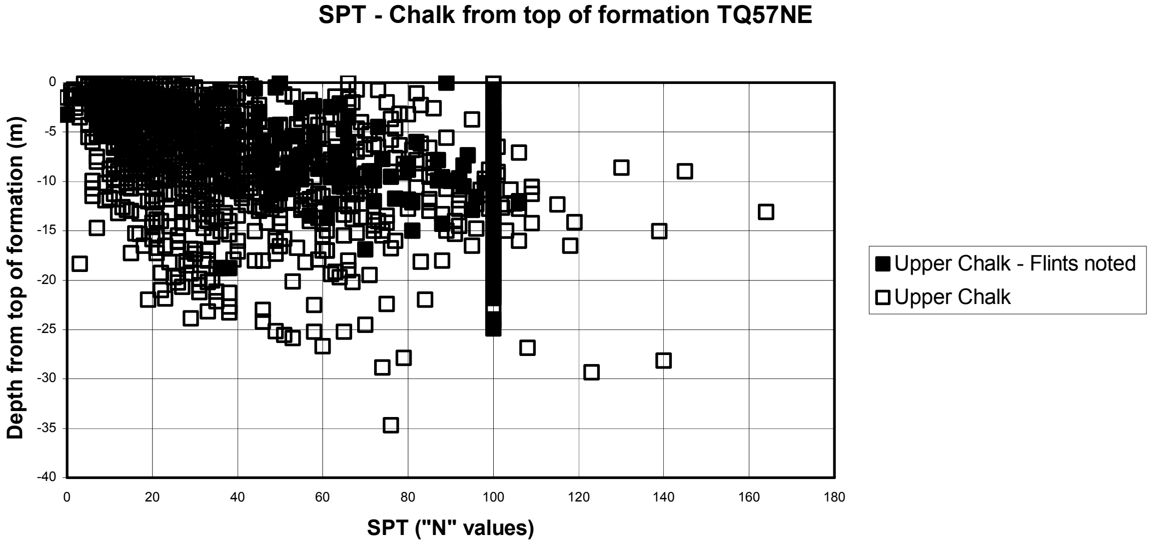


Figure 36. 3D solid model showing the variation of SPT ‘N’ values for the glacial till of the Salford and Manchester area (blue = very soft to soft, green = firm to stiff, red = very stiff). The model covers an area of approximately 15 km by 5km. The long axis of the area runs east-west from the right hand side.

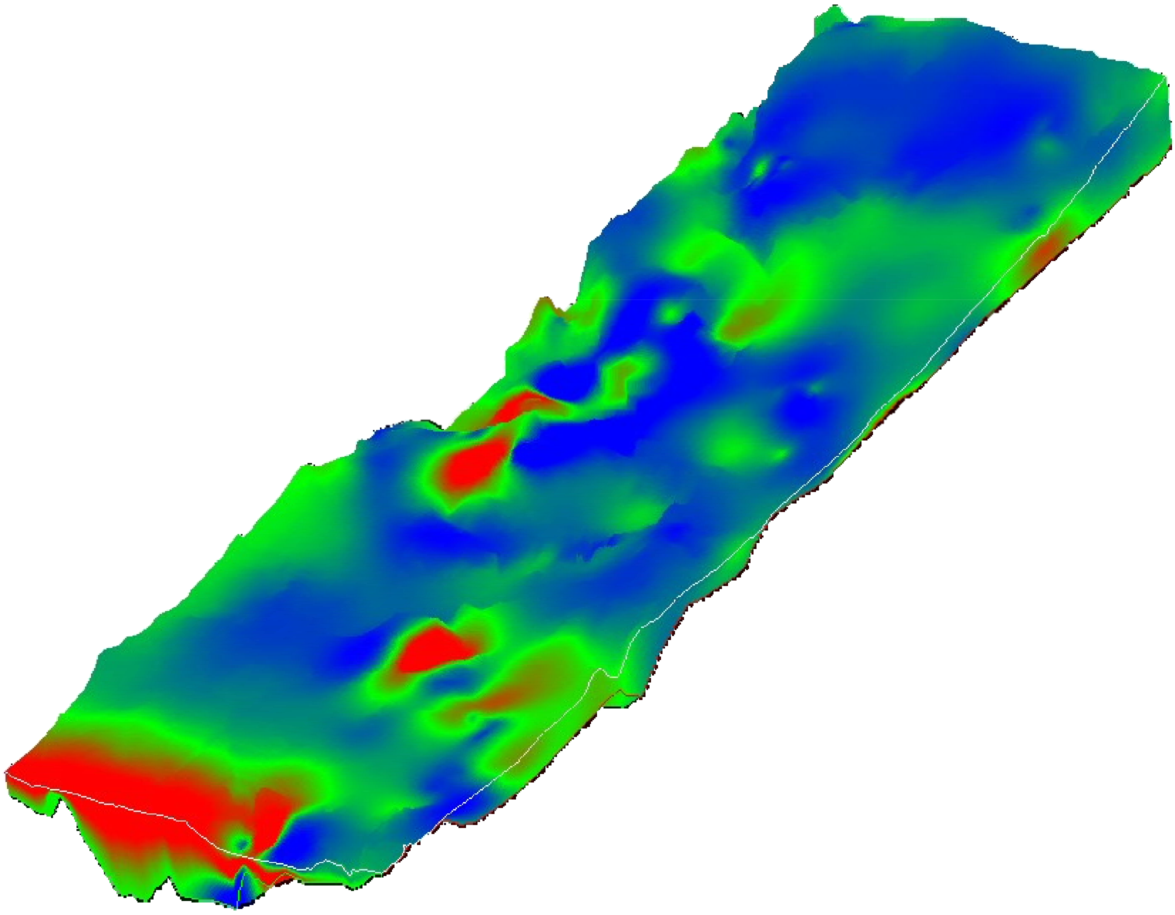


Figure 37a. Natural cavities (purple triangles) plotted against geology for the Newbury area of Berkshire, UK, recorded in the Applied Geology Ltd. (1993) database.

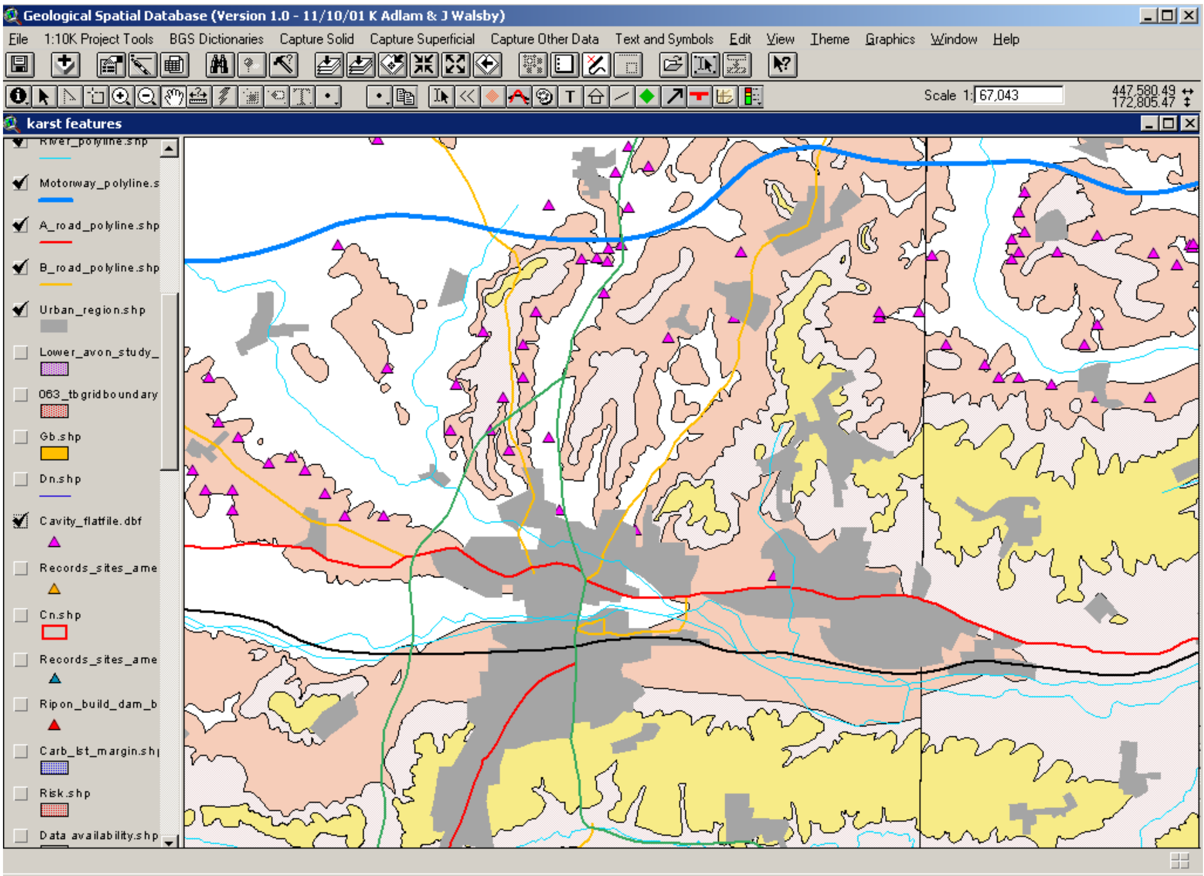


Figure 37b. Springs, dolines and stream sinks identified by ground mapping plotted against geology for the Newbury area of Berkshire, UK (Blue line is the M4 motorway; red dots = stream sinks, blue dots = springs, green dots or areas = sinkholes
).

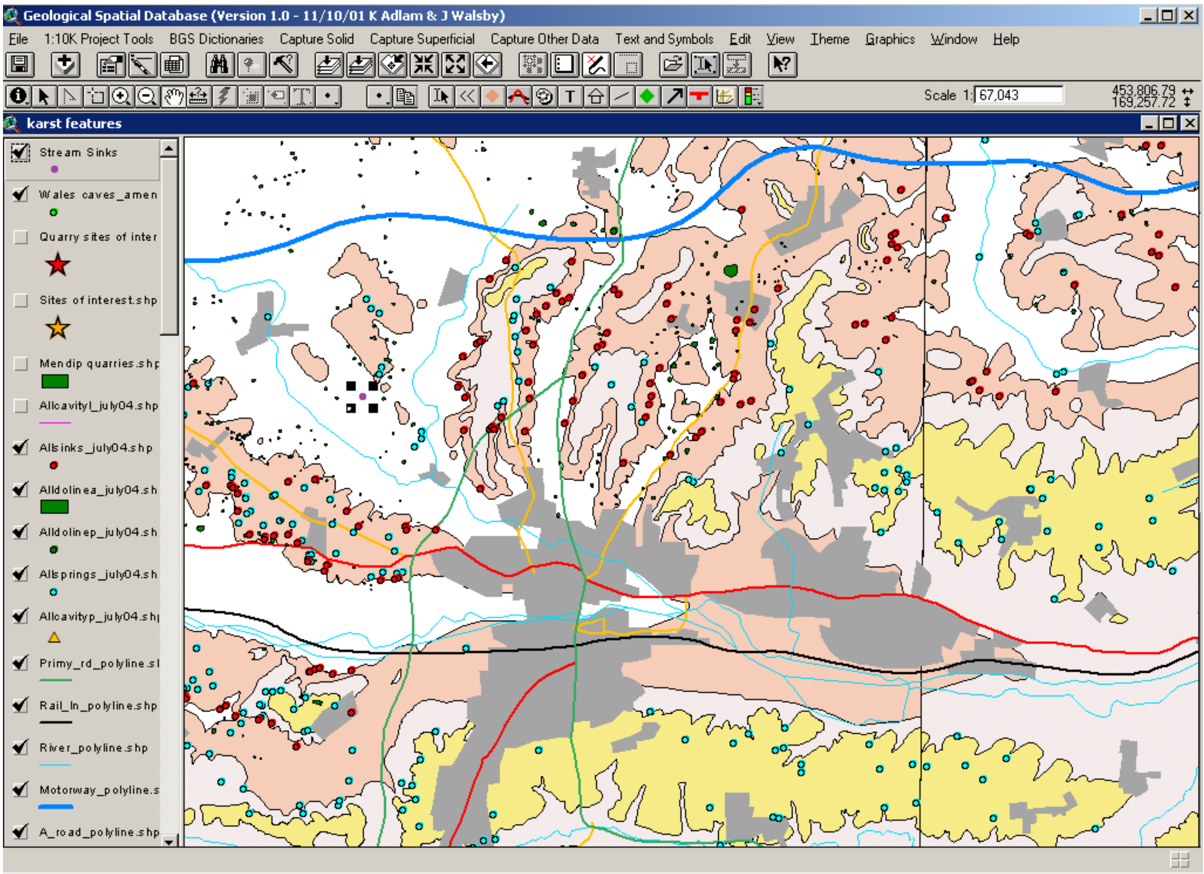


Figure 38. Relative geohazard ratings for postcode sectors (for example CM12 9 and full postcodes (for example, CM12 9AB; centroids shown as O symbols) for part of Essex, south east England) [colour scale is from red = highest hazard rating, through pink, grey, light blue to dark blue = lowest hazard rating].

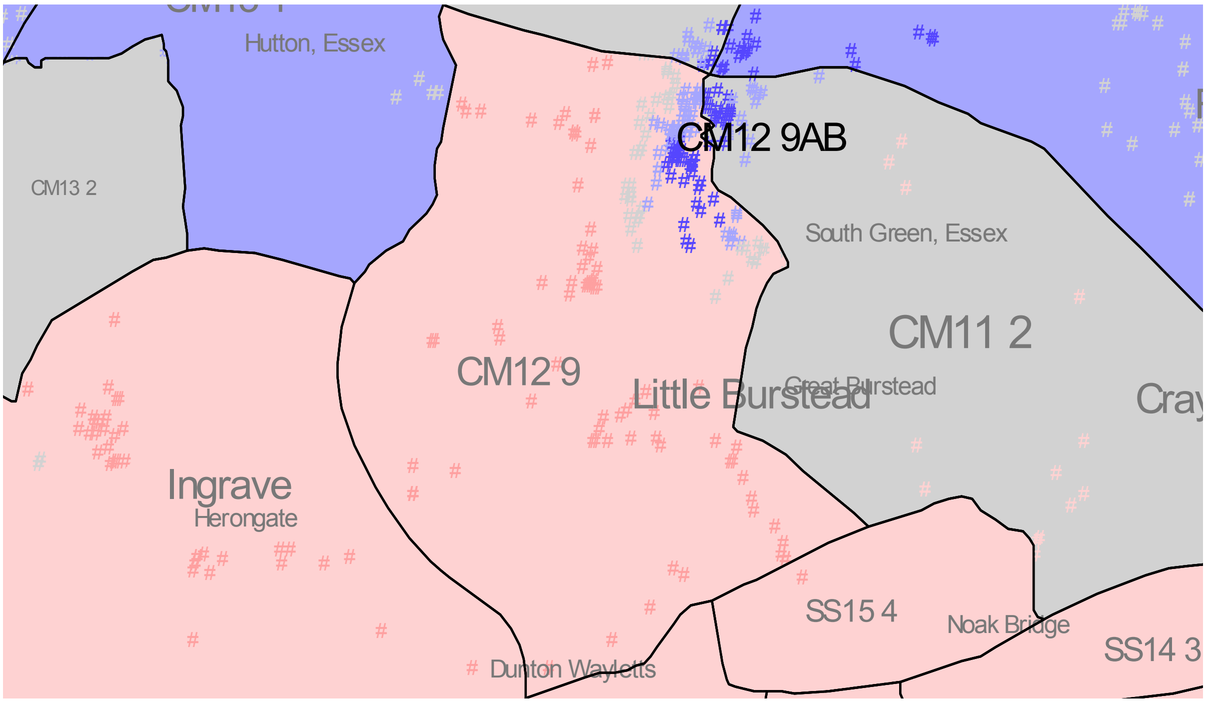
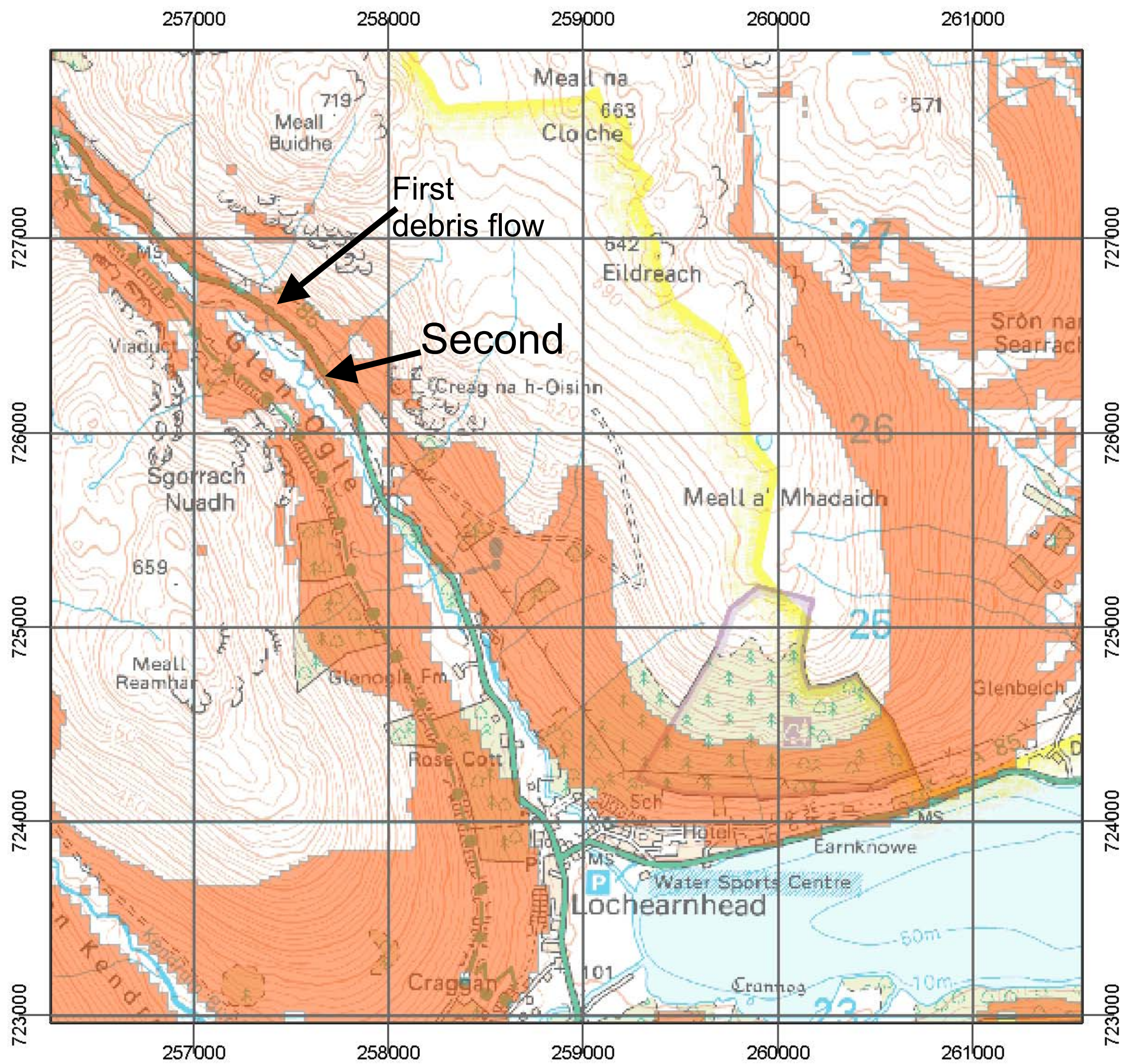


Figure 39. Site of A85 Glen Ogle landslides (August 2004) in relation to landslide hazard zonation.



Landslide hazard A85 Glen Ogle

Slope hazard class

High potential for slope instability