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THE 2010 HANS CLOOS LECTURE: THE CONTRIBUTION OF URBAN GEOLOGY TO THE DEVELOPMENT, REGENERATION AND CONSERVATION OF CITIES

M G Culshaw
School of Civil Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK and British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK

S J Price
British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK

ABSTRACT

Urban geology began to develop in the 1950s, particularly in California in relation to land-use planning, and led to Robert Legget publishing his seminal book "Cities and geology" in 1973. Urban geology has now become an important part of engineering geology. Research and practice has seen the evolution from single theme spatial datasets to multi-theme and multi-dimensional outputs for a wide range of users. In parallel to the development of these new outputs to aid urban development, regeneration and conservation, has been the growing recognition that city authorities need access to extensive databases of geo-information that are maintained in the long-term and renewed regularly. A further key advance has been the recognition that, in the urban environment, knowledge and understanding of the geology need to be integrated with those of other environmental topics (for example, biodiversity) and, increasingly, with the research of social scientists, economists and others.

Despite these advances, it is suggested that the value of urban geology is not fully recognised by those charged with the management and improvement of the world's cities. This may be because engineering geologists have failed to adequately demonstrate the benefits of urban geological applications in terms of cost and environmental improvement, have not communicated these benefits well enough and have not clearly shown the long-term contribution of geo-information to urban sustainability. Within this context future actions to improve the situation are proposed.

INTRODUCTION

For the last decade, in the United Kingdom (UK) and the United States of America (USA) at least, engineering geology has been going through something of an identity crisis, or, as Tepel (2009) put it, the engineering geological profession operates in "*a state of identity confusion.*" This concern resulted in a number of meetings to discuss the future of engineering geology and, indeed, further define its purpose. In the UK, a meeting took place in November 1999 and the strategy report developed (Anon. 2000) was updated six years later (Anon. 2006a). In the USA a series of conferences took place between 2002 and 2004 under the banner "Visioning the future of engineering geology" (Anon. 2004a). The concerns remain and were discussed again at the IAEG's 10th Congress in Nottingham, UK (Culshaw *et al.* 2009a) and, more recently, by Tepel (2010).

At first sight, this 'navel gazing' might appear strange as, for many, the purpose of engineering geology has always been clear. For example, Dearman (1991) said that "T*here is no difficulty in defining engineering geology. It is one branch of applied geology which, broadly, is the application of geology to industry – not some special type of geology but the whole spectrum of the science. Engineering geology is the discipline of geology applied to civil engineering, particularly to the design, construction and performance of engineering structures interacting with the ground...*" However, Knill (2003), whilst recognising the long-term appropriateness of this type of definition, noted that engineering geology had become much broader in its scope, as environmental issues had increased in importance. Tepel (2010) sought to explain why engineering geology was important by stressing its societal worth, engineering geology being: "*the management of geologically-sourced risks that affect people and their institutions as they interact with their built and natural environment.*" In particular, Tepel stressed the importance of engineering geologists becoming "*separate from working for and reporting solely to, engineers*".

In addition, Knill recognised the importance of engineering geologists not only contributing at the site-scale, familiar to geotechnical engineers, but also covering broader areas. He referred to these different scales of operation as the 'near-field' and the 'far-field.' In France, these problems of the definition of 'engineering geology' were less noticeable as the broader term 'applied geology' was used until the mid 1960s when the formation of the International Association of Engineering Geology (IAEG) made direct translation necessary (Arnould 1967).

One of the difficulties that the profession of engineering geology has faced is convincing those applied geologists working in the 'far-field' that they really are engineering geologists. The value of assessing geological hazards far beyond the immediate vicinity of an engineering site has long been recognised as being of great importance if the risks that they pose are to be fully understood. However, geohazard assessments may be carried out by physical geographers or other non-geologists and it is difficult to convince them that they are contributing to engineering geological knowledge and understanding. As the authors of this paper believe that all those geologists working in the urban environment should be described as engineering geologists, this term is used in the text that follows.

Engineering geologists who work in urban environments recognise a very wide range of 'users' for their information and interpretations, reaching far beyond civil engineers. This is because development and regeneration of the urban environment involves many professionals ranging from land owners, financiers and insurers to planners, surveyors and archaeologists, as well as the general public. Consequently, working in the urban 'far-field' requires the engineering geologist to understand all their needs.

De Freitas (2009) in a discussion of the importance of scale in geotechnical engineering also recognised the importance of engineering geologists working in the 'far-field.' With reference to 1:25 000 and 1:50 000 scale geological maps he noted that: *"They represent data gathered from the 'far field' that have been seen somewhere other than the area of the site or volume of ground being studied (i.e. the 'near field'). The far field represents the accumulation of huge amounts of data, not all of which need be of direct concern but all of which provide windows into the geology of the region in which the site is situated. Such data should inform the near field because the far field demonstrates that the feature(s) in question are present and prompt those investigating a site to ask 'are they here?'"*

This paper explores how engineering geology in the 'far-field' has developed in the urban environment, making use of new technology to provide those who are responsible for the future of the world's cities and those who live in them with an understanding of the nature and variability of the ground to enable development and regeneration to take place in a more sustainable way. The contribution of new technologies, such as geographical information systems (GIS), three dimensional modelling software and high resolution remote sensing, and of new ideas, such as multi-theme outputs and casting spatial models specifically in terms of (non-geological) users needs, will be outlined.

The paper is also an attempt to address many of the frustrations that the authors have felt in trying to convince a range of potential users that 'urban geology' really is of value. Why have engineering geologists had only relatively limited success in convincing city authorities that knowledge of the applied geology of their cities and the availability of up-to-date geo-information databases will make development and regeneration easier, better and cheaper? The paper discusses these and a number of other issues. It deliberately includes an extensive referenced review of how urban geology has developed and offers some views on future directions.

WHAT IS URBAN GEOLOGY?

Intuitively, engineering geologists realise that geology is important for urban development and regeneration. After all, cities are built on, and in, the ground. In his ground-breaking book on urban geology, Legget (1973) explored the importance of geology for the planning and construction of cities over the last 4000 years (back to Babylonian times). However, neither in his book nor in an earlier short paper on urban geology (1969) did Legget define 'urban geology' specifically. The nearest he got to a definition was *"Since the science of geology is concerned with all aspects of the crust of the earth, the use of geological information, and of geological methods to obtain new information about local subsurface conditions, should therefore be an essential part of the physical planning of all cities."* (Legget 1973).

Dearman (1991) devoted a chapter of his book on engineering geological mapping to urban maps. This chapter mainly consisted of a series of world-wide case histories. Dearman made little distinction between engineering geological maps of urban areas and those from elsewhere and he did not recognise urban geology as in any way distinct from engineering geology applied to building and construction. He perceived the users to include engineers as well as planners. Specifically, Dearman envisaged maps of urban areas to be created either by the interpretation of the classical geological map for engineering purposes or the addition of further information to aid understanding of important (from an engineering point of view) geological formations, particularly superficial deposits.

Rau (2003) suggested that the term 'urban geology' was first proposed by McGill (1964) in a United States Geological Survey Circular. The publication was based on a lecture to the Geological Society of America in November 1963 but, in it, McGill refers to a urban geology as a subject that is "*growing in importance"* implying that it was already an acknowledged sub-discipline of geology. Further, Rau suggested that the earliest urban geological work took place in California in the 1950s and 1960s. Alfors *et al.* (1973) prepared an 'Urban geology master plan' for California. However, this plan, like earlier work (for example, Jahns 1958, Leighton 1966, Leeds 1966) was focussed on geological hazards and reducing the financial and human losses that they caused. While far-sighted, the title of the report by Alfor *et al.* (1973) is a little misleading, in that it only covers one particular (though important) aspect (geohazards) of urban geology. However, the sheer quantity of both published and unpublished information produced on the relationship between geology and urban development both for California, in general, and Los Angeles, in particular (Cooke 1984), makes this part of the world the most likely mid-wife for the newly developing subject.

However, in considering how urban geology developed, care is needed to distinguish between urban geology publications and publications on the geology of urban areas. For example, Legget (1973) referred at some length to Charles Kingsley's book on “Town Geology” (Kingsley 1877). Kingsley, as well as publishing a number of popular novels (Legget gives details), had a great interest in, and lectured on, geology. His 1877 book has a slightly misleading title in that it is really about conventional aspects of geological processes and how rocks are formed but gives examples of common uses of particular rocks as title headings for different chapters. For example, metamorphism is discussed under the heading “The slates on the roof.” In a more recent example, Nott (2003) in a paper entitled “The urban geology of Darwin, Australia” actually discussed how better understanding of weathering processes and structural controls have led to a reinterpretation of the local geology. There are many other similarly ambiguously titled publications (for example, Bennett *et al.* 1996).

Fuchu *et al.* (1994) defined urban geology as: “...*the study of land resources and geologic hazards as they relate to the development, redevelopment and expansion of urban areas.”* De Mulder (1996) and Anon. (1996a) went further and both defined urban geoscience (urban geology) as “*an interdisciplinary field in the geo- and socio-economic sciences addressing Earth-related problems in urbanised areas.”* Both definitions have the advantage of not focussing specifically on land-use planning as the main beneficiary of geological understanding and also referring to problems in urban areas that have the ground as their source, at least in part.

Perhaps because Robert Legget spent his working life in Canada, that country has a strong history of applied research into the subject. This led to publication by the Geological Association of Canada of a volume on the “Urban Geology of Canadian Cities” (Karrow & White 1998a). In the Preface to that volume, the editors wrote that urban geology: “*... spans both regional and applied geology. Some emphasis is usually assumed in the application of geological principles and knowledge to the solution of construction, and now environmental, problems in or near urban areas.*” (Karrow & White 1998b). The Geological Survey of Canada (Anon. 2008) defined urban geology as providing *“engineers, planners, decision makers, and the general public with the geoscience information required for sound regional planning in densely populated areas.”* This is not a specifically science research-based description in that it deals with the provision of information. The authors of this paper propose that an alternative would be to consider urban geology as:

> **The study of the interaction of human and natural processes with the geological environment in urbanised areas, and the resulting impacts, and the provision of the necessary geo-information to enable sustainable development, regeneration and conservation.**

Of particular importance is that human 'activity' is very varied and has been generalised, particularly in relation to the urban environment, in terms of sustainability, that is, trying to improve the quality of life within the constraints of the resources available. This concept, in turn, includes the social and economic aspects of human activity, as well as the environmental. In this context, geology is but a relatively small part of the environmental aspects of sustainability. However, because so much of the building, construction and infrastructural aspects of urban development are related to the ground, geology has an under-pinning importance that has not always been fully appreciated. This takes geology in the urban environment beyond simply identifying appropriate geological resources, threats to safety and suitable foundation conditions. The definition above also identifies the crucial importance of appropriate information being available to decision-makers. In addition, geology has an input to the *management* of the city and even its political and cultural development. For example, geology is important in the disposal of waste water (sustainable urban drainage), the maintenance prioritisation of leaking water pipes, the unscrambling of cities' historical development and the identification of the places most at risk from the consequences of past industrial activity.

In their consumption of raw materials and resources to support their growth, in the disposal of waste materials generated within them and in their complex linkages to agricultural resources in the rural environment, it has been argued that cities function like a living organism, though this is an inexact analogy (Lynch 1981). The political, cultural and socio-economic drivers for city growth and development define the city as a part of an ecosystem that provides services to support human and biological well-being. These concepts open up possible new applications of geology to urban sustainability, which, in part, are driven by the greater availability of new information, the development of new technology and the increasing willingness of engineering geologists to work with all the professionals involved in urban development.

THE HISTORICAL DEVELOPMENT OF URBAN GEOLOGY

There is almost certainly no specific point in time at which urban geology came into existence. One of the first driving forces for the involvement of geologists in the state of urban environments was public health. As early as 1843, the then Prime Minister of Great Britain (Sir Robert Peel) invited Lyon Playfair (later Lord Playfair) to sit on a Royal Commission that was to "*inquire into the state of large towns and populous districts*" from the point of view of public health (Anon. 1900). Playfair, who shortly after the completion of this report became a chemist at the Geological Survey, was responsible for reporting on Lancashire towns (in north-west England). He noted that 10% of people in Manchester and 15% of people in Liverpool lived in cellars. Drainage and water supply were causing serious health problems as demonstrated by the cholera epidemics in Britain, first in 1831 and again in 1848, 1853 and 1866. In 1861, Queen Victoria's husband, Albert, died of typhoid, another hygiene-related disease. Later Henry Penning (1872), an applied geologist at the Geological Survey, wrote a short pamphlet on "...nuisances, drains and dwellings..." Even earlier in Paris, in 1777, Louis XVI set up a service to gather information about the collapse of gypsum mines and the location of uncollapsed mines and to supervise their remediation (Gazel *et al.* 1982, Toulemont 1995).

In Austria, there were also concerns about public health in Vienna. This resulted in Eduard Suess (1862) writing a book (in German) on "Der Boden der Stadt Wien" ("The ground of the city of Vienna"). According to Dorsch (2004), this book discussed not only the geology of the bedrock, superficial deposits *and* artificial deposits but also the use of geological materials for building and construction and, particularly, the relevance of geology to public health. Drainage, groundwater supply and water quality were all discussed. Dorsch (2004) suggested that the book "*should be considered as the historical foundation of the geoscience branch of urban geology*." Dorsch added that Suess considered this book to be his most important professional work, even though he is much better known for his work on classical geology (for example, Suess 1885-1908).

Mono-thematic urban geology

So, public health in cities was a subject of concern from the first half of the 19th century and it remained so throughout the remainder of it. Towards the end of the century Horace Woodward, who joined the Geological Survey of England and Wales on the same day as

Henry Penning (see above), wrote a memoir on the soils and substrata of London from a sanitary point of view (Woodward 1897) which sold out and was republished in a second edition (Woodward 1906). This memoir, which included a map of the sub-soils of the country around London (essentially, the Greater London area), was cited by Culshaw (2004a) as one of the earliest published examples in the UK to try "*to explain the geotechnical, hydrogeological and geo-environmental influences of geology on the building and construction of urban areas."* The map differed markedly from a traditional geological map in that stratigraphy was barely mentioned. Rather, the geology is classified into a "Clayey series", a "Gravelly series" and a "Sandy series." Limestone (the Cretaceous Chalk) and marshland (Holocene alluvium) are also depicted. In addition to the basic geology, the memoir covered topics such as sites and foundations for houses, water supply and drainage, general sanitary considerations and the location of cemeteries.

This publication is of further interest because it was produced as a result of public demand. In the Geological Survey's annual report for 1897 (Anon. 1898), it was noted that the memoir was published to provide greater awareness of issues arising from enquiries by the general public. Towards the end of his career, Woodward (1912) rewrote the memoir as a book but nothing like it was published again, for London, until nearly a hundred years later (Forster 1997).

Karrow & White (1998b) and White & Karrow (2001) discussed the development of urban geology in Canada. The earliest work was done by Henry Ami who published on the geology of several Canadian cities (Ami 1885, 1891, 1892, 1897) culminating in a paper on the cities of Eastern Canada (Ami 1900). However, these papers are not really concerned with the application of geology.

These developments did not continue after the 1st World War. This may have been due to the rise of soil mechanics (Terzaghi 1925) in the first half of the 20th century, though, based on Peter (1966), Dearman (1991) described a number of mono-thematic urban geological maps produced mainly in Germany. The earliest of these maps date back to the early part of the 20th century and mainly consisted of geotechnical maps and plans of cities such as Erfurt, Frankfurt, Danzig (now Gdańsk in Poland) and others. De Mulder *et al.* (2001) mentioned "*special soil maps*" produced in Germany in the 1930s and atlases for a significant number of German cities, which included thematic land-use maps (Mückenhausen & Müller 1951). Unfortunately, some of these examples given by Dearman are not referenced. However, he regarded maps of foundation soils for Warsaw, Poland (Sujkowski & Rozycki 1936) as "*a pioneering work in urban geology.*" Dearman indicated that further developments in urban engineering geological mapping continued after the 2nd World War in eastern Europe, particularly in the then Czechoslovakia, possibly driven by the political belief in national planning (of all types). One interesting development in Eastern Europe was the use of the strip/stripe method to try to produce three dimensional (3D) representation (Zereba 1947). However, this approach was little used in Western Europe, though it saw a mini-revival in the UK on one of the applied geological maps of Wigan (Forster *et al.* 2004) and on a geotechnical map of Nicosia, Cyprus, produced jointly by the BGS and the Cyprus Geological Survey (Cratchley *et al.* 1982, Hobbs 1982). By the 1970s the importance of geology to urban planning was becoming recognised and it was realised that the maps produced need to provide information that addressed many more issues than simply those relevant to civil engineers.

Multi-thematic urban geology

In the UK, a major initiative on urban geology began in the mid-1970s driven both by renewed government policy in the 1960s to establish 'new towns' (major urban developments of certain villages in rural areas) (New Towns Act 1946 and 1964) and, in 1972, a major transfer of funding from the Geological Survey (then known as the Institute of Geological Sciences [IGS]) to government departments which then commissioned a series of applied research projects specified by them. One of these government departments, the then Department of the Environment (DoE), was responsible for the development of land-use planning policy and guidance. It also 'acquired' a significant part of the transferred funds. These funds were used, initially, for two main projects: one was concerned with obtaining strategic information about aggregates and other industrial mineral resources in England and Wales by means of a new survey and other investigations (in Scotland similar work was directed by the Scottish Development Department). The other was concerned with obtaining geological information relevant to the planning of the proposed 3rd London Airport, which was to be built, in the sea, on the north side of the Thames estuary, and its hinterland in south Essex (Fig. 1) (Cratchley *et al.* 1979). In particular, a preliminary assessment of ground conditions was to be made to guide land allocation and identify the most cost effective forms of site investigation. The main data collection related to primary geological mapping, engineering geological mapping and mineral assessment. Geologically, the bedrock consists of sedimentary deposits of the Tertiary Thames Group. These consist of overconsolidated clays of the London Clay Formation, inter-bedded sands and clays of the Claygate Member and sands of the Bagshot Formation (Northmore *et al.* 1999). Quaternary superficial deposits consist mainly of Brickearth (loess and redeposited silts) (Northmore *et al.* 1996) and Holocene Alluvium. The engineering geology was described in terms of geotechnical groups and units based on lithology and geotechnical characteristics. Of particular interest is that the Alluvium was divided into five units that could be identified across the area. Different profiles of the five units were mapped (Fig. 2a and b). Three of these consisted of silty clays, clayey silts and silty sands which offered poor foundation conditions; the other two units consisted of sandy gravels. A series of maps were produced showing, for example, the location of boreholes, penetrometer tests and geophysical soundings, variation in a range of geotechnical properties, isopachytes and depths to specific horizons, landslides and summary engineering geological conditions. This project was innovative in many ways. A key advance was the digitisation of geological information at a time when even the simplest computers were physically large, slow, expensive and not user-friendly. Digital mapping was in its infancy and the use of digital databases started with hand-coding of data and then input to the computer using punched-cards! As the project was, in part, research driven, experimentation was encouraged and a very wide range of map types was produced, including one of contours on the Tertiary Thames Group, London Clay Formation – Claygate Member surface that could be viewed in 3D, using green and red anaglyph spectacles. Others included trend surface maps, isopachyte maps and perspective views derived directly from the digital data. Of particular interest is the summary “Engineering Planning Map.” The map showed areas that were generally suitable for different types of construction and, also, detailed suggested site investigation procedures (Culshaw & Northmore 2002). Had the airport gone ahead (it was eventually cancelled but, more recently, new interest has been shown), this map would have been an important tool for the land-use planning of the urban area that would have been created around the airport.

In Scotland, similar applied research was carried out but this time in relation to the location of heavy industry in the Firth of Forth and Cromarty Firth estuaries. In the mid 1970s the Scottish Development Department (SDD) set out national planning guidelines with regard to land use and conservation of resources. An important issue was identification of land for major industries, particularly those related to the then growing oil industry, driven by the exploitation of oil reserves under the North Sea. The Upper Forth estuary (Fig. 1) was identified as a potential development site, so an investigation was carried out to:

- assess geological conditions affecting heavy industrial structures;
- identify geological hazards and areas favourable or unfavourable to development;
- describe the relevant characteristics of geological strata;
- give guidance on necessary detailed site investigation if development took place;
- give guidance for land use planning and national and local levels and provide a scientific basis for advice to ministers on the best use of land resources (Gostelow & Browne 1986).

Three geotechnical factors were used to assess ground suitability for heavy structures:

- allowable bearing pressure;
- depth to a suitable founding horizon;
- extent of site investigation required prior to development.

Geologically, the area consists of Carboniferous limestones, sandstones, mudstones and coals, Permo-Triassic volcanic tuffs, basalts and dolerites and Quaternary glacial tills and sands and gravels, a range of alluvial and other estuarine deposits and artificial deposits. The coal-bearing rocks had been worked beneath the estuary. The rocks and soils were classified in engineering terms and presented in a series of maps and cross sections. A output was summarised in a “Geotechnical planning map for heavy structures,” which classified the ground into six zones ranging from very good for heavy foundations (zone A) to unpredictable (very poor to fair) (zone F). An extract of the map with its key and descriptive tables are shown in Figure 3a-d. A similar study for the Cromarty Firth (Fig. 1) was carried out as a desk study only (Gostelow & Tindale 1980).

Urban geology was not formally recognised in the UK as a distinct sub-discipline of geology until probably the late 1990s when the British Geological Survey (BGS) renamed the applied research programme responsible for engineering geology as the 'Urban Geoscience and Geological Hazards Programme.' This happened following the recommendations of an external review. Urban geoscience remains a funded activity, now within the 'Land Use Planning and Development' science area. However, an extensive programme of urban geological mapping and research was carried out from 1980 to 1996, variously termed, 'environmental geological mapping,' thematic geological mapping' and 'applied geological mapping.' The applied research projects carried out in England and Wales were briefly described by Smith & Ellison (1999) and for the whole of Great Britain up to 1988 by Culshaw *et al. (*1988). These urban geological mapping projects were funded by the DoE (and its successor Departments) in England, the Welsh Office in Wales and the SDD in Scotland. The purpose of the research was to “*investigate the best means of collecting, collating, interpreting and presenting, in sets of maps and reports, geological results of direct applicability in land-use planning.*” (Brook & Marker 1987). The map output of each study consisted of 'factual' maps, 'interpretative' maps and, in many projects, a summary map showing the main geological concerns for planners. The earliest project in the programme covered an area of 100 km^2 to the north-west of Glenrothes in Fife, Scotland (Fig. 1). Eighteen 'factual' (or 'basic') maps were produced, together with four 'interpretative' maps and five summary maps (Nickless 1982).

The final urban geological study in the applied research programme outlined above was for the Bradford Metropolitan area of West Yorkshire, England (Fig. 1). The bedrock geology of the area consists of Carboniferous Coal Measures and Millstone Grit. These are overlain over much of the area by glacial and post-glacial superficial deposits and both are overlain locally by artificial deposits. By the time that the research was carried out (1993-96), geographical information systems (GIS) had come into common use. Consequently, the maps were produced digitally, though printed versions accompanied the report (Waters *et al.* 1996). The report was in two parts: a guide, mainly for land-use planners, to the use of geological information in planning and development and a technical guide for engineers and geologists to ground conditions. The guide for planners included a map of geological factors relevant to planning and development (Fig. 4a & b). These factors are compared with the main planning and development issues in Table 1. Those factors that are of minor significance are shown by an 'x' symbol and those that are of major significance by an 'xx' symbol. The technical guide included maps of bedrock geology, superficial deposits, mineral resources and surface mineral workings, mined ground and shafts, slope steepness and landslides, engineering ground conditions and water resources and flooding. The map of engineering ground conditions was composed of four separate maps showing foundation conditions, suitability of deposits as engineered fill, excavatability and thickness of superficial deposits. The keys to each of these maps are shown in Figure 5a-d. The report was also accompanied by five digital databases that provided information on:

- boreholes and trial pits;
- site investigation reports;
- landslides;
- landfill sites;
- sandstone quarries.

Unfortunately, the databases were compiled using the dBase III+ program that was in common use at the time. However, now, the databases would be hard to access. It is not known if the local authority (City of Bradford Metropolitan District) kept the database up-to-date. However, some of the data, particularly with regard to site investigation reports and borehole and trial pit information, is likely to have been added to by the original contractor (the BGS). Similarly, the information on landslides may have been added to as the BGS operates the National Landslide Database (Foster *et al.* [paper submitted]). This highlights one of the key issues with regard to information for urban areas – keeping the information current and accessible. This is discussed more below.

Table 1. Summary of planning and development issues and relevant geological factors in Bradford, West Yorkshire, UK.

	GEOLOGICAL FACTORS							
PLANNING AND DEVELOPMENT ISSUES	Made ground conditions	Shallow undermining	Mineral resources	Surface mineral workings	Geological faults	Landslide areas	Water resources	Washland areas liable to flooding
Housing and industrial development	xx	xx	x	x	x	x	x	x
Improvement of the transport network	xx	xx	x	x	x	xx		x
Protection and development of	x	x	xx	x	x	x	x	x

mineral resources								
Provision of waste disposal facilities	xx	xx	x	xx	x	x	xx	x
Control of pollution	x	x		xx	xx		xx	
Protection and development of water resources	x	x	x		x		xx	
Protection of washland areas and flood prevention	x	x	x	x			x	xx
Landscape and nature conservation	x	x	x	x				

In 1982, the Association of Geoscientists for International Development (AGID) initiated a series of conferences on land-use planning. The first of these ('Landplan I') was held in Bangkok in 1982 had a broad focus, covering soils, climate, agriculture, water, landform, engineering and planning, as well as geology (Nutalaya *et al.* 1982). ‘Landplan 1’ did include a fairly detailed study of the urban geology of Accra, Ghana (Kumapley 1982) and Chiang Mai, Thailand (Thanadpipet *et al.* 1982). However, the three subsequent conferences (Landplan II, III and IV) did focus more on geology and the planning of urban areas (Tan & Rau 1986, Whiteside 1987, Wang Sijing & Wang Cunyu 1994). AGID published a further book on urban geology in 1996 (McCall *et al.* 1996).

Also in 1982, the Geological Society of America published, in its 'Reviews in Engineering Geology series, a volume entitled “Geology under Cities” (Legget 1982). This volume is of particular interest as it was edited by Robert Legget who is often referred to as the 'father of urban geology' (for example, Walton 1982). The book contained papers on nine USA and Canadian cities – Boston, Chicago, Edmonton, Kansas City, New Orleans, New York, St. Paul and Minneapolis, Toronto and Washington, D. C. Legget regarded the book as the starting point to correct the lack of information on urban geology on individual cities in North America.

In 1985, the Economic and Social Commission for Asia and the Pacific (ESCAP - a United Nations regional commission based in Bangkok, Thailand) initiated a programme on urban geology. According to Rau (2003), governments in the region were concerned by the impact on cities of damaging geological and other hazards. Fifteen publications were produced between 1985 and 2003, all but the first (Anon. 1985) being part of the “Atlas of Urban Geology” (Anon. 1988a, b, c, 1990a, b, 1991, 1995a, 1996a, b, 1999a, b, 2001a, b, 2003a). Many of the papers presented in these volumes were short case histories of the major cities in the region, for example, Hong Kong, China (Burnett 1988), Kuala Lumpur, Malaysia (Sun 1988), Bangkok, Thailand (Khantaprab & Boonnop 1988), Surabaya, Indonesia (Wongsosentono, S. & Purbo-Hadiwidjoyo 1988), Nantong, China, (You & Shing 1988), Shanghai, China (Xinguo 1990), Dhaka, Bangladesh (Asaduzzaman 1996), Jaipur, India (Natani 1996), Bandung, Indonesia (Suhari 1996), Colombo, Sri Lanka (Prame 1996), Kathmandu, Nepal (Tuladhar 1996), Delhi, India (Kaul & Dasgupta 1999), Jakarta, Indonesia (Apandi & Wiriosudarmo 1999), Ho Chi Minh City, Vietnam (Phu & Hung 1999), Calcutta, India (Anon. 2003b), Vientiane, Laos (Phommakayson 2003), Istanbul, Turkey (Siyahi 2003) and Tashkent, Uzbekistan (Mavlyanov 2003). However, other papers were more strategic, for example, Anon. (1996a) – a 'how-to-do-it' manual, Ellison & Callow (2001) on the value of geo-information and Rau (2003) on the state of 'geosecurity' (that is, the relationship between development and the threats to health and safety from physical and chemical geohazards). At least one training course was also delivered (Anon. 1995b). While the programme finished in 2003, its success can be measured by the vast increase in awareness of geological issues in urban development and the fact that urban geology sections have been set up in more than a dozen geological surveys in Asian and Pacific countries (Anon. 2003a).

A number of other papers on the urban or engineering geology of individual cities have been published, including on Banda Aceh, Indonesia (Culshaw *et al.* 1979), Bath, UK, (Forster *et al.* 1987), Cardiff, UK (Gordon *et al.* 2004), Glasgow, UK (Browne *et al.* 1986), Kuala Lumpur, Malaysia (Kong & Komoo 1990), Newcastle and Sunderland, UK (Dearman *et al.* 1979, Dearman & Strachan, A. 1983), Paris, France (Arnould *et al.* 1979), Pessac, France (Marache *et al.* 2009), Piracicaba City, Brazil (Grecchi & Pejon 1998), Perth, Australia (Gozzard 1985), Swansea, UK (Power & Statham 2004, Waters *et al.* 2005), Tongchuan, China (Fuchu *et al.* 1994), Valencia and Gran Canaria, Spain (Cendrero *et al.* 1990), Wigan, UK (Forster *et al.* 2004) and Wrexham, UK (Culshaw 2004b).

The Association of Environmental and Engineering Geologists (AEG) has encouraged more formalised publications on a number of world cities. The cities discussed include Albuquerque, USA (Clary *et al.* 1984), Boston, USA (Woodhouse *et al.* 1991), Boulder, USA (Bilodeau *et al.* 1987), Cairo, Egypt (Shata 1988), Christchurch New Zealand (Brown *et al.* 1995), Dallas, USA (Allen & Flanigan 1986), Denver, USA (Costa & Bilodeau 1982), Hong Kong, China (McFeat-Smith *et al.* 1989), Indianapolis, USA (West & Warder 1983), Johannesburg, South Africa (De Beer 1986), Kansas City, USA (Hasan *et al.* 1988), Las Vegas, USA (Wyman *et al.* 1993), Lima, Peru (Karakouzian *et al.* 1997), Long Beach, USA (Randell *et al.* 1983), Los Angeles, USA (Bilodeau *et al.* 2007), Monteal, Canada (Boyer *et al.* 1985), Port Elizabeth, South Africa (Carter 1987), Reno and Truckee Meadows, USA (Gates & Watters 1992), Rome, Italy (Thomas 1989), Salt Lake City, USA (Gwynn *et al.*1990), Seattle, USA (Lund *et al.* 1991). While the papers were published in the journal 'Environmental and Engineering Geoscience' and its predecessor, the Bulletin of the Association of Engineering Geologists, they were brought together on a CD-ROM published by the AEG (Anon. 2006b). In addition, papers on four further cities in South Africa, Cape Town (Mountain & van der Merwe 1981). Durban (Maud 1981a), Pietermaritzburg (Maud 1981b) and Pretoria (Kraft 1981) (originally published in the Proceedings of a Symposium on the Engineering Geology of Cities in South Africa) were also included. However, these papers are usually rather short, though they are often accompanied by other papers on additional aspects of the engineering geology of the cities (Anon. 2006b).

Similarly, the Geological Association of Canada has published a volume on the urban geology of twenty three Canadian cities, all with populations greater than 100 000 (Karrow & White 1998a). Of particular interest is the discussion on urban geotechnical/geological databases. In the 1970s, the Canadian Geological Survey developed a number of these for Canadian cities. However, by the time of the publication of this book, only nine were still being maintained and expanded. This is discussed in more detail below.

In Australia, a group of engineering geologists and geotechnical engineers brought together some of the large amount of the geo-information available for the Sydney Region (Pells 1985). The book was intended as a first point of reference with regard to site investigations and construction projects. Consequently, it does not cover all aspects or the urban geology. Included is information on the basic geology (including anthropogenic deposits), the geotechnical properties of the different formations, some geohazards, construction material and building stone, foundation design and performance, tunnelling and excavation, there is little on groundwater, pollution or contamination and many other topics. Very few maps were included, most of those shown being at small scale. The book is intended for use by engineering geologists and geotechnical engineers, not the much broader range of urban professionals. A similar volume for was produced later for Melbourne (Peck *et al.* 1992).

In France, the RIVIERA (Risks in Towns and Cities: Equipment, Networks and Archaeology) project, paid for by the French Government, "*aims at developing methods and tools for the preliminary evaluation of geotechnical, hydrogeological and archaeological hazards at the scale of a city and its suburbs*" (Bourgine *et al.* 2009). Bordeaux was used as a test site for the methodologies developed.

Comprehensive urban geological assessments have been carried out in Shanghai, Beijing, Hangzhou, Guangzhou, Tianjin, and Nanjing under the auspices of the China Geological Survey and local organisations. The purpose of the research was to:

- identify and evaluate the geological background, resources and geological environment to obtain the necessary information for urban planning, construction and management services;
- establish an urban geological survey methodology and guidelines for other cities;
- research investigation methods (including geophysical ones) in different locations;
- develop 3D visualisation and information systems (Zhuang *et al.* 2010).

Research in Shanghai has resulted in the publication of an atlas of Shanghai urban geology and an accompanying memoir (Anon 2010a, b). The atlas presents a series of maps, at scales ranging from 1: 500 000 to 1:100 000, on bedrock and Quaternary geology, engineering geology, hydrogeology, geochemistry, land subsidence and the near-shore areas. Though the maps have been created digitally and the content is broader, there are interesting similarities with the approach of Anon. (1977) in South East Essex, UK described by Cratchley *et al.* (1979). As a result of the extensive research in China, an international symposium on urban geology and sustainable development was held in Shanghai at which a wide range of presentations were made on topics ranging from the theory of urban geology to applications, technical methods and information systems (Anon 2010c).

A recently completed project called (GeoInforM), part funded by the European Union 'LIFE' programme, has produced a geological atlas for St Petersburg, Russia (Anon. 2009). This includes a wide range of geological maps at a variety of medium and small scales. Topics covered include the general geology, hydrogeology, engineering geology, mineral resources and geohazards. In addition, maps showing constraints on construction and a combined geohazard matrix map that weights and combines the different geohazards to show overall geohazard levels were produced. Each map is accompanied by explanatory text. An extensive volume on the urban geology of Moscow has also been published (in Russian) (Osipov & Medvedev 1997).

The AEG has been active in leading research in urban geology in the USA. However, others have also been involved. In 2000, the American Geophysical Union held a session at its Spring meeting on “Earth Sciences in the Cities.” Many of the presentations were eventually published (Heiken *et al.* 2003). The book was intended both as an introduction to urban geology and a response to a perceived “*lack of geoscientific analysis in urban development.*” More recently, the AEG has started a new project to publish papers on around fifty cities around the world. As with the earlier publications (Anon. 2006b), the papers are to be produced following a template (Table 2). The papers published by the AEG are comprehensive in their scope and probably represent the limit of what can be published on an individual city in a conventional academic publication.

Table 2. Recommended content of urban geology of the world's cities papers for the AEG Special Publication

ABSTRACT

PREFACE

1.0 BACKGROUND
- 1.1 Location
  - (General physiographic and historical geologic introductory remarks)
- 1.2 History of Founding
- 1.3 Geologic Influences Affecting Founding
  - (e.g. major terrain features, historic transportation routes and/or other physiographic conditions)
- 1.4 Public Interaction of Professional Geologists & Geological Engineers
  - (how professional geologists bring enhanced value to public and private entities during land use development and hazard assessment, risk assessment mitigation, emergency planning and preparedness and emergency operations, including response and recovery).

2.0 GEOLOGIC SETTING
- 2.1 Brief on Regional Geology
- 2.2 Geology of The City
  - 2.2.1 Basement Rocks
  - 2.2.2 Sedimentary Rocks
  - 2.2.3 Physiographic Region (with geotechnical practice implications)
  - 2.2.4 Surficial Geologic and Soil Units
  - 2.2.5 Stratigraphic Chart with Basic Engineering Characteristics

3.0 GEOTECHNICAL CHARACTERISTICS
- 3.1 General Foundation-Related Geologic Units
- 3.2 Exploration Methods
- 3.3 Typical Foundation Types in Use
- 3.4 General Laboratory Test Methods
- 3.5 Regionally Important Geologic Materials
  - (RIMs; those exhibiting unusual properties/characteristics of a negative geotechnical nature)
- 3.6 Regionally Important Geologic Anomalies
  - (locally-negative engineering geologic conditions; e.g. karst, pseudo-karst, anomalies of glaciated terrane, troublesome stratigraphic disconformities, all manner of geomorphic “holidays;” etc.)

4.0 MATERIALS of CONSTRUCTION
(soil, weak rock, stone, aggregate, borrow)
4.1 Traditional Types and Uses
4.2 Sources and Extraction Methods
4.3 Regulations and Zoning Affecting Extraction and Closure
4.4 Environmental Impact of Extraction

5.0 GEOLOGIC CONSTRAINTS
5.1 Classification
(e.g. ground instability; loss of ground, subsidence, unstable soils and/or weak rock units, volcanic eruptions, tsunami, etc.)
5.2 Geologic Elements of Hazards Detection and Warning Systems and Loss-Reduction Applications
5.3 Geologic Aspects of Natural Risk
5.3.1 Unstable Soil & Weak Rock
5.3.1.1 Collapse-Prone Soils
5.3.1.2 Expansive Soils
5.3.1.3 Slaking Weak Rock
5.3.2 Loss–of-Ground Phenomena
5.3.2.1 Subsidence
(natural ground and of underground workings)
5.3.2.2 Karstic Ground Failure
5.3.2.3 Mass movement
5.3.3 Geologic Effects of Violent Weather
(including cyclonic storms, hurricanes and typhoons)
5.3.3.1 Debris-Flows
5.3.3.2 Geologically-Channeled Floods
5.3.3.3 Storm-Induced Slope Failures
5.3.3.4 Wildfire Suppression
5.3.4 Earthquake-Induced Geologic Effects
5.3.4.1 Ground-Motion Amplification
5.3.4.2 Liquefiable Soils
5.3.4.3 Tsunami
5.3.5 Geologic Effects of Volcanism
5.3.5.1 Volcanic Eruptions
5.3.5.2 Ash Falls
5.3.5.3 Pyroclastic flows
5.3.5.4 Lava Flows
5.3.5.5 Lahars
5.3.5.6 Toxic Gas Clouds
5.4 Recurrence and Forecasting
5.4.1 Classification and Nature of Threat
5.4.2 Practical Estimation of Recurrence Intervals
5.4.3 Uses of Forecasting and Predictions in Loss Reduction or Avoidance
5.5 Mitigation of Risk
(presenting only geologic considerations and effects)
5.5.1 Planning for Disaster Response:
5.5.2 Response Techniques
(to include planning, preparedness, mitigation, and evacuation)
5.5.3 Post-Event Recovery and Mitigation

6.0 RESOURCE RECOVERY

- 6.1 History
- 6.2 Classification of Resources
  - (water, industrial minerals, petroleum)
- 6.3 Areal Extent of Each Resource
- 6.4 Constraints to Resource Recovery
- 6.5 Mitigation of Recovery Effects
  - (physical/chemical threats; e.g. loss of ground, subsidence, pollution/contamination, saline encroachment)

7.0 SEISMICITY OF THE CITY

- 7.1 Historic Record
- 7.2 Notable Events
- 7.3 Generalized Recurrence Interval
- 7.4 Ground Motion Amplification Factors
- 7.5 Loss of Ground (e.g. liquefaction, hillside failures)
- 7.6 Seismic Design Provisions in Force
  - (legislation, codes and other forms of geologically-based risk mitigation measures)

8.0 ENVIRONMENTAL CONCERNS

- 8.1 Water Supply
  - (surface and subsurface sources, reclamation of water)
- 8.2 Wastewater Treatment
- 8.3 Waste Management
  - (solid, special, hazardous and radioactive)
- 8.4 Remediation of Uncontrolled Hazardous Waste Sites
  - 8.4.1 Historic Dump Sites
  - 8.4.2 Contaminated Sediment
  - 8.4.3 Contaminated Water
    - (surface and subsurface)
  - 8.4.4 Remediation Case History Briefs of Notable Site Cleanups
    - (uncontrolled hazardous waste sites remediated under national laws)
  - 8.4.5 Brownfield Redevelopments
- 8.5 Reclamation of Mined Ground
  - 8.5.1 Mining Permitting, Reclamation and Closure Issues
    - 8.5.1.1 Discharges into Aquifers and Surface Waters,
    - 8.5.1.2 Monitoring and Mitigation
      - (including Acid Mine Drainage
    - 8.5.1.3 Asbestiform and Other Toxic Mineralization
    - 8.5.1.4 Stability of Beneficiation Slimes and Tailings Dams
  - 8.5.2 Low- and High-Level Radioactive Waste & Stored Ores & Concentrates
  - 8.5.3 Applicable Government Programs in Force
- 8.6 Wetlands Factor
- 8.7 Flooding
- 8.8 Shoreline Erosion
  - 8.8.1 Geologic Conditions Susceptible to Erosion
  - 8.8.2 Geologic Parameter Influential to Mitigation Design
- 8.9 Sea Level Changes
  - 8.9.1 Impacts on Land Use

8.9.1.1 Salt Water Intrusion into Fresh Water Aquifers
8.9.1.2 Inundation of Infrastructure, Farm Lands, and Structures
8.9.2 Geologically-Based Mitigative Techniques

9.0 MAJOR ENGINEERED STRUCTURES

10.0 USE of UNDERGROUND SPACE
10.1 Introduction and History
10.2 Water Supply Conveyance Tunnels
10.3 Transportation Routing Tunnels
10.4 Sewerage and/or Flood Control Tunnels
10.5 Commodity Storage Caverns
10.6 Energy Storage Caverns
(natural gas, petroleum, compressed air)
10.7 National Defense Caverns

11.0 GEOLOGIC PARAMETERS ATTENDANT to SOCIO-POLITICAL CONDITIONS
11.1 Living Space, Natural Hazards, Vulnerability, and Acceptable Risk
11.2 Moving People
(to and from employment locations)
11.3 Complex Emergencies and Natural Resources and Hazards; Past and Present
11.4 Related Effects of Warfare or other Anthropogenic Calamities
11.5 Global Climate Change Impacts as Known and Projected through 2100 A.D.
11.6 Human Migration Affected by Changes in Natural Resources, Natural Hazards or Changes in the Sustainability of Locations versus Population Needs.

12.0 SUMMARY
12.1 Conclusions
12.2 Predictions and Major Projects Under Consideration
12.3 Recommendations

13.0 ACKNOWLEDGEMENTS

REFERENCES

ILLUSTRATIONS
(images, diagrams, maps)
Frontispiece
(preferably a color oblique view of central business district)
Index Map
Generalized Geologic Planimetric Map
Stratigraphic Column
Geotechnical Cross Section
(actual or typical, showing typical inter-relationships between named or generic geologic units and typical topography)
Seismicity Plot
(major event epicenters; seismic source structures; seismo-tectonic zonation)
Other Drawings, Charts, Images, Tables

In addition, the Congresses of the International Association for Engineering Geology and the Environment (IAEG) have resulted in a wide range of further single city papers, particularly following the 2006 Congress which focussed on 'tomorrow's cities' (Culshaw *et al.* 2009a). These include papers on Almeria, Spain (Fernandez *et al.* 1982), Bhopal, India (Ranga Rao *et al.* 1982), Bucharest, Romania (Ciugudean-Toma & Stefanescu 2009), Covilhã, Portugal (Cavaleiro *et* al. 2009), Durban, South Africa (Richards 2002, Maud & Bell 2002), Gumushane, Turkey (Tudes & Ceryan 2009), Istanbul, Turkey (Undul & Tugrul 2009), Kuala Lumpur, Malaysia (Tan 2009), Kunming, China (Chen *et al*. 2010), parts of Lisbon, Portugal (Da-Silva & Rodrigues-Carvalho 2009, Matildes *et al*. 2010), Madrid, Spain (Yagüe 1986), Mainz, Germany (Krauter *et al.* 1990), Makkak Al Mukarramah, Saudi Arabia (Al-Solami *et* al. 2009), Maputo, Mozambique (Vicente *et al.* 2009), Moscow, Russia (Osipov 2009, Mironov 2010), Munich, Germany (Bauer *et* al. 2009), Nottingham, UK (Bell *et al.* 2009), Patras, Greece (Rozoz *et* al. 2009), Pietermaritzburg, South Africa (Richards *et al.* 2009), Oporto, Portugal (Afonso *et al.* 2009, Oliveira *et al.* 2009), Rio de Janeiro, Brazil (Barroso *et al.* 1986, Amaral & Barros 1994), Salamanca, Spain (Nespereira-Jato *et al.*2009), Sana'a, Yemen (Al-Suba'i & Barat 2009), São José do Rio Preto, Brazil (Mendes & Lorandi 2002), São Paulo, Brazil (Do-Val *et* al. 2009), Tehran, Iran (Ghayoumian *et al.* 2009), Turin, Italy (Bottino & Civita 1986), Ujjain City, India (Kapoor 1982) and Yogyakarta, Indonesia (Karnawati *et al.* 2009). These papers are of varying depth and quality but do provide an introduction to the geological conditions, in relation to development and regeneration, for each of the cities.

This huge volume of published information on the urban geology of the world's cities appears to provide a sound basis for development, regeneration and sustainability in urban areas around the world. However, in reality, much of the information, while of great general interest, is of limited use to those who have to manage urban areas. The reason is that the spatial information in many of these papers is not easily usable. The scales at which maps are reproduced are often medium to small. As the maps are printed on paper, it is not easy to compare maps showing different types of information. While it is likely that much of the spatial data are taken from larger scale (paper) maps, the places where these source maps are located are not always stated. A word of warning was given in the preface of the final volume of the Atlas of Urban Geology (Anon. 2003a): "...*until the geological data that fills the files of geological survey departments across Asia and the Pacific can be translated into a dynamic easy-to-use format (GIS or something better), the data are likely to remain in those files, unused for ever.*" The rapidly advancing availability of non-geological forms of digital spatial information (for example, Google Earth, which is already finding applications in site investigations [Puchner 2010]) means that geo-information will need to be similarly available if it is to be properly used in the urban environment. This is an important point that is discussed further below.

Multi-dimensional urban geology

2003 can be regarded as a very significant date in the development of urban geological methods. A conference was held in the Belgian town of Spa on "New paradigms in subsurface prediction" (Rosenbaum & Turner 2003). It was here that engineering geologists and others began to seriously examine how three-dimensional, digital, spatial modelling could be best applied in the urban environment. Hack *et al.* (2006) pointed out that the main reason that such models were not (then) used more in geo-engineering was that the benefits did not exceed the cost of using complicated software. The key to greater use has been the development of easy-to-use, PC-based software to enable geologists to build and visualise three-dimensional geological models of the subsurface (for example, Culshaw 2005, Kessler *et al.* 2009a). Hack *et al.* (*op cit*) identified a further constraint as the difficulty in quantifying uncertainty, particularly with regard to the quality of expert knowledge used to create the spatial model. Turner (2006) noted other issues including a shortage of "*definitive*" data. However, in many urban areas in more-developed countries, with long histories of acquiring geological data and managing the databases, the amount of available data is approaching sufficiency to carry out detailed spatial modelling at large scale. Turner (*op cit.*) also suggested that the requirements of users of digital models in urban environments were likely to be rather different from users of geological data in the past who were 'resource' orientated. Urban users were likely to be less able to interpret geological information, requiring it in different forms that were more understandable and related specifically to the problems for which they required solutions (Turner 2003). These differences are summarised in Figure 6a and b. For 'resource' based users, academic geologists researched geological processes related to the emplacement of various minerals. Geological Survey geologists gathered field data and presented it largely in map (spatial) form in a traditional geological map. Finally, geologists from mineral exploration organisations combined the two types of information to identify areas likely to warrant more detailed exploration (Fig. 6a). In environmental geological studies, particularly in urban areas, the relationship is different. Funding for applied research in urban environments is harder to obtain, partly because traditionalists do not regard such research as fundamental; geological surveys struggle to understand exactly what it is that users require; the users themselves do not appreciate how geology might be relevant to their particular problem (Fig. 6b).

Nevertheless, the development of three/four dimensional digital, spatial, geological modelling for the urban environment has stimulated new ways of providing information for a wider range of users. In the UK, the pace of (particularly) software development with regard to three/four dimensional modelling and also visualisation has almost outstripped the researchers' ability to apply the new tools. At the BGS, for example, an original intention, developed in 1997 following a major internal review of Survey research in urban geology to improve the way knowledge of topics such as ground contamination and abandoned mineworkings was provided, was overtaken by the rapid development of modelling and visualisation software. Projects were changed to make use of the new tools and kept evolving as further advances took place. Projects in the Clyde Basin (Glasgow), the Mersey Basin (Liverpool to Manchester) and the Thames Basin (Greater London) (Price *et al.* 2007) that include three and, in some case, four dimensional models, are discussed.

Urban geology in the Clyde Basin

In the 1980s, an urban geological study of Glasgow took place (Browne & Hull 1985, Browne *et al.* 1986). The outputs were mainly paper based and the maps were not (originally) digitised. A large, multidisciplinary project encompassing Glasgow (Fig. 1) and the wider Clyde region was subsequently undertaken in partnership with several stakeholders, including Glasgow City Council, to provide, geo-environmental information to support major regeneration following economic decline in one of Britain's major industrial cities. Provision of three dimensional, attributed geoscientific models and data is supporting major regeneration projects including site development for the 2014 Commonwealth Games. The legacy of former coal mining and ship-building, amongst other industries, has resulted in environmental deterioration in the form of contaminated land, mining subsidence and flooding. Attributed three dimensional geological models of superficial deposits (including artificial ground) and shallow bedrock (to depths of about 200 m) are being developed to inform decision-making and guiding use of the subsurface to support re-development (Merritt *et al*. 2007).

Nearly 36 000 borehole logs in the Glasgow area alone were available and of these around 26 000 were interpreted and digitised. The remaining logs were either of poor quality, inadequately located or duplicated nearby boreholes. Figure 7 shows the distribution of the boreholes used in the study across the city. This information, together with mining and map data, has been used to determine geological complexity uncertainty, which is greatest where there is least data and where the dip changes rapidly (Campbell *et al.* 2010) using a methodology developed by Lelliott *et al. (*2009). Also, through integration with subsurface physical and mechanical property data, including data derived from the National Geotechnical Borehole database, the models have been used to provide subsurface geological and geotechnical data to predict the variability of the urban subsurface (Entwisle *et al.* 2008). Figure 8 shows an example of such an attributed model. In this case, the Quaternary deposits three dimensional geological model for the eastern part of Glasgow has been attributed in terms of plasticity.

While the three dimensional geological model provides a powerful and easily accessible means of characterising the subsurface and its geological and geotechnical properties, the value of such models can be further enhanced through integration with other geoscientific data and information. In Glasgow, three dimensional geological models have been used to provide a geological framework from which numerical groundwater models have been derived to address issues of recharge, flooding and geothermal potential (Campbell *et al*. 2010). Contaminant studies have been carried out on a city scale for Glasgow's soils, stream waters and estuarine sediments. These data are being integrated with three dimensional geological models to develop GIS risk-based tools to assess the vulnerability of groundwater to inorganic pollution.

Urban geology in the Mersey Basin

The River Mersey, in north-west England, provided the focus for major industrial and urban expansion during the 18th and 19th centuries that saw the growth of cities including Manchester, Liverpool and Salford (Fig. 1). Industrial activity, including textiles, coal mining, chemical manufacture, shipping and metal-working, followed by widespread economic decline in the mid 20th century, has resulted in a legacy of variable ground conditions, artificial ground, contaminated land, reduced groundwater levels and polluted groundwater. Regeneration projects in north-west England include the creation of MediaCityUK in Salford, major water-front development in the former docklands of Liverpool and transport infrastructure including a new crossing of the River Mersey between Runcorn and Widnes.

Three dimensional geological models of superficial deposits and shallow bedrock in north-west England have been developed at a range of resolutions to provide ground information at regional to city scales. Regional models using cross-sections constructed approximately 5 km apart were used to provide the geological context for higher resolution, detailed city-scale ('far-field') geological models (Price *et al*. 2008a). The wider, regional to catchment context of city scale and, ultimately, site-specific ('near-field') ground models, is essential to understand the variability in the subsurface and the geological and anthropogenic processes responsible.

Higher resolution, city-wide 3D geological models have been constructed for Manchester, Warrington and Liverpool. The models have been used to define the distribution, geometry and geotechnical and hydrogeological properties of the subsurface. In particular, methods for the three dimensional characterisation of artificial ground have been developed (Burke *et al*. 2009). Artificial ground represents often thickly developed (up to 15 m) material and excavations resulting from multiple phases of urban development and industrial activity (Fig. 9). Artificial ground is often associated with contaminated soils and variable geotechnical ground conditions. In heritage cities settled before rapid industrial development in the 18th and 19th centuries, artificial ground also includes archaeological deposits and artefacts. Therefore, integration of geological and anthropogenic deposits models is essential to characterise the full range of subsurface conditions in urban environments.

As the urban areas adjacent to the River Mersey overlie the nationally important Sherwood Sandstone Group aquifer, the geological models have been applied to assess the relative recharge potential and vulnerability of the aquifer to the downward migration of pollutants (Terrington *et al*. 2008, Lelliott *et al*. 2006,). This has been achieved through the attribution of three dimensional geological models with a relative assessment of permeability based on lithological composition of the geological material. Partners including the UK's environmental regulator, the Environment Agency, have applied the models to enhance the management of urban groundwater resources.

Geological models, at different resolutions, provide different levels of detail and division of the subsurface. The resolution is determined by the available scales of geological and geographical data, the density of borehole data, the level to which the geological information is interpreted and the purpose for which the modelling is being undertaken. A scalable approach to geological modelling to meet the needs of users at the city scale provides a robust means of integrating geological and geotechnical characterisation across spatial scales.

Urban Geology in the Thames Basin

Attributed three dimensional geological models are being developed in the London urban area and the wider catchment of the River Thames (Fig. 1). In response to rapidly changing legislative drivers, three dimensional geo-information is being provided to underpin re-development and brownfield regeneration in areas such as the Thames Gateway, including the 2012 Olympic site (Royse *et al.* 2006). The modelled area in London and the Thames Gateway is approximately 3200 km^2 and extends to depths of 150 m. The geological models include superficial deposits down to Tertiary and Cretaceous bedrock where the Chalk comprises Britain's primary aquifer. The resolution of geological modelling in this area follows a similar approach to that described above for the Mersey Basin area in north-west England. Regional geological framework models are being constructed that define geological units in the subsurface, equivalent to those shown on the 1:50 000 geological map. This framework model is being further enhanced to include high resolution subdivision of Quaternary deposits (including artificial ground) and those geological units that are known to be associated with difficult engineering ground conditions due to lithological and geotechnical variability such as the Lambeth Group (Ford *et al.* 2008, Royse *et al.* 2008). Figure 10 shows the model for the site of the London Olympics in east London together with automatically generated geological and engineering geological cross sections. Users of the 3D geological model and its derived outputs have included not only urban planners but private sector environmental consultants and the Environment Agency.

THE USERS

Much of the research carried out until recently was aimed mainly at the needs of two professional groups: land-use planners and civil engineers. However, urban development and regeneration involves three broad user groups: geological professionals, non-geological professionals and the general public, which can each be subdivided. Table 3 gives the subdivisions of these main groups and their main geological requirements.

Table 2. Principal users of geological information in the urban environment and their requirements.

MAIN USER GROUP	PRINCIPAL SUB-GROUPS	MAIN GEOLOGICAL INFORMATION REQUIREMENTS
Geological professionals	Engineering geologists and geotechnical engineers	Distribution and physical, mechanical and chemical properties of natural and artificial geological materials and groundwater. Geological processes acting and time-scales. Foundation conditions, excavatability, use of geological materials as fill, slope stability, geohazard susceptibility. Most appropriate site investigation techniques.
	Contaminated land specialists	Distribution of past land use and artificial deposits. Groundwater distribution and physical and chemical properties. Distribution and properties of natural geological materials. Pathways and potential receptors.
	Hydrogeologists	Distribution and properties of natural and artificial geological materials. Groundwater distribution and physical and chemical properties. Geological structure. Pathways.
	Environmental geologists	Distribution and properties of natural and artificial geological materials. Groundwater distribution and physical and chemical properties.
	Industrial and other mineral resource geologists	Distribution and properties of natural geological materials. Geological structure. Groundwater conditions. Distribution and quantities of industrial minerals.
Non-geological professionals	Developers	Potential geological

		constraints on development and building. Georisks
	Financiers	Potential geological constraints on development and building. Georisks.
	Architects	Geohazard susceptibility, foundation conditions, geological resources.
	Civil and structural engineers	Distribution and geotechnical and geochemical properties of natural and artificial geological materials. Groundwater conditions. Foundation conditions, excavatability, use of geological materials as fill, slope stability, geohazard susceptibility. Most appropriate site investigation techniques. Georisks.
	Surveyors	General geological conditions – distribution, properties and processes acting to change the *status quo.* Foundation conditions. Geohazard susceptibility, particularly in relation to ground movement and structural stability.
	Builders	Foundation conditions. Geohazard susceptibility, particularly in relation to ground movement and structural stability.
	Utility and transportation providers	General geological conditions – distribution, properties and processes acting to change the *status quo.* Groundwater distribution and physical and chemical properties. Pathways and potential receptors. Distribution and physical, mechanical and chemical properties of natural and artificial geological materials.
	Planners	Potential geological constraints on, and resources for, development and regeneration.

	Archaeologists	Distribution of past land use. Distribution superficial and artificial geological materials and groundwater. Geological processes acting and time-scales.
	Conservationists	General geology and ground conditions in relation to distribution, properties and processes acting to change the *status quo,* particularly in relation to important natural and human-made heritage.
	Building control officials	Geohazard susceptibility, foundation conditions, groundwater conditions.
	Environmental regulators	Distribution of past land use. Distribution superficial and artificial geological materials and groundwater. Geological and anthropogenic processes acting and time-scales.
	Health and safety regulators	Geohazards and georisks.
	Insurers	Geohazards and potential impact on insured elements.
	Lawyers	General geological conditions and how development and regeneration might be impacted. Detailed information on geological conditions, geohazards and georisks in specific cases.
	The media	Geological information not necessarily required other than as a background to 'the story.'
	Policy-makers and politicians (last but by no means the least important)	Understanding of why geological information and knowledge, particularly in the urban environment, is important to strategic development and decision-making.
General public	Geohazard victims (those who have experienced a geohazard first-hand)	Understanding of what has happened to them and how that may alter their lives in the

		future.
	Potential future geohazard victims	What may happen in the future and how vulnerability might be reduced.
	Non-victims	Knowledge of the impact of geology on decisions and actions that may affect them, particularly with regard to housing.

Marker (1996) suggested that if non-geo-professionals were to use geo-information more they needed to understand better why the geology should be taken into account and that regulations and guidance should require this. The needs of the geological professionals and some of the non-geological professionals are specified in national and international standards, regulations and guidance. For example, in the UK, planning guidance on land stability (Anon. 1990c, 1996c, 2002a), on flooding (Anon. 2006c), and on pollution control (Anon. 1994), which indicate, in general terms, the geological information required, are available to local authority planners; building regulations specify foundation requirements and the geological conditions that are relevant (Anon. 2004b); European standards specify site investigation and testing requirements (for example, Anon. 2002b, 2003c, 2004c). Similar guidance and standards are available in many other countries. However, the key issue is whether the information required is available and, if so, where it is available. Marker (*op. cit.*) also suggested that awareness of geological issues needed to be raised from school through to the continuing professional development stage.

Perhaps the two most important non-geological professional users are the media and politicians/policy-makers. With regard to the former, geologists and other scientists need training and advice from media specialists to be able to get their 'story' over adequately. In addition, Nield (2008) pointed out that the news media exist to entertain rather than educate, that education does not make good public relations and that the point of public relations is to generate "*warm feelings.*" He concluded that by understanding and accepting these principles contact with the media was likely to be more successful.

For the general public, information must be provided in a way that they can understand and that they can act upon (Karnawati *et al.* 2004). For other professionals with little or no formal training in geology, clear communication is similarly important. Problems of communicating with these two groups and guidance on how this is best done (and not done) have been provided by Liverman *et al.* (2008). One conclusion is that working out how to adequately communicate geological information and knowledge about the urban environment should involve a considerable amount of effort. In particular, to be effective it is necessary to:

- understand institutional and decision-making structures;
- disseminate as well as present;
- tailor outputs to audiences;
- use communication experts;
- work with social scientists.

GEO-INFORMATION FOR URBAN AREAS

Types of geo-information

Traditionally, geo-information for urban areas has been provided in two forms:

- spatial data, originally in two dimensions printed on paper but more recently in digital form in two and a half, three and four dimensions;
- databases (now digital) of point information now increasingly combined with the spatial models (for example, Culshaw 2005).

The principle sources of these data are:

- site investigation borehole and parameter data;
- mapping of bedrock, superficial and artificial deposits;
- mining records;
- past land-use records;
- well records and water extraction information;
- investigations of ground movement.

However, more effort needs to be expended in urban areas to collect these data and bring them together in properly managed databases.

While data have been available from site investigation for some time, increasingly, new and improved remote sensing and geophysical monitoring techniques are finding applications in the urban environment. These newly developing investigation methods include LIDAR (*LI*ght *D*etection *A*nd *R*anging), PSInSAR (*P*ermanent *S*catterer *In*terferometry *S*ingle *A*perture *R*adar) and electrical tomography. The techniques can be located on the ground, in the air or in space and some have the advantage that, once located, their data are accessed remotely and repeatedly. It is beyond the scope of this paper to discuss these techniques in detail but the literature contains many examples of what is possible. For example, Meisina (2008) discussed the use of PSInSAR to monitor ground movements caused by ground water pumping in towns in Northern Italy, while Culshaw *et al.* (2009b) described the use of the same system to observe ground movement related to abandoned mineworkings and Parcharidis *et al.* (2009) used it to monitor active faults in Patras and Pyrgos, Greece.

Schulz (2004) described the use of airborne LIDAR to map landslides in the Seattle area. He found that LIDAR was better than traditional aerial photograph and ground checking methods at identifying larger landslides with significant historical activity. Repeat ground-based LIDAR surveys have also been used to monitor changes in active landslides (for example, Hobbs *et al.* 2002).

There are many geophysical techniques that have application for monitoring in urban areas. For example, Ogilvy *et al. (*2009) discussed the use of an automated electrical resistivity tomography system for monitoring saline intrusion in southern Spain. Seismic monitoring has been used for decades to monitor natural earthquake activity and that associated with mining.

A further development is with regard to the availability of almost worldwide spatial data directly from the worldwide web. The information is usually available as both topographic maps and satellite images. Increasingly, ground-based images, at least along roads are also available, linked to the satellite images. In urban areas, this is a huge resource both for gathering information and presenting it. Geologists are already becoming familiar with linking their geological information to the topographic data available on the web and this is likely to be enhanced by the development of the OneGeology initiative (www.onegeology.org) which seeks to make a digital, surface geological map of the world available at a scale of 1:1 000 000 (Jackson 2009). In time, provided issues associated with the funding of the data collection can be resolved, larger scale maps, and of different types, are likely to become available.

Management of geo-information

The urban environment differs from most large-scale engineering sites, often located in remote and/or rural areas, in that usually there exists a legacy of geological information, mainly from past site investigations, water extraction or mining activities. The first difficulty is finding the information. That there is a considerable amount of it has been demonstrated by a number of thematic geological mapping projects for urban and semi-urban areas in the UK. For example, Barclay *et al.* (1990) reported that for an area of 150 km^2 around Castlefield, to the south east of Leeds in West Yorkshire, that is only semi-urban but has been extensively mined for coal, they were able to increase the number of records held by the British Geological Survey for boreholes, trial pits and shafts by around 250% (from 931 to 3267). Perhaps even more time-consuming is converting the data into a digital form that ensures compatibility between datasets and enables 3D digital modelling (Culshaw 2005, Kessler *et al.* 2009a). In the past, it would have been sufficient to simply record details of the location and source of each borehole log and plot the location on an index map. Now, to enable digital modelling of the data contained in the log, it must be digitised, including litho-stratigraphic boundaries and, if geotechnical data are to be incorporated into the model, they must be digitised too (Royse *et al.* 2009).

However, whilst collection and conversion of data are significant issues, the biggest challenge for those who wish to use the data in the urban environment is the long-term management of the data. There are several crucial questions that need to be addressed with regard to geo-information:

- Should the geo-information collected from hundreds or thousands of site investigations, water wells and mineral surveys be collected together?
- If so, should the information be collected and then updated at specific intervals or should the databases be continuously updated?
- Should the information simply be stored in its original form or digitised?
- Who should perform these tasks and how should they be funded?
- Is this process likely to be cost effective?

Really, these questions need to be answered in reverse. If it can be shown that the bringing together and storage of geo-information is cost effective then the other questions are, to some degree, secondary. It might be argued that the very existence of geological surveys in most countries around the world answers this question. Would the surveys have been set up if governments did not perceive that there was an overall benefit? However, these days, governments (and taxpayers) require stronger justification than that. A number of studies of the cost effectiveness of both geological maps and geological surveys have been carried out (for example, a geological survey: Anon. 2003d, geological maps: Bernknopf *et al.* 1993, Bhagwat & Ipe 2000, engineering geological maps: De Mulder 1988). All of these studies demonstrated the significant cost-effectiveness of the activity being analysed. While such an analysis for a full urban geology study has not been found (though De Mulder's study is similar), there seems little reason to doubt that the results would be very positive.

So, if it is likely that collecting and managing geo-information for an urban area is likely to be cost effective, what organisation should carry this out? Traditionally, geological and geotechnical data have been managed by either the city authorities or the national or regional geological survey.

Geological surveys as long-term geo-information managers?

Given that many geological surveys around the world have existed for over 100 years, these organisations would seem to be an obvious location for the long-term storage and management of subsurface data. As part of their geological mapping remit, a wide range of geo-information is acquired, particularly in urban areas. As well as details of the near-surface distribution of natural and artificial geological materials, information on quarries and mines, waste disposal sites, site investigations, wells, mineral investigation boreholes, geotechnical, hydrogeological, mineralogical and petrological properties of materials, and more, is likely to be collected. However, geological surveys are under pressure to evolve (that is, change and/or reduce in size). These pressures come not only from politicians, who may be looking for financial savings, particularly from state-funded organisations that have existed for some time, but, increasingly, from academics who regard some of the surveys' activities as 'non-scientific' and, perhaps, resent the funding that these organisations receive. Of course, pressure on geological surveys to 'finish' their activities is nothing new. In 1884, less than 50 years after the creation of the Geological Survey in Britain in 1835, an article in the 'Times' newspaper of 15 February, reprinted in Nature the next week, commented on the completion of the geological survey of England and Wales. Holmes (1884) discussed this article and noted that "*When the whole of England and Wales shall have been geologically surveyed on the six-inch scale,*" (1:10 560) "*and the result transferred to accurate one-inch"* (1:63 360) *"maps, the duties of the Geological Survey of that part of the United Kingdom will consist simply in keeping the maps up to date – but not until.*"

In the UK, the task is still not complete but geological mapping is a reducing activity. In the last twenty years, the time allocated to geological mapping has reduced from around 143 person years in 1990 to 22 person years in 2010. Of the 321 map sheets (at 1:50 000 or 1:63 360 scale) covering England and Wales, 21 are still only printed at the 1:63 360 scale (even though conversion began decades ago). 11 maps are currently under field survey, while surveying is complete for another 19 maps and they are being prepared for publication. This will probably take 1-3 years. A further 14 maps can be regarded as inadequate for user requirements and urgently need remapping. For 6 maps (mainly in remote rural areas) there is no detailed survey coverage at large scale, and previous surveys are earlier than 1860! Finally, there are 37 so-called 'provisional' map sheets - mainly desk study compilations – that are in need of proper survey. It can be argued therefore, that, ignoring the maps that have been remapped but are not yet published and those that are currently being remapped, 57 out of 321 map sheets are not fit-for-purpose, that is, nearly 18%. On top of this 16 map sheets covering major urban areas are in need of serious update to account for anthropogenic activity and there are questions about the adequacy of some of the mapping of superficial deposits.

The difficulty for the BGS and other long-standing geological surveys is that, originally, they were defined by their role of making geological maps (at a variety of scales). As that task, first defined in the 19th century, is perceived to be nearing completion the very existence of the surveys comes to be questioned. What is not understood adequately, by some of those who control the future of geological surveys, is that the real role (through monitoring and observation) is the collection, validation, storage, management, interpretation, modelling and dissemination of all types of geological information for the long-term, national benefit. Ideally, what surveys should carefully limit is competition with academics in the 'pure' research field and with the private sector in commercial consultancy. However, the reality is that they often do both. The 'quality' of the surveys' scientific activity is judged by various measures related to academic publication and surveys are pushed towards consultancy by the need to enhance income to cover the costs that are not met by central or regional government funding. Because of both pressures, there is a tendency towards 'short-termism' and an increasing reluctance to fund the long-term costs associated with information management.

However, many surveys have developed sophisticated and technologically advanced methods for managing geo-information (for example, Culshaw *et al.* 2006a). The new developments in three and four dimensional digital modelling open up new opportunities for the providers and, particularly, the users of urban geological information. The technology is not the problem. Rather, as Culshaw *et al.* (*op. cit.*) pointed out, "*Unless taxpayers, through their governments, are willing to pay the increased costs of digitisation and digital data management, the era of public bodies, such as geological surveys, freely providing access to geological information will pass completely.*" If this happens, it will mean that the vision of a long term database of urban geo-information will not be realised unless the city authorities or private sector data companies take on the task.

City authorities as long-term geo-information managers?

Although most local authorities collect data of some sort, it is not one of their main activities. Consequently, when geo-information has been collected it may be because of the initiative of an individual or because a particular department sees a need. Where databases of geo-information have been created for cities they have not been sustained in the longer-term. The situation in Canada is a salutary example.

The Science Council of Canada carried out a review of geology in Canada in 1971 (Blais *et al.* 1971). One of the chapters was concerned with engineering geology and the physical environment. In its conclusions it made two key recommendations: that detailed (1:50 000 scale or larger) geological mapping of urban areas should be carried out with a focus on superficial deposits, landforms and hydrogeological data and that each major city should have at least one geotechnical engineer who would be responsible for the collection of geo-information from available sources and its use for urban planning and construction. These recommendations were later repeated by Legget (1973) in his book on urban geology. As a result of the review, the Geological Survey of Canada (GSC) took advantage of some short term government funding to begin and urban geology programme (Scott 1998). This included the assemblage of geological and geotechnical data for each of 27 Canadian cities in a series of (non-digital) databases. Unfortunately, while the value of the databases was recognised by the city authorities' officials who were "...*willing to accept the data banks...*" the cities would not commit to financing their maintenance and development (Scott *op. cit.*). The GSC urban geology programme continued until the 1978 when, in the absence of sufficient interest and support from the cities, it was closed down. Most of the original databases became defunct, though in nine of the cities the databases have been digitised and, in a few cases adapted for use in a GIS (Karrow & White 1998c). In the UK, a similar geological and geotechnical database on microfiche, created as part of an urban geology mapping project for the cities of Newcastle-upon-Tyne and Sunderland (Strachan & Dearman 1982, Dearman *et al.* 1977), became essentially defunct with the closure of the geology departments at the two cities' universities. However, despite difficulties arising from having geotechnical personnel based in three departments, Glasgow City Council has developed a digital geological and geotechnical database system that is used regularly (Mellon & Frize 2009).

The conclusion from these limited examples is that most city authorities do not have the resources or the enthusiasm (perhaps because of a lack of understanding of the importance od geo-information) to build, maintain and develop geological and geotechnical databases that underpin the use of geological knowledge in urban areas.

Private companies as long-term geo-information managers?
Increasingly, publicly-acquired information is being used by private companies to develop and sell services based on it. This includes geological information. In the UK, such information is used in relation to property transactions, for example, with regard to geohazards that might impact on a property. The companies involved have licensed the geological information and then packaged it together with other data sets relating to property to provide a service that is often used by potential property buyers.

In urban areas, which are rich in subsurface information, it is possible that such information companies might be interested in acquiring and marketing geo-information that could be used for urban development, conservation and regeneration. However, they would be only willing to do this if they were convinced that there was a profitable market. Further, these companies do not usually collect new data. Rather, they obtain the data from organisations that may have this as part of their role – usually public bodies such as geological surveys and local authorities.

For such private companies, there is no guarantee that they will continue to operate and maintain their databases in the long-term. Whilst it is true that public bodies may cease some (or all) of their data acquisition activities, it is unlikely that they will cease to maintain the databases that they have already, even if they do not add to them. Consequently, it is unlikely that private companies will be suitable for managing databases of urban geo-information for the foreseeable future.

FUTURES

New applications

The many publications mentioned above must have covered many tens of themes. It is hard to imagine, therefore, that there are any themes relevant to the urban environment for which an example has not been developed. However, as society changes, it is not surprising that some new applications of geological information are required. Three of these, covering sustainable urban drainage, utility maintenance and archaeological assessment are discussed briefly.

Sustainable drainage systems - Manchester
Sustainable drainage systems (SuDS) are an alternative to conventional drainage systems that seek to replicate natural drainage and deal with surface-water run-off through re-use, storage and infiltration to the ground. The design depends on local factors, including the geology, and relies on attenuation, treatment and infiltration techniques to deal with the run-off (Anon. 2001c). Hough *et al.* (2006) described how a three dimensional geological model could be used, together with information on slope angle (from a digital terrain model), transmissivity of the near-surface deposits and thickness of the unsaturated zone (from data on first water strikes in boreholes), to identify areas more suitable for disposal of water by infiltration. Constraints such as surface sealing and potential for contamination can be incorporated into the model. A three dimensional, spatial, geological model of central Manchester and Salford (Fig. 1) was developed (Culshaw 2005) and used to assess a trial area. Susceptibility polygons were based on actual land use, rather than being regular in shape (Fig. 11). This allowed the grouping together of areas with similar surface sealing capacity.

Dearden (2010) described the development of a GIS-based decision-support tool, utilising geological information, that enables drainage designers to determine whether a site might be suitable for infiltration to the ground. The tool identifies whether the ground is permeable enough, whether the flow is in superficial deposits or bedrock, whether groundwater quality is likely to be affected, the nature and thickness of the unsaturated zone and whether potential geohazards might be present that could be triggered by infiltration. These factors are scored and the suitability of a site is determined by the least favourable condition.

Utility maintenance - Knowsley, Liverpool

Knowsley is located on the north-eastern outskirts of Liverpool in north-west England (Fig. 1). An industrial site was constructed in the early 1960s on a former munitions factory site. There is little topography and the site is underlain by a major Triassic aquifer (the Sherwood Sandstone Group) which, in turn, is overlain by Quaternary glacial till, Holocene alluvium and peat and Anthropocene artificial deposits. The till varied in thickness from 0-11 m. Utilities beneath the site consisted of a network of foul, surface water and combined sewers and were in poor condition and in need of maintenance. A three dimensional, digital, geological model of the site was created and the utility network was incorporated into the model (Price *et al.* 2008b).

The aim of the study was to develop and apply the three dimensional model to a qualitative assessment of the vulnerability of the underlying aquifer to potential pollution from the sewer system. Each of the geological units overlying the Sherwood Sandstone was classified in terms of its permeability. Weakly permeable superficial deposits (only the glacial till) beneath the site could provide a barrier to potential pollution of groundwater in the aquifer. Those utilities overlying less than 2.5 m of till were interpreted to represent the most vulnerable parts of the underlying aquifer. The greatest relative vulnerability to the aquifer occurred in the south and south-west of the project area (Fig. 12). This approach enabled the development of a hazard identification and prioritisation scheme for future improvements to the buried sewerage network.

In this example, the user is not the city authorities but a private utility company and the national environmental regulator, the former having responsibility for maintenance of the sewer network and the latter ensuring that major aquifers are protected from pollution. The methodology could easily be utilised for other buried utilities, provided information about the spatial location of the utility is available.

Archaeological assessment

The shallow subsurface beneath towns and cities often includes the physical evidence of settlement and development that has taken place over millennia. The material left behind as a result of this activity includes archaeological heritage deposits as well as those associated with industrial activity, wastes and contaminated land. So significant is human impact on the landscape that many authors have proposed that people are a geological and geomorphological agent (Sherlock 1922, Douglas & Lawson 2001, Price *et al*. 2011). In heritage cities such as York, north-east England (Fig. 1), ground conditions reflect urban development since the Roman period. In places, an artificial ground ‘stratigraphy’ has developed up to 10 m thick. The integration of 3D geological and archaeological deposits models in urban environments provides a way of characterising the shallow zone of human interaction (De Beer *et al*. 2010, Price *et al*. 2010). The interaction of geological and anthropogenic processes is a significant factor in Quaternary landscape evolution and has left its imprint as excavations or constructional landforms above and below the ground (artificial ground) (Price et al. 2004, Ford *et al*. 2006, Price et al. 2011).

Integration of combined three dimensional, geological and archaeological deposits models with groundwater models is being used to develop risk-based models of the resilience of *in situ* archaeological deposits to decay or destruction from development activities and changes in moisture content (De Beer *et al*. 2010, Holden *et al*. 2009). Human interaction with the subsurface and its resources is by no means exclusively an urban process. However, urban areas represent a focus for population settlement, growth and resource use and processing that is unrivalled in rural or peri-urban areas. Engineering and geological characterisation of this historical activity and its integration with future forecasts of environmental (including land-use) change will enable modelling of the future response of the subsurface to human interaction.

Environmental multidisciplinarity – geology's contribution

Geology is but one of the environmental sciences. For land-use planners, developers and others working in the urban environment, all aspects of the environment are likely to be of relevance. Sometimes, geology has greater importance, for example when an unanticipated landslide occurs. However, once the effects of the landslide have been dealt with, other environmental issues may become more important. This apparent willingness to simply react to events, rather than anticipate them, together with the realisation that there are a wide range of environmental issues that impact on the urban environment led to the development of a new research programme in the UK called URGENT (Urban Regeneration and Environment). The programme cost nearly £10m and was one of the most ambitious in Europe at the time (1997 to 2005); it focussed on four main science themes: air, water, soil and ecology (Leeks *et al.* 2006). One of the research projects was intended to cover all the themes and provide a decision support system for land use planners in local authorities (Culshaw *et al.* 2006b).

The environmental information system for planners (EISP) was designed to support three main planning functions:

- pre-planning enquiries;
- development control decisions;
- strategic planning.

The system included information on eleven key environmental issues:

- air quality;
- ground instability – shallow undermining;
- ground instability - landslide susceptibility;
- groundwater protection;
- flood risk;
- drainage;
- land contamination;
- landfill;
- biodiversity;
- natural heritage designation;
- human-made heritage (including archaeology).

The environmental issue of noise was not included in the system.

The system was designed by creating a digital logical flow diagram for each of the eleven environmental issues. These were structured to follow the legislation, guidance and procedures that planners are required to use in the UK, by means of a series of questions. These were answered by reference to an environmental data set or model. An example of part of one of these flow diagrams (for proximity to landfill) is shown in Figure 13. The flow diagrams were integrated using standard web technologies and, consequently, the system can be accessed from almost anywhere (with appropriate permissions). The system provides text aids showing regulations, standards etc. The operation of the system is underpinned by a GIS that includes information and models relevant to each of the themes. The user enters the system, defines the site of interest and can then follow the flow diagrams that are relevant. The output is a 'report' on the relevant environmental issues and with recommendations as to whether, for example, a planning application should be accepted or rejected on environmental grounds. If rejection is recommended, the system provides a summary of the reasons. The EISP provides support to the planner in making a decision, rather than making that decision.

There were geological inputs to five of the eleven modules – the two on ground instability, groundwater protection, drainage and land contamination. The system is being expanded to include additional ground stability modules in relation, for example, to swelling and shrinking soils and karst hazards.

What development of the system showed was that land-use planners have to deal with a wide range of environmental issues, not just geological ones. The planners need information that covers all the environmental issues and it is easier if that information is integrated into a single system rather than being provided in varied formats for each of them.

Complete multidisciplinary – sustainability - geology's place

With the rapid development of methodologies briefly described above, urban geology will eventually reach another point at which further development slows. However, it is also becoming clear that the provision of information to users solely concerned with the geology is not enough. First, with regard to the environment, users are interested in far more than geology alone. Second, the development of cities is dependant not only on the environment but also on social and cultural interactions, economic change and political drivers. Planning the future of our cities requires interaction between all those involved in the process, including those who live there. Some recent research entitled 'Urban Futures' is looking at how sustainable urban development and regeneration decisions are likely to be. As this depends on how cities, themselves, develop in the future, various decisions are being tested against four future city scenarios (from the project website at http://www.urban-futures.org/overview.htm):

- "*Policy Reform: strong government action achieves social equity and environmental protection.*
- "*Market Forces: competitive, open and integrated global markets drive world development.*
- "*Fortress World: in protected enclaves elites safeguard their privilege by controlling an impoverished majority and managing critical natural resources.*
- "*New Sustainability Paradigm: a more humane and equitable global civilization.*"

Eight topics are being looked at to see how sustainable they will be under the four scenarios:

- Biodiversity
- Air quality
- Water and waste
- Subsurface built environment, infrastructure and utility service
- Surface built environment and open spaces
- Density and design decision-making
- Organisational behaviour and innovation
- Social needs, aspirations and planning policy.

Geology is only relevant to the third and fourth of these topics and yet is fundamental to the overall way in which physical development takes place (Hunt *et al.* 2009, 2010). In the future, it will be necessary for urban geological knowledge to be integrated within this broader framework in trying to understand the consequences of different developmental and regenerational decisions.

With this in mind, Kessler *et al.* (2009b) have developed the concept of the environmental modelling platform. The intention is to "... *provide access to data and knowledge as well as geospatial, conceptual and numerical models through a subsurface management system akin to Geographic Information Systems in use today.*" The vision is to "*provide the data standards and applications seamlessly to link data models concepts and numerical simulations concerned with the surface and subsurface.*" It is also intended that the models can be linked to socio-economic, and other, models, for example, on population change or commodity prices. This vision fits well with the objectives of the Urban Futures research.

Internationalism

The interest in urban geology in the 1980s and 90s, particularly in Asia, contributed to the formation of the International Working Group on Urban Geology (IWGUG) in 1993 (De Mulder 1994, De Mulder *et al.* 2001). The Group was set up under the auspices of the International Union of Geological Sciences Commission on Geological Sciences for Environmental Planning (COGEOENVIRONMENT), the IAEG and the International Association of Hydrogeologists (IAH). The objectives of the Group were to improve communication between disciplines working on cities (as well as between urban geologists), to raise awareness of the importance of geo-information to urban development, to initiate and support research and to disseminate its findings, to 'represent' urban geology internationally and to arrange multidisciplinary training for urban specialists. The IWGUG completed its activity in 2008/9. This means that urban geology no longer has a specific international focus, even though in some countries, for example, China, there is much active research. Similarly, while many geological surveys have sections devoted to urban geological activities, umbrella organisations such as EuroGeoSurveys are now more focussed on geological resources (energy, soil, minerals, water) rather than the relationship between geology and the environment.

It is hard to know why this decline in interest in the importance of geology in the urban environment has taken place. Possibly, it is as a result of the increased perception that geological resources, particularly with regard to oil and gas, are both affecting climate and in decline. Perhaps it is inevitable that, after a 'burst' of urban geological research, a period of reflection will follow – we may have to wait while the users of the research and related information utilise them and comment back. Or maybe, engineering geologists have failed to adequately demonstrate and communicate the importance of geology to urban development, conservation and regeneration. Whatever the reason for the current diminished enthusiasm for urban geology, it is unfortunate because the rapid development of easy-to-use software for three and four dimensional geological modelling and attribution has particular application in urban areas. These models are revolutionising our ability to visualise, understand and predict geological conditions and processes beneath our cities. Now is not the time to move on to other topics.

DISCUSSION AND CONCLUSIONS

The future of urban geology is uncertain. Over the last 200 years, geologists have shown how knowledge and understanding of the ground beneath cities and the geological processes acting upon it can be applied to a very wide range of problems that those charged with developing, regenerating and conserving urban areas have to solve. A vast array of different map types has been developed for cities around the world, though particularly in Europe, eastern Asia and North America.

As new technologies such as relational databases, GIS and three dimensional digital modelling have been developed, these have been adapted to enhance the geologists' outputs. Recent developments in four dimensional modelling, particularly with regard to groundwater, are being applied in urban areas.

Similarly, with the development of digital means to collect, store and manage large quantities of spatial data, geological surveys, in particular, have started to accumulate and process increasing amounts of geo-information from urban areas. Finding this information is not the problem; digitising and managing the information present much greater issues, particularly in terms of cost. For urban areas, it is essential that the information is collected and processed on a continuous basis, with the resulting models updated regularly too. This is a task that is almost certainly beyond the means and vision of most city authorities who are subject to the pressures resulting from the relatively short electoral cycle and the consequent short-term pressure to constrain costs. Similarly, private companies that specialise in the provision of information and information products do not see enough profit in collecting new data themselves, rather than disseminating that collected by others. That leaves only geological surveys as the long-term custodians of our geo-information heritage. Yet, they, too, are becoming increasingly pressured both to produce more 'academic' science outputs and reduce their costs or increase their income.

A further problem is that while the science of urban geology has developed considerably, it can be argued that engineering geologists have been less successful at convincing city managers that geo-information and knowledge is important enough for the city authorities to invest long-term in supporting the maintenance of the knowledge base. Clearly, better and sustained communication is needed; this probably requires much greater demonstration of the benefits of urban geology both in terms of cost and more sustainable development. However, this communication should be not only with the city authorities and the wide range of other direct users of the knowledge base in urban areas but also with the policy-makers and politicians who, ultimately, determine whether urban geology is important enough to support.

More specifically, there are a number of actions that those geologists working in urban areas need to address.

Geo-information providers (including national geological surveys) need to:

1. Gather and digitise urban data, particularly:
    - borehole and parameter data, hence building the database;
    - mapping of artificial deposits;
    - abandoned mineworkings;
    - past land use;
    - shallow groundwater;
    - ground movement.
2. Create 3D-4D models of the shallow subsurface and attribute these models with relevant parameter data – linking the databases to the model.
3. Give an indication of the uncertainty associated with the models and explain what it means.
4. Engage in two-way discussions with the wide range of potential users.
5. Provide interpreted outputs of spatial information in exactly the form required by the users and indicate the limitations.
6. Carry out cost-benefit studies to demonstrate the value of urban geo-information.

7. Integrate physically-based 3D ground models with process and socio-economic models to assess the vulnerability/resilience of the urban subsurface to future environmental change.

Researchers need to:

1. Develop the generic methodologies and techniques to visualise and explain 4D change and uncertainty.
2. Provide the understanding of the processes that bring about these changes.
3. Research and develop new technologies for monitoring the urban environment such as LIDAR, PSInSAR and geophysical systems.

Consultants need to:

1. Carry out more thorough desk studies, particularly developing and using three dimensional spatial, digital models.
2. Move from current site investigation methodologies, which tend to be necessarily prescriptive based more on current guidelines and standards, to ones based on testing the geological model. This will require a new culture for site investigation, with the development of new standards and the modification of old ones.

All geologists working in the urban environment need to:

1. Learn how to better communicate with the wide range of users of geo-information. This should involve professional communication experts.
2. Seek to persuade the policy-makers and politicians who, ultimately, control spending on geo-information in our cities, that continuing to do so is cost effective and environmentally beneficial.

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FIGURES

dimensional geological model for Glasgow, UK. Grid lines are orientated north-south and east west and are 5 km apart.

Figure 8. Three dimensional geological model of Quaternary deposits in eastern Glasgow, UK, attributed in terms of plasticity. (Not to scale. The model is orientated with north to the left and south to the right).

Figure 9. 3D Model of the anthropogenic deposits in Warrington, UK. (Scale as indicated by the 1 km grid on the base map; grid lines are orientated north-south, with north to the top left) [OS topography © Crown Copyright. All rights reserved. BGS 100017897/2010].

Figure 10. 3D geological model of the Lower Lea Valley, Stratford, east London, UK (site of the 2012 Olympics) with automatically generated geological and engineering geological cross-sections through the middle of the Lower Lea Valley. (Not to scale; north is approximately at the top left of the 3D model). OS Topography © Crown Copyright. All rights reserved. 100017897/2008s. (After Royse *et al.* 2009)

Figure 11. Map of suitability for sustainable urban drainage systems (SUDS) in central Manchester and Salford, UK. Red = unsuitable; yellow = potentially suitable; green = suitable. The grid ticks are orientated north-south and east west and are 5 km apart. (After Culshaw 2005).

Figure 12. Sewer locations relative to till thickness beneath them in Knowsley, Liverpool, UK. The grid lines are orientated north-south and east west and are 1 km apart. Utilities locations published with permission of United Utilities. OS topography © Crown Copyright. All rights reserved. 100017897/2008. (After Price *et al.* 2008b).

Figure 13. Part of a logical flow diagram (for 'Proximity to landfill') in the Environmental Information System for Planners (EISP). (After Culshaw *et al.* 2006b).

FIGURES

Figure 1. UK location map. Not to scale.

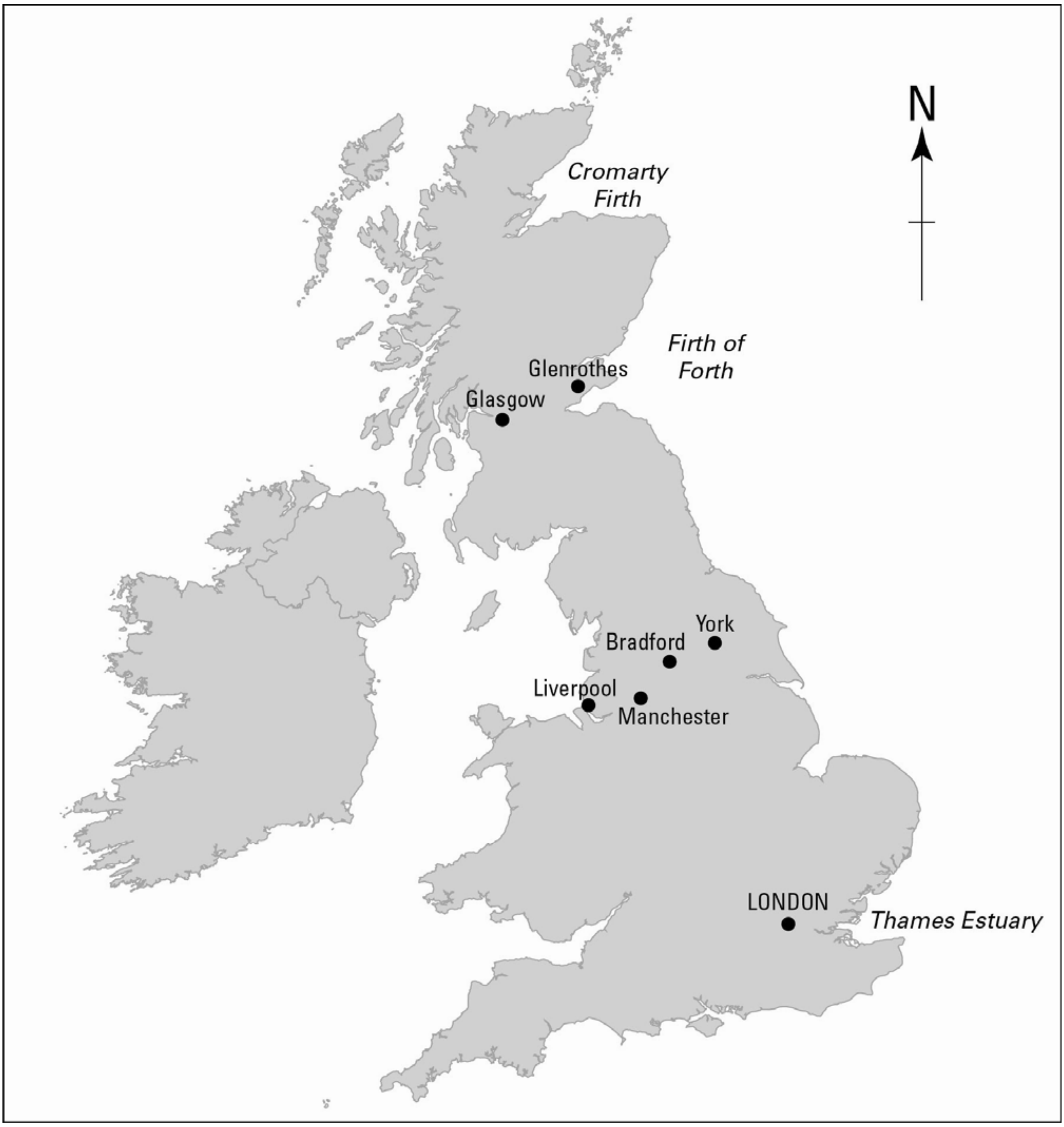


Figure 2a. Part of a profile map of Alluvium in south-east Essex, UK. The grid lines are orientated north-south and east-west and are 1 km apart. (After Anon. 1977).

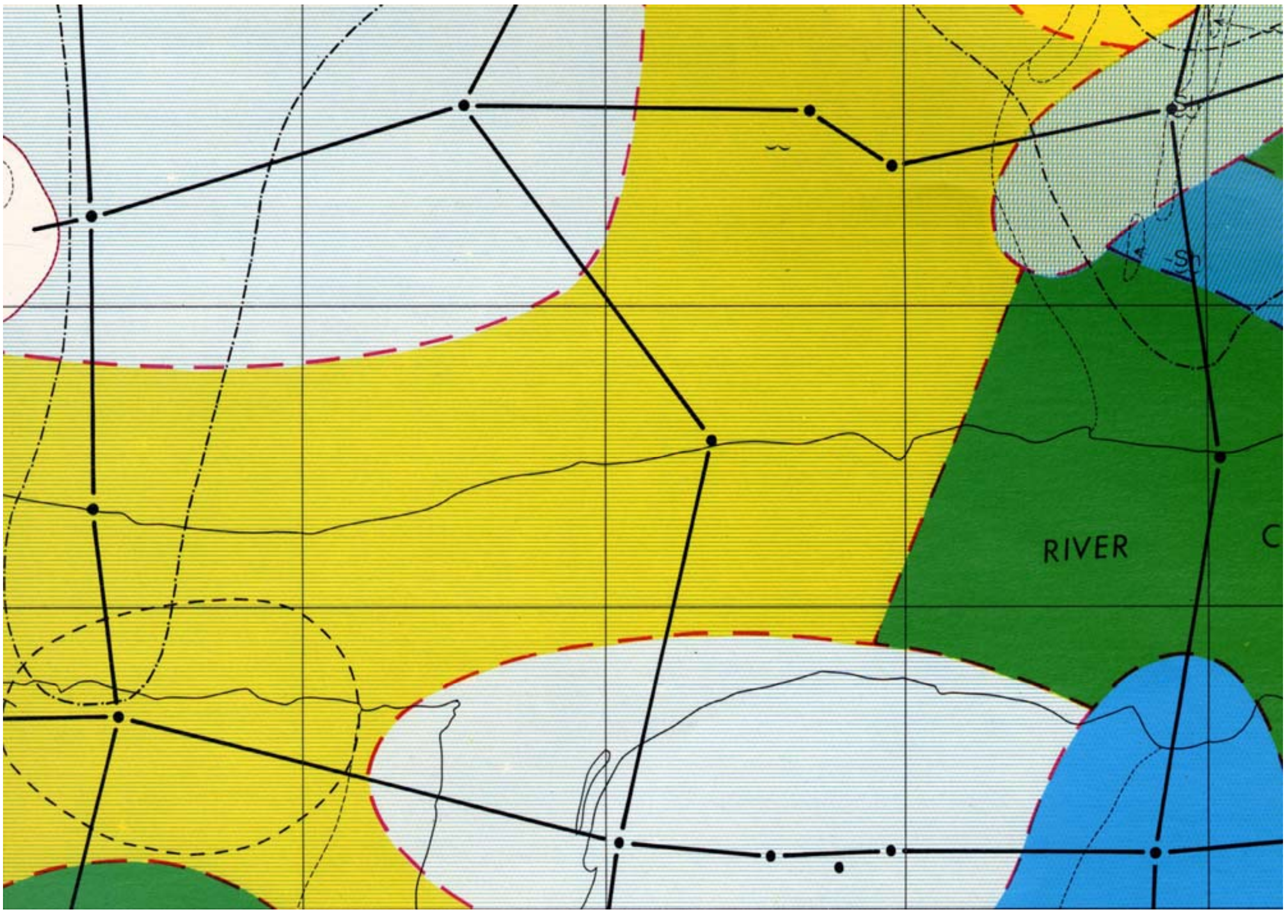


Figure 2b. Key for a profile map of Alluvium in south-east Essex, UK. (After Anon. 1977).

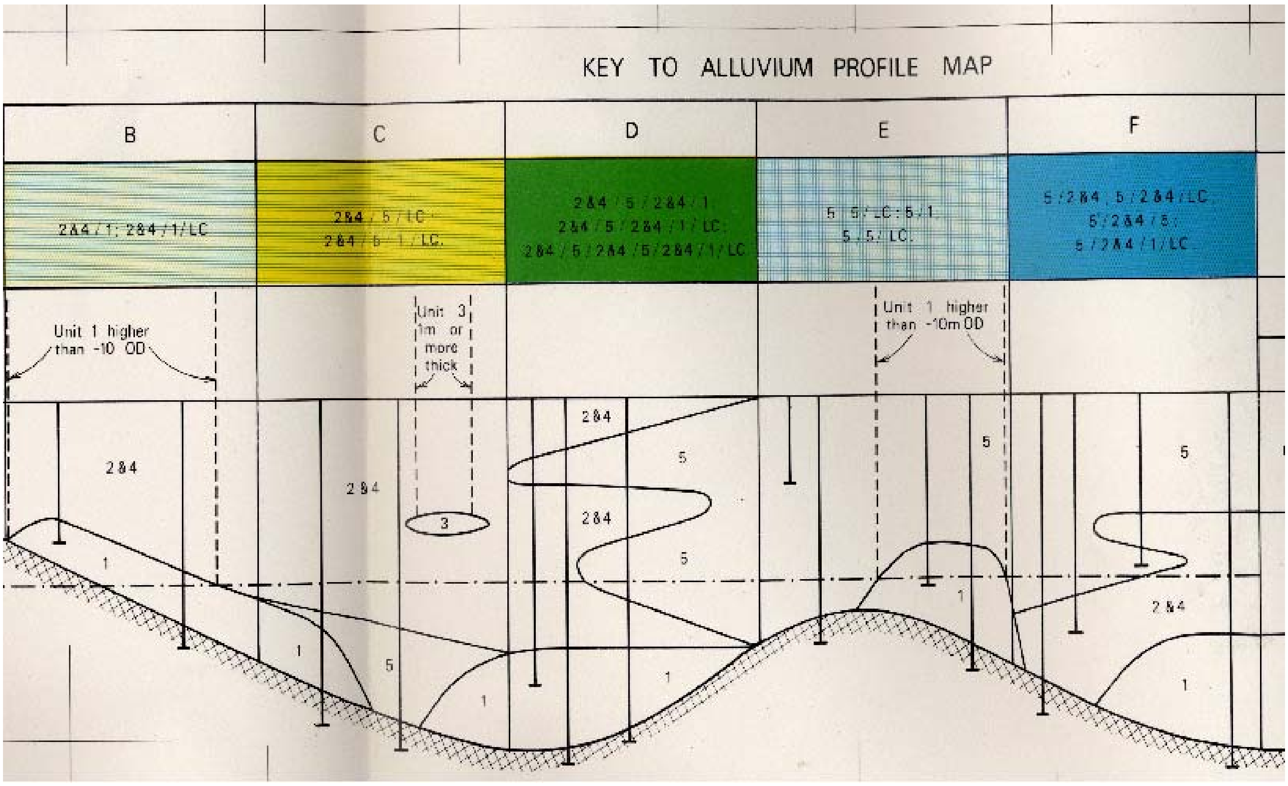


Figure 3a. Extract from the geotechnical planning map of the upper Forth Estuary, Scotland, UK, for heavy structures. The grid lines are orientated north-south and east-west and are 1 km apart. (After Gostelow & Browne 1986).

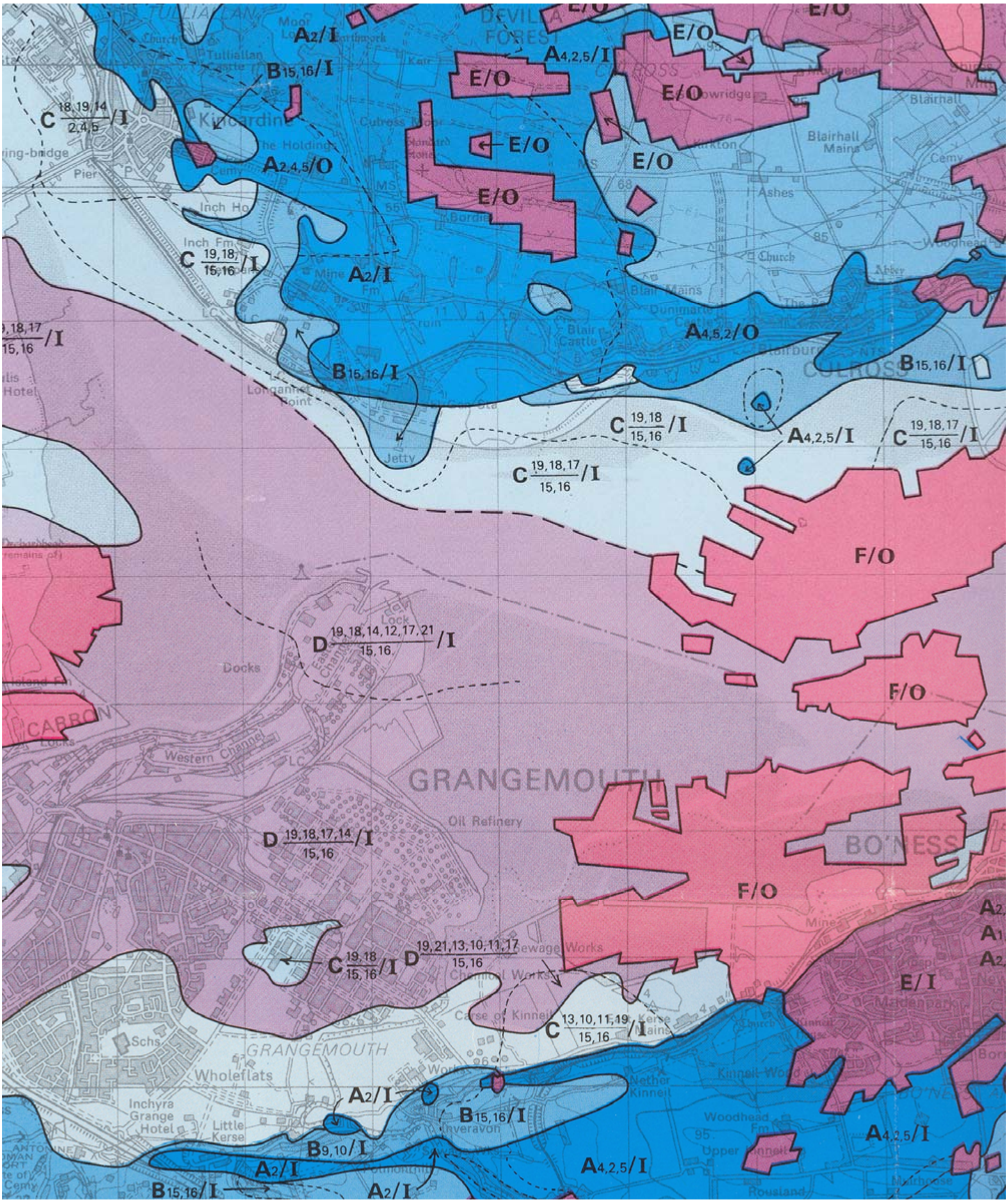


Figure 3b. Key to the geotechnical planning map of the upper Forth Estuary, Scotland, UK, for heavy structures. (After Gostelow & Browne 1986).

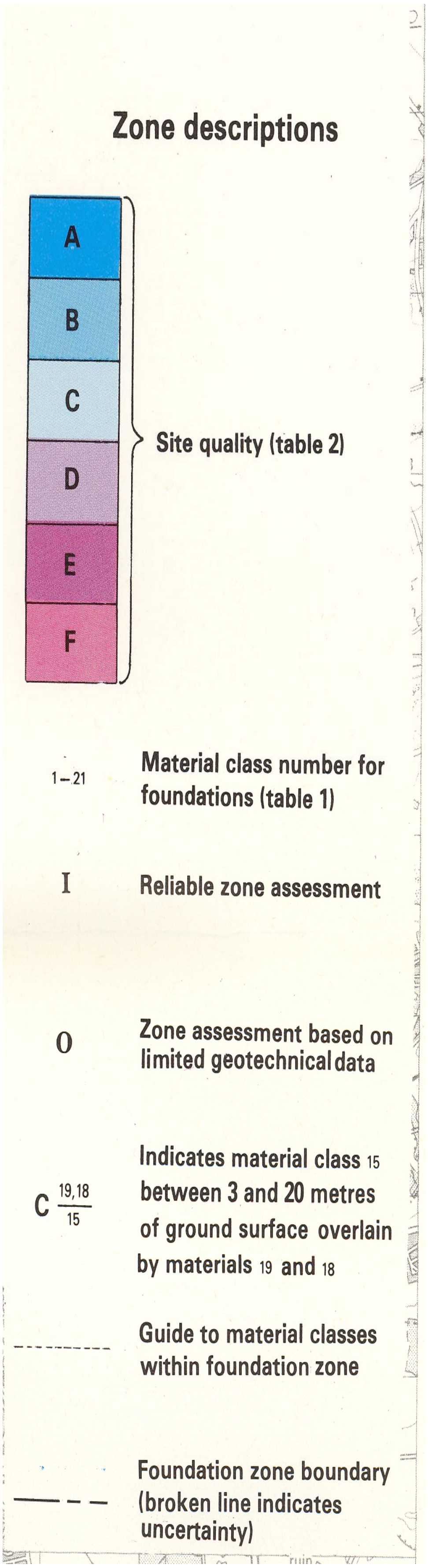


Figure 3c. Ground classification scheme for heavy structures for the geotechnical planning map of the upper Forth Estuary, Scotland, UK. (After Gostelow & Browne 1986). See Figure 3d for definitions of Groups and Classes.

GROUND CLASSIFICATION FOR PLANNING HEAVY FOUNDATION SITES	NORMAL FOUNDATION TYPE	MATERIAL GROUP AND CLASSES	SITE INVESTIGATION/ TESTING REQUIREMENTS	PRESUMED BEARING VALUE
A – Very good	Shallow	Group I, class 1-8, within 3 m of ground surface	Rotary cored boring; estimated RQD (rock quality designation) from logs. *In-situ* plate loading tests for very heavy structures. Point load testing on rock core.	600 – 10 000 kPa
B - Good	Shallow and ground improvement for low presumed bearing values	Group II, classes 9-10, 12, 13. Group III classes 15 & 16 within 3 m of the ground surface (with reliability of I, not underlain by soft or loose sediments)	Light cable percussion boring; undisturbed drive samples or SPTs (Standard Penetration Tests). Laboratory tests to include undrained triaxial and oedometer. Dutch cone soundings in granular deposits.	200 – 600 kPa
C - Fair	Deep/intermediate	Bearing stratum of A and B groups for driven piles between 3 and 20 m of the ground surface (with a reliability of I, not underlain by soft or loose sediments)	Light cable percussion boring through overburden with drive and piston samples. Dutch cone soundings where appropriate. Laboratory tests to include undrained triaxial, oedometer, index properties. Rotary coring to prove the condition of bearing stratum.	200 – 10 000 kPa
D - Poor	Deep/intermediate	Bearing stratum A and B groups greater than 20 m. Structures often requiring friction piles, or buoyant foundations	Light cable percussion boring with drive and piston samples. Dutch cone soundings. Laboratory tests to include undrained triaxial, oedometer, index properties.	75 – 200 kPa
E – Unpredictable (very poor to very good)	Shallow and ground improvement	Assessment zone material A and B within 3 m of ground surface, with shallow mine workings (longwall or stoop and room) within 20 m of foundation level	Geophysical techniques, rotary cored boring, careful examination of mine plans and relevant maps for cavities. RQD evaluation, point load testing on rock core. Plate bearing tests for very heavy structures. Consideration of ground improvement schemes.	Less than 200 kPa but assessed after inspection; check data reliability; possibly better ground than B in parts
F – Unpredictable (very poor to fair)	Deep/intermediate and ground improvement	Assessment zone material A and B greater than 3 m from ground surface, underlain by mine workings (longwall or stoop and room) within 20 m of foundation level. Landslipped areas	Geophysical techniques where appropriate. Light cable percussion boring, rotary boring. Dutch cone soundings. Examination of mine plans and relevant geological maps. Laboratory tests to include undrained triaxial, oedometer. Consideration of ground improvement schemes.	Less than 200 kPa but assessed after inspection; check data reliability; possibly better than D and E in parts
(E and F zones, I = very poor)				

Figure 3d. Presumed bearing values under vertical loading for the geotechnical planning map for heavy structures of the upper Forth Estuary, Scotland, UK. (After Anon. 1972, Gostelow & Browne 1986).

GROUP	CLASS	TYPES OF ROCKS AND SOILS	PRESUMED BEARING VALUE kPa	PRESUMED BEARING VALUE kgf/cm^2 or ton/ft^2	REMARKS
I Rocks	1	Hard igneous and gneissic rock in sound condition	10 000	100	These values are based on the assumption that the foundations are carried down to unweathered rock
	2	Hard limestone and hard sandstone	4 000	40	
	3	Schist and slate	3 000	30	
	4	Hard shale, hard mudstone and soft sandstone	2 000	20	
	5	Soft shale	600 to 1 000	6 to 10	
	6	Hard sound chalk, soft limestone	600	6	
	7	Thinly bedded limestone, sandstone, shale	To be assessed after inspection		
	8	Heavily shattered rock			
II Non-cohesive soils	9	Compact gravel or compact sand and gravel	> 600	> 6	Width of foundation (B) not less than 1 m. Groundwater level assumed to be at a depth not less than B below the base of the foundation
	10	Medium dense gravel, or medium dense sand and gravel	200 to 600	2 to 6	
	11	Loose gravel, or loose sand and gravel	< 200	< 2	
	12	Compact sand	> 300	> 3	
	13	Medium dense sand	100 to 300	1 to 3	
	14	Loose sand	< 100	< 1	
III Cohesive soils	15	Very stiff boulder clay and hard clay	300 to 600	3 to 6	Group III is susceptible to long term consolidation settlement
	16	Stiff clay	150 to 300	1.5 to 3	
	17	Firm clay	75 to 150	0.75 to 1.5	
	18	Soft clay and silt	> 75	>0.75	
	19	Very soft clay and silt	Not applicable		
IV	20	Peat and organic soil	Not applicable		
V	21	Made ground or fill	Not applicable		

Figure 4a. Map of geological factors relevant to planning and development in Bradford, West Yorkshire, UK. (After Waters *et al*. 1996). The grid lines are orientated north-south and east-west and are 5 km apart.

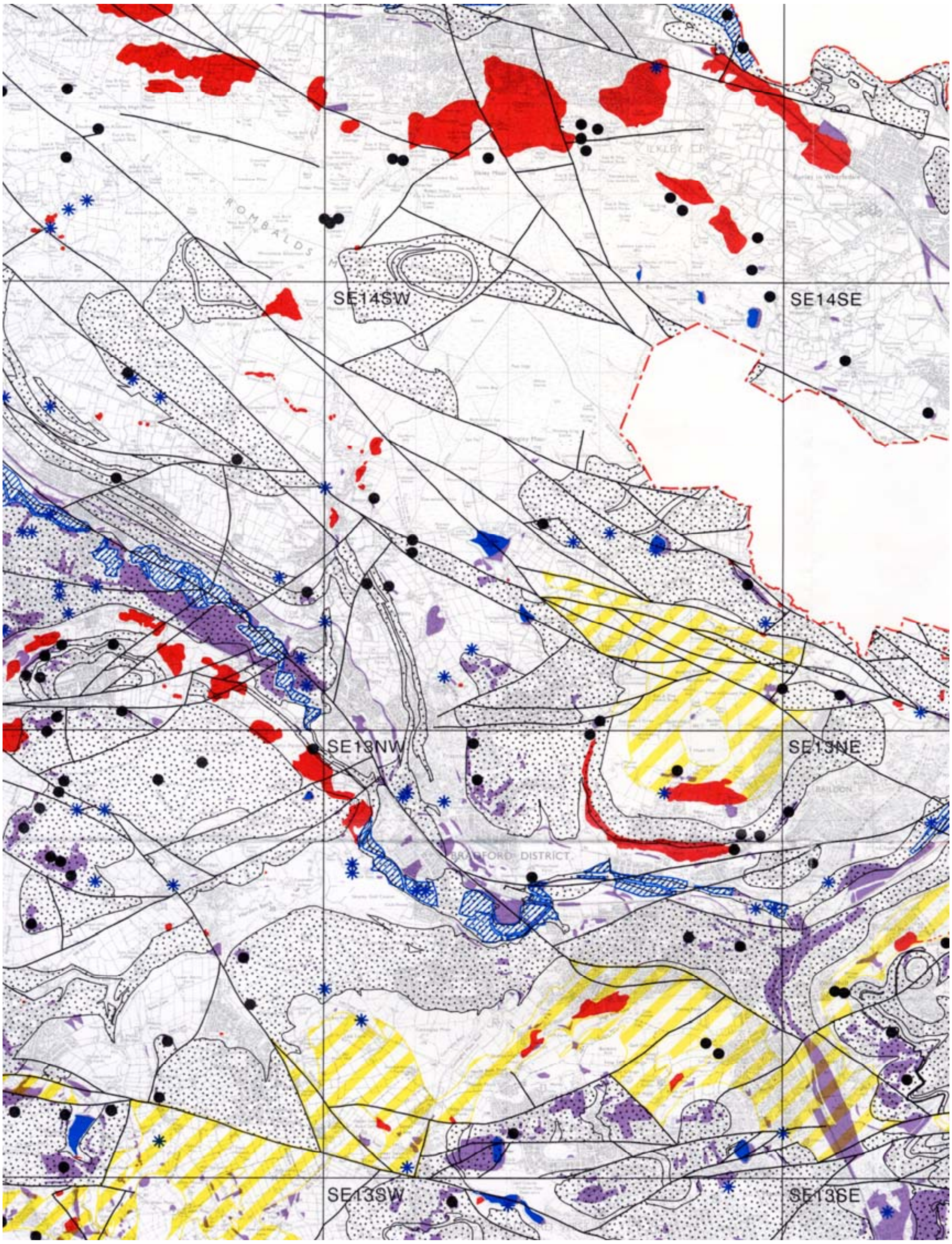


Figure 4b. Key to the map of geological factors relevant to planning and development in Bradford, West Yorkshire, UK. (After Waters *et al*. 1996).

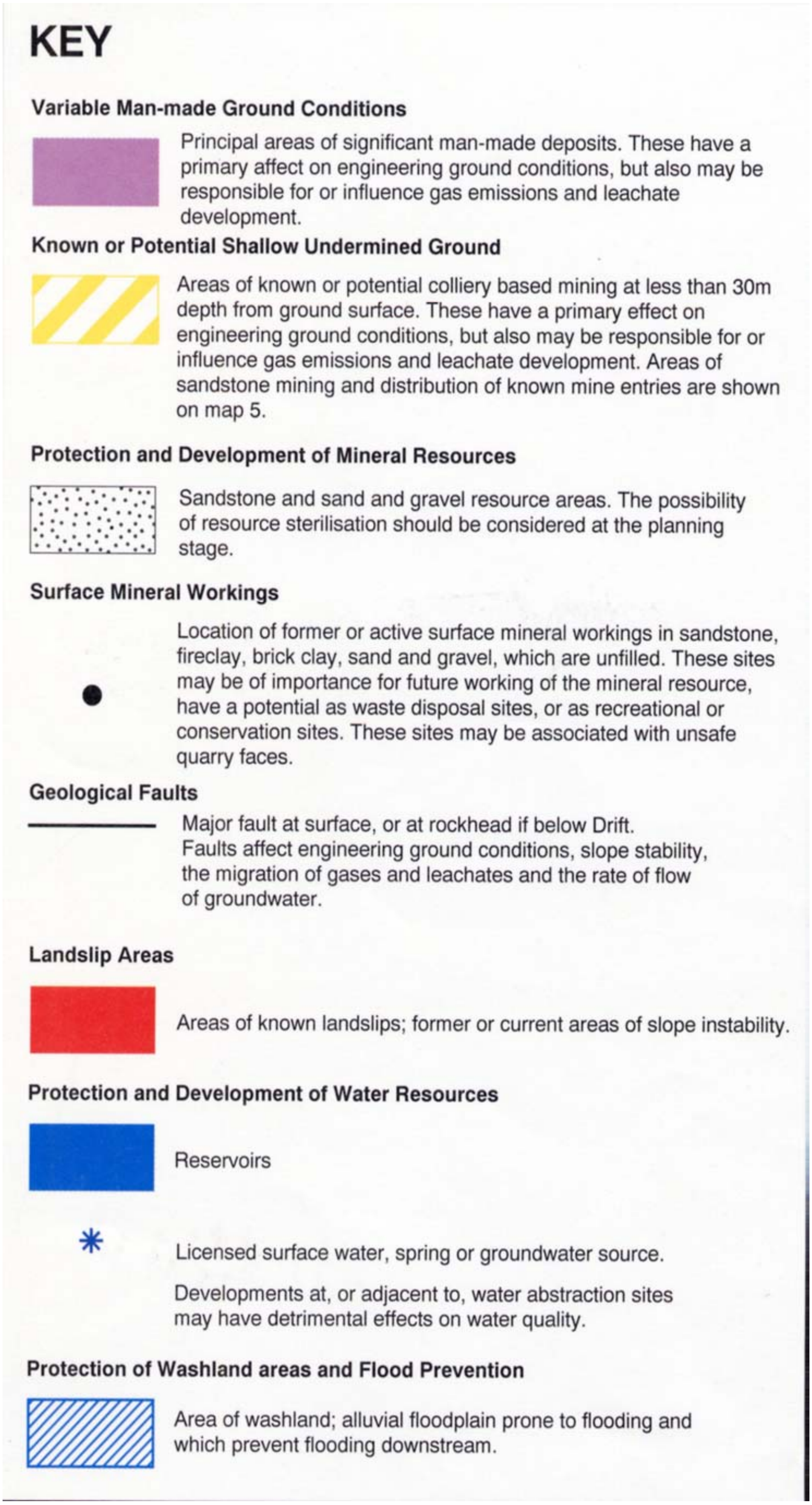


Figure 5a. Key to the map of engineering ground conditions of the bedrock and superficial deposits: foundation conditions for Bradford, West Yorkshire, UK. (After Waters *et al*. 1996).

Foundation conditions	Geological units *[Refer to Maps 2 & 3]*	Lithological characteristics	Comments	Recommendations for site investigation
BEDROCK				
	Rocks of the Millstone Grit and Coal Measures	Moderately to well-jointed, thinly to thickly-bedded, fine to coarse-grained SANDSTONES, with mudstone and siltstone interbeds, strong to moderately strong when fresh or slightly weathered; <u>and</u> fissured, weak to moderately strong, SHALES, MUDSTONES and SILTSTONES weathering to a firm to stiff silty clay.	Usually good foundation conditions. Bed thickness and depth of weathered zone important in design. Some mudstones may have tendency to deteriorate rapidly when wetted on exposure, requiring protection of foundation levels in open excavations.	• Important to determine depth and properties of lithologically variable weathered zone and thickness of individual beds. • *In situ* loading tests advisable to assess bearing strengths at selected sites.
SUPERFICIAL DEPOSITS				
	Till (boulder clay) Glaciofluvial Deposits River Terrace Deposits Hummocky Glacial Deposits	Stiff to very stiff, stony, sandy CLAY (boulder clay), with bands of laminated clays and interbeds and lenses of sand and gravel; <u>and</u> medium dense, fine to coarse-grained SANDS and medium dense to dense GRAVELS with occasional cobbles, sandy clays and silts, sometimes laminated, occur locally.	Generally good foundation conditions but dependent on presence of water-bearing sand and silt layers/lenses. Thick deposits in buried river channels may be significant in foundation design.	• Important to determine deposit thickness and lithology, particularly the presence of laminated clays and water-bearing sands/silts. • Important to ascertain the presence and dimensions of buried channels and characteristics of infilling deposits. • Geophysical methods may be advisable.
	Alluvium Glaciolacustrine Deposits Head	Variable, very soft to firm, occasionally laminated, sandy, silty alluvial CLAYS and SILTS with impersistent peat, and loose to dense fine to coarse-grained SANDS and GRAVELS with clay lenses; <u>and</u> soft to firm sandy silty CLAY Head with stones which locally may be silty sand or gravel. Clayey Head may contain relict shear surfaces of low shear strength.	Soft, highly compressible zones may be present, with risk of severe differential settlements; rafts or piles to dense gravels or sound bedrock may be required. Shallow thickness of Head deposits usually allows economic removal prior to placing shallow foundations	• Important to determine the depth and extent of soft compressible zones and depth to sound strata. • Closely-spaced boreholes may be required. • Important to determine Head thickness/ extent and presence of relict shear surfaces which may adversely affect stability of cuts/excavations in Head-covered slopes.
	Made Ground Infilled Ground	Highly variable in composition, depth and load-bearing characteristics from site to site. Hazardous waste and/or gases (e.g. methane, CO_2) may be present.	Possibility of severe total and differential settlements. Ground improvement methods may be suitable/applicable.	• Essential to determine depth, extent, type and condition of fill material and chemistry of groundwaters. • Special techniques/precautions may be necessary.
	Peat Landslip **[*See also Map 6*]**	Fibrous/amorphous PEAT deposits up to 4m thick are developed on some moorland plateaux, selectively worked to shallow depth in some areas. Peat also occurs as impersistent subsurface layers and lenses within alluvium deposits Composition of LANDSLIP deposits varies widely from dominantly clay to variable amounts of clay, mudstone and sandstone debris, usually containing slip surfaces of low shear strength. Rockfall detritus may be of considerable extent below major sandstone scarps.	Peats are very weak, highly compressible deposits. Acidic groundwaters likely. Deposits at surface should be removed, or designed for if below normal foundation depth. Landslip deposits are generally unsuitable for built development unless made suitable by appropriate engineered remedial works.	• Important to determine extent and depth of soft peat deposits. • Groundwater acidity should be determined prior to selection of buried concrete. • Essential to ascertain stability conditions of landslip site <u>and</u> adjacent slopes prior to any development and/or design of remedial works.
ADDITIONAL CONSIDERATIONS				
	Zone where undermining may occur within 30 m of ground surface. **[*See also Map 5*]**	Consideration should be given to the localised development of 'crown holes' at ground surface due to collapse of shallow colliery-based workings and/or the penetration of foundations into near-surface voids. Similar considerations may apply to shallow sandstone workings (shown on Map 5) within and beyond these zones. The presence, depth and extent of shallow workings should be ascertained by site investigation prior to all construction. Appropriate void stabilisation methods (e.g. grouting) may be required.		
	Geological fault at surface (not shown)	Fault lines are characterised by zones of shattered rock which tend to promote deep weathering profiles and possible pathways for methane gas and contaminated groundwaters. Competent rock may also be juxtaposed with less competent strata. Structures straddling fault zones may be liable to uneven settlements unless accounted for in foundation design. Extent and nature of faulted ground should be ascertained by site investigation prior to construction.		
	Coal seam at outcrop (not shown)	Coal exposed at foundation levels poses the risk of combustion and should be removed and replaced/sealed prior to construction (e.g. with mass concrete). Agreement of the mineral owner is required before any entry to or disturbance of the coal; this is generally the Coal Authority.		

Figure 5b. Key to the map of engineering ground conditions of the bedrock and superficial deposits: suitability of deposits a engineered fill for Bradford, West Yorkshire, UK. (After Waters *et al*. 1996).

Suitability as fill for earthworks and support of buildings	Category	Geological unit [*Refer to Maps 2 & 3*]	Comments
SUITABLE	ROCK/ GRANULAR FILL	Sandstones of the Millstone Grit and Coal Measures	May be suitable as rockfill if care is taken in selection and excavation. However, use as a high grade fill may be limited due to variable amounts of silt and clay-size particles which form the cementing medium of many of the sandstones, and the common occurrence of intercalated clay/mudstone bands. For earthwork compaction purposes many sandstones are generally classed as a well graded 'granular soils '.
	GRANULAR FILL	Glaciofluvial Deposits River Terrace Deposits	Glaciofluvial and River Terrace Deposits may generally be suitable as a source of 'granular soil' (sand/gravel) fill. In some areas, near-surface deposits show a tendency to be uniformly graded, becoming more well-graded with depth (eg. in the Wharfe Valley). Sandstones (see above) may in general be classed as 'granular soil' fill.
	COHESIVE FILL	Mudstones and shales of the Millstone Grit and Coal Measures Till (boulder clay)	Highly to moderately weathered mudstone and shales are generally classified as 'cohesive soil' fill for earthwork compaction purposes, and fresh to slightly weathered rocks as 'dry cohesive soils'. These materials tend to be particularly sensitive to compaction moisture contents and 'field' moisture conditions need careful control during earthwork construction. May be unsuitable for fill below light structures due to potential for shrinking and swelling associated with changing moisture conditions. Clay Till (boulder clay) should be suitable as 'cohesive soil' fill if care is taken in selection and extraction. Laminated clays and silts which may occur locally within the Till are generally unsuitable for use as fill, as may be boulder clay occurring near water-bearing layers of sand and gravel.
POSSIBLY SUITABLE	VARIABLE	Alluvium Glaciolacustrine Deposits Hummocky Glacial Deposits Head	Alluvial silts and clays, often with intercalated peat, are usually unsuitable for use as fill but alluvial sands and gravels may be suitable as granular fill if care is taken in selection and excavation. Hummocky Glacial Deposits, generally very variable in composition, may be suitable as granular fill but may often contain high proportions of mudstone. Head deposits may be suitable for use as bulk fill but where dominantly clayey may be too wet to achieve satisfactory compaction.
	HIGHLY VARIABLE	Made Ground Infilled Ground	Areas of Made Ground and Infilled Ground may contain a variety of materials arising from industrial, mining and domestic wastes in addition to natural soil and rock. Some materials may be recovered for use as engineered fills in earthworks and below structures, if carefully selected. Colliery spoil or waste (minestone) is generally not suitable for use as fill below lightweight structures/dwellings due to expansion problems and possible susceptibility to spontaneous combustion.
UNSUITABLE	ORGANIC SOIL	Peat	Soft, highly compressible organic material unsuitable for use as fill.
	LANDSLIP DEPOSITS	Landslip	Generally unsuitable due to often highly variable composition (eg. clay, boulders, vegetation), the presence of wet zones associated with seepage horizons, and the risk of initiating further instability during ecavation. Isolated upland hillslope locations, difficult access and/or limited extent of many landslip deposits make their use as a source of fill material unviable.

Figure 5c. Key to the map of engineering ground conditions of the bedrock and superficial deposits: excavatability for Bradford, West Yorkshire, UK. (After Waters *et al*. 1996).

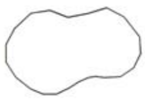
Excavation requirements	Geological unit *[Refer to Maps 2 & 3]*	Comments
Blasting, pneumatic tools, ripping	Sandstones and siltstones of the Millstone Grit and Coal Measures	Excavation methods will be dependent on degree of weathering, joint/bedding spacing and local variations in strength of intact rock. Highly weathered sandstone may possibly be excavated by mechanical scraping or digging. Less weathered well-jointed or flaggy sandstones will usually require ripping. Excavation in confined spaces will require pneumatic tools, with blasting necessary for major excavations in massive sandstone.
Pneumatic tools, ripping, digging	Mudstones and shales of the Millstone Grit and Coal Measures	Weathered mudstones and shales may be excavated by mechanical scraping or digging. Ripping or pneumatic tools will generally be required for less weathered rocks at depth or for major excavations.
Diggable	Superficial Deposits	All the superficial deposits may be excavated by mechanical digging or scraping. Some deposits (eg. peat) may be excavated by hand tools. Cobbles and boulders may make digging difficult at some localities. On clayey deposits (eg. boulder clay and Head) ponding of surface water may cause problems during working. Running conditions may occur in sands below the water table (eg. alluvium and glaciofluvial deposits in buried channels) and trench support and dewatering is usually required for excavations in these deposits. Wet, soft ground conditions may also be encountered in areas of moorland peat deposits. Areas of Made Ground and Infilled Ground can comprise a variety of materials arising from industrial, mining and domestic wastes in addition to natural soil and rock. Hazardous waste may be present, requiring special precautions during excavation.
	Boundaries of engineering soils (superficial deposits) as shown on Map7	
	Geological fault	

Figure 5d. Key to the map of engineering ground conditions of the bedrock and superficial deposits: thickness of superficial deposits for Bradford, West Yorkshire, UK. (After Waters *et al*. 1996).

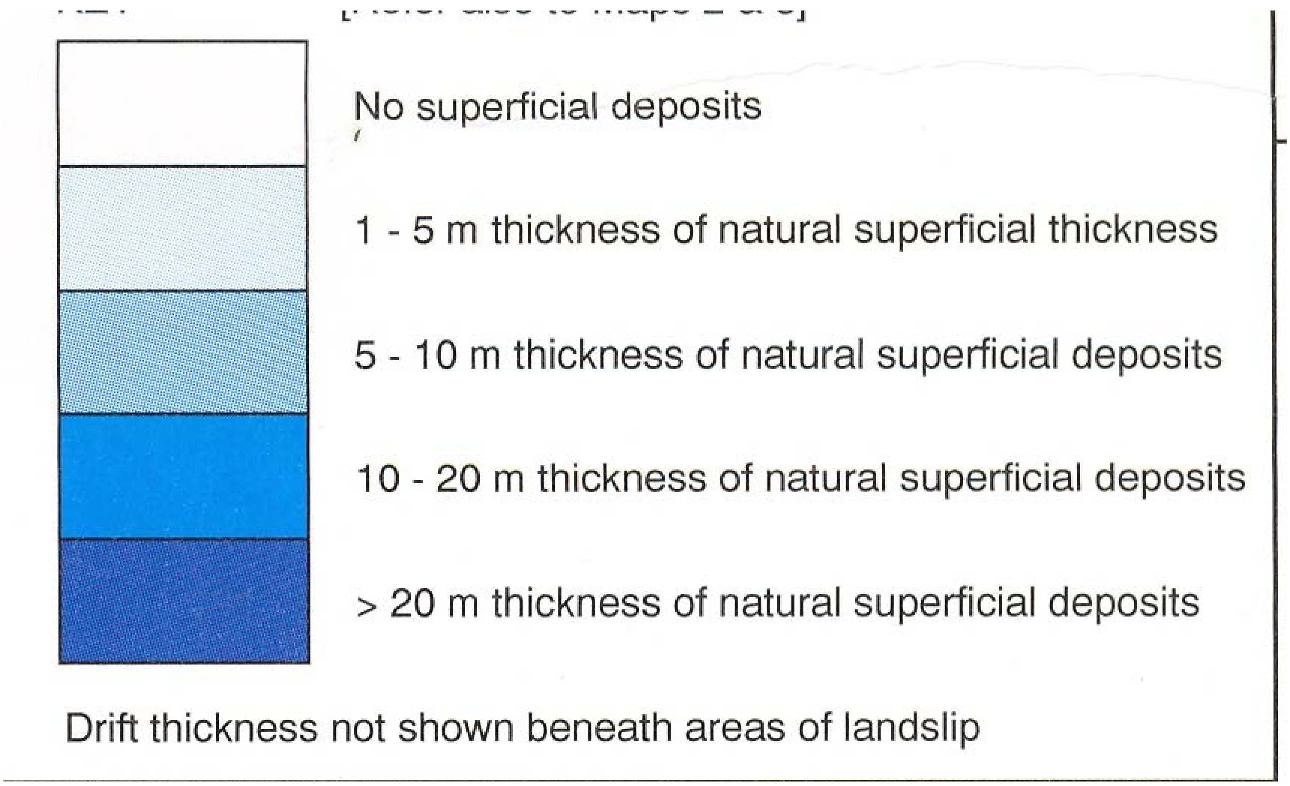


Figure 6a. Traditional geological producer – user relationship with regard to resources.

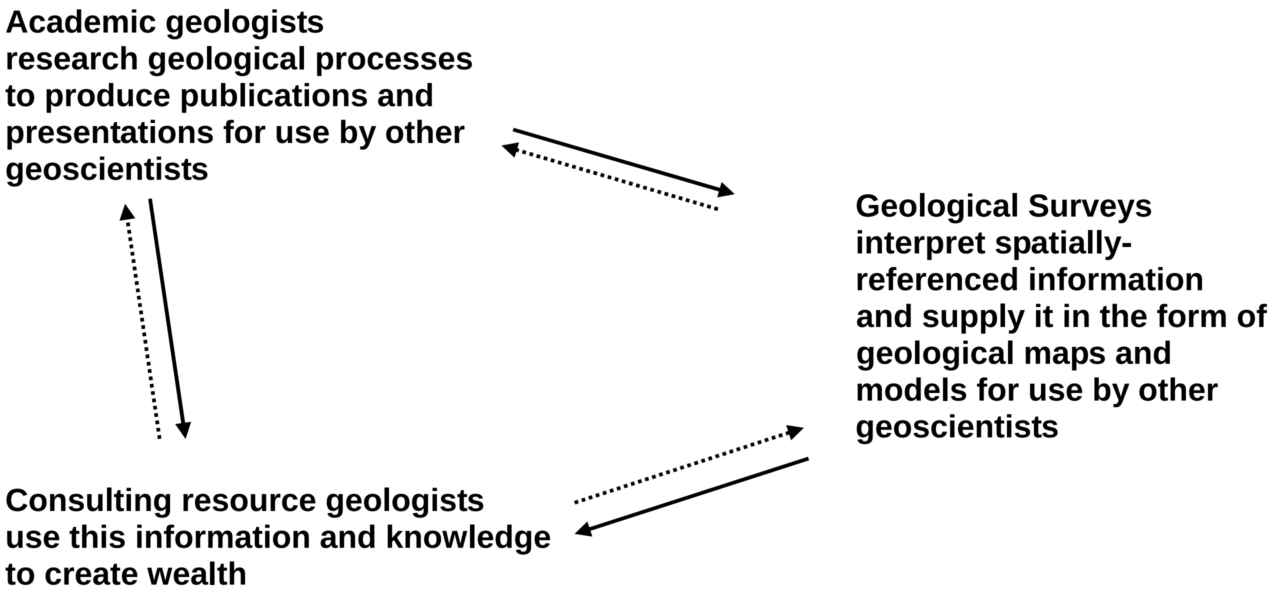


Figure 6b. Geological producer – user relationship applied to the urban environment.

Academic geologists are less interested in applied and, particularly, useable research

Geological Surveys still struggle to understand the varied needs of the wide range of new types of user and need additional funding to meet them

Consulting engineering geologists are mostly concerned with the site-specific (the near-field) and struggle with the city-wide picture (the far-field)

Wide range of users

Figure 7. Map showing the distribution of boreholes used to develop the three dimensional geological model for Glasgow, UK. Grid lines are orientated north-south and east-west and are 5 km apart.

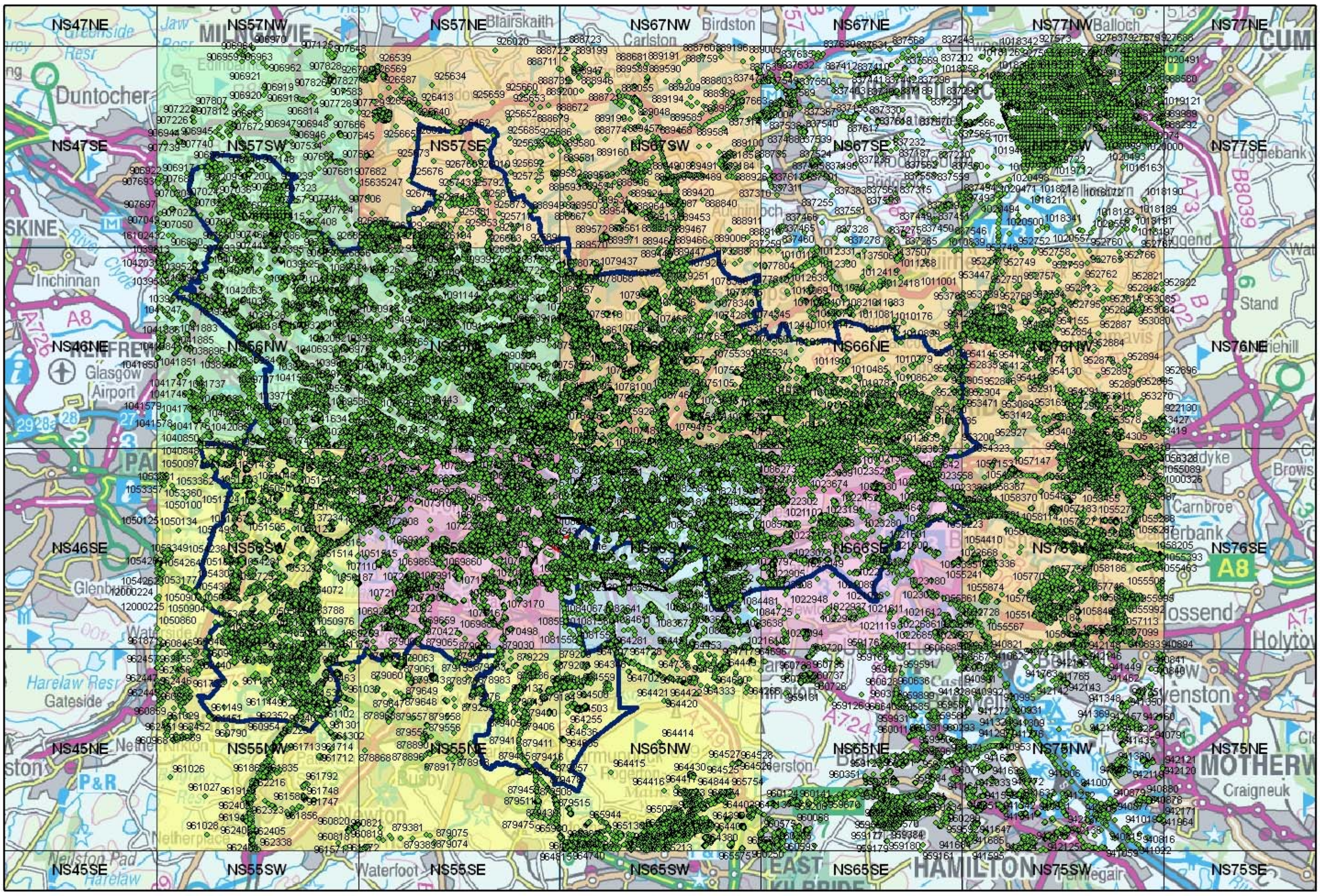


Figure 8. Three dimensional geological model of Quaternary deposits in eastern Glasgow, UK, attributed in terms of plasticity.

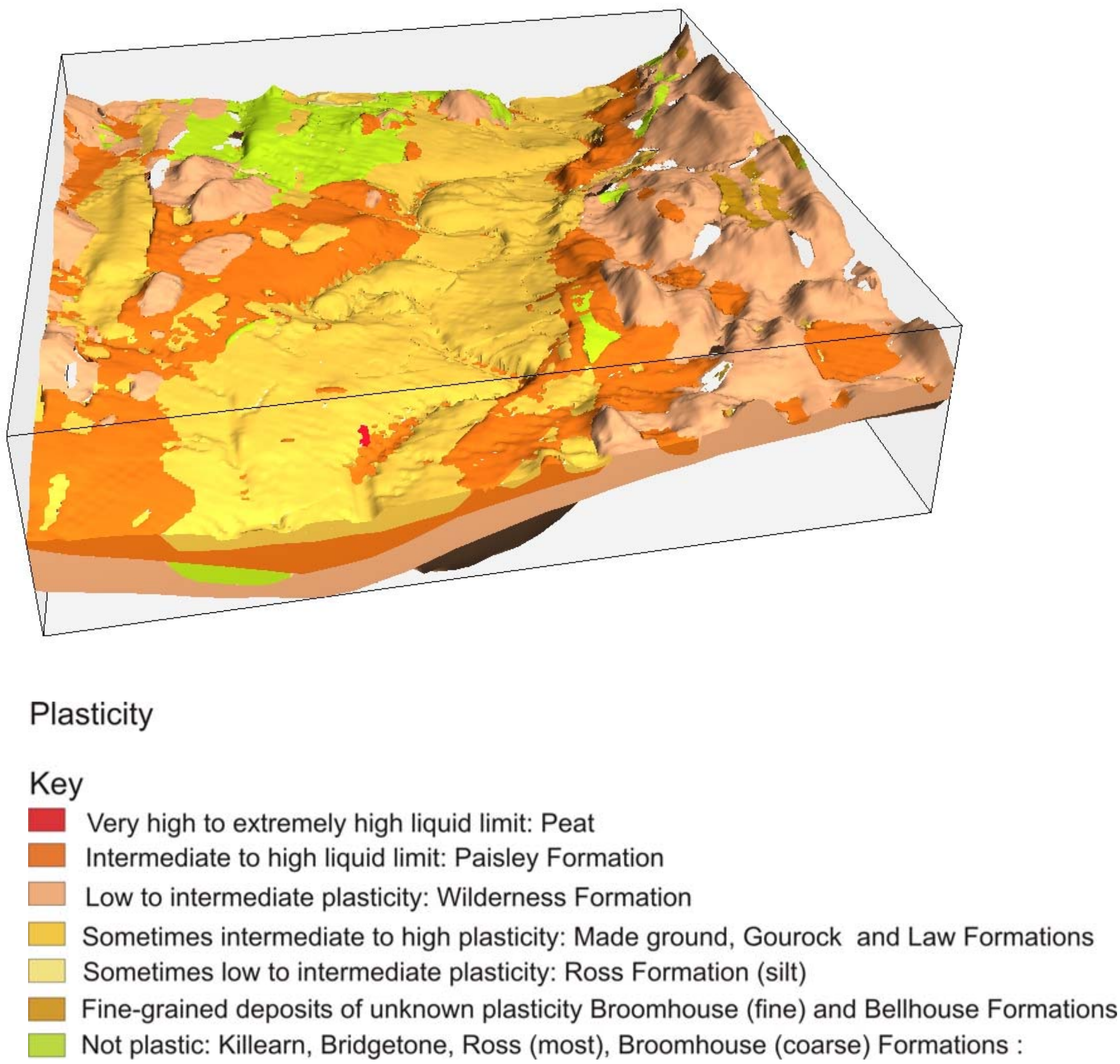


Figure 9. 3D Model of the anthropogenic deposits in Warrington, UK. (Scale as indicated by the 1 km grid on the base map; grid lines are orientated north-south, with north to the top left) [OS topography © Crown Copyright. All rights reserved. BGS 100017897/2010].

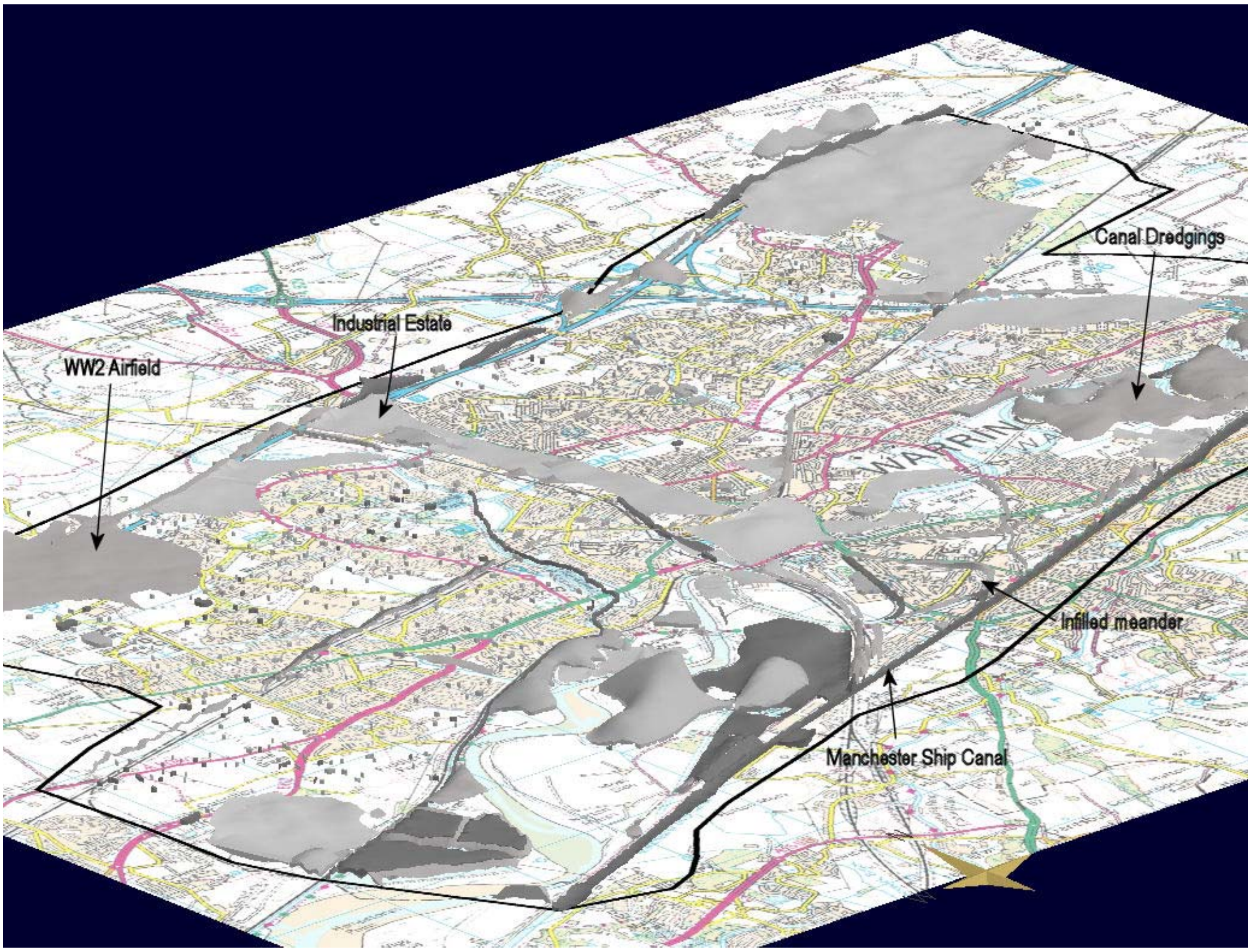


Figure 10. 3D geological model of the Lower Lea Valley, Stratford, London, UK, (site of the 2012 Olympics) with automatically generated geological and engineering geological cross-sections through the middle of the Lower Lea Valley. OS Topography # Crown Copyright. All rights reserved. 100017897/2008s.

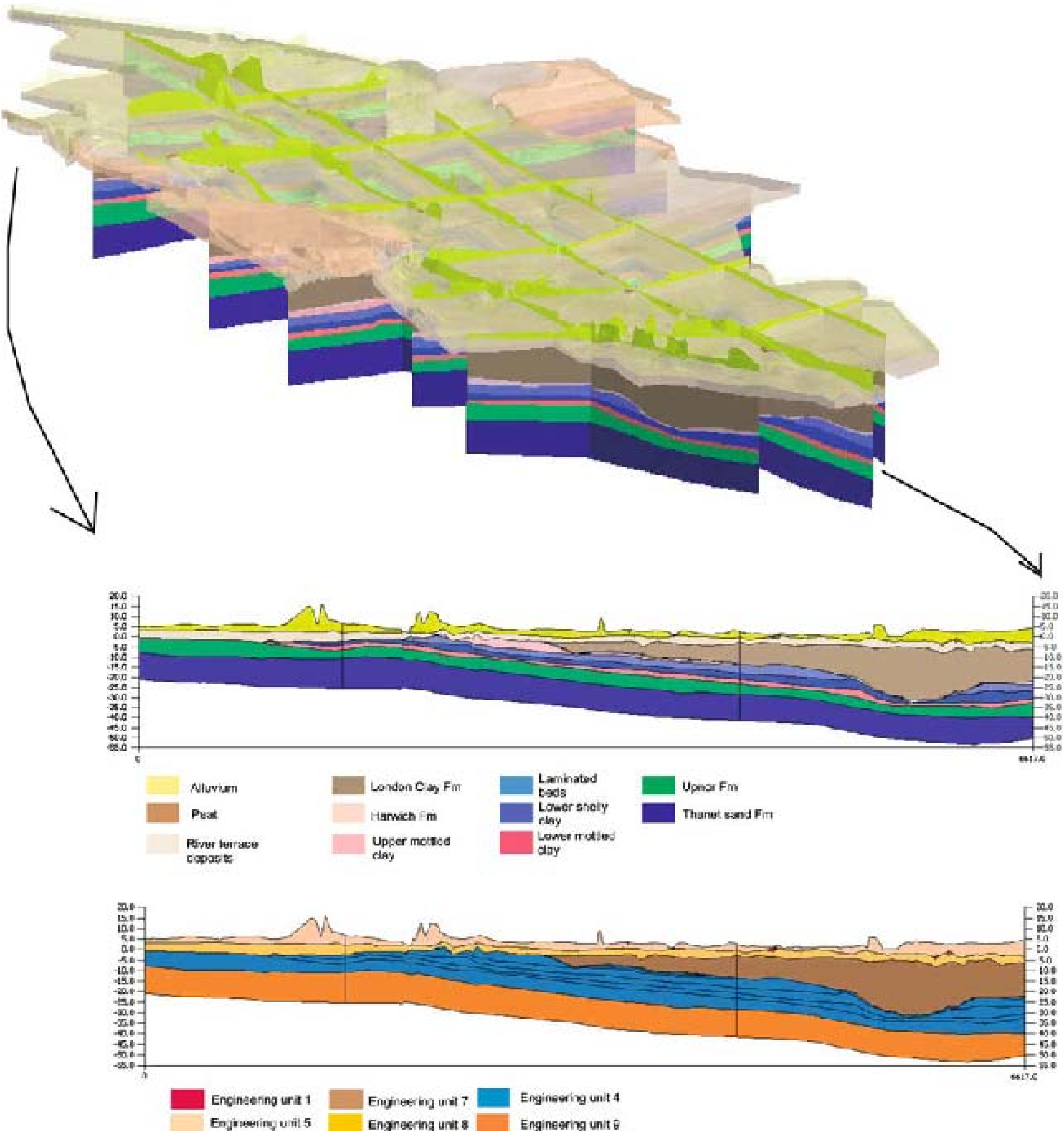


Figure 11. Map of suitability for sustainable urban drainage systems (SUDS) in central Manchester and Salford, UK. Red = unsuitable; yellow = potetnially suitable; green = suitable. (After Culshaw 2005). Grid ticks are orientated north-south and east-west and are 5 km apart.

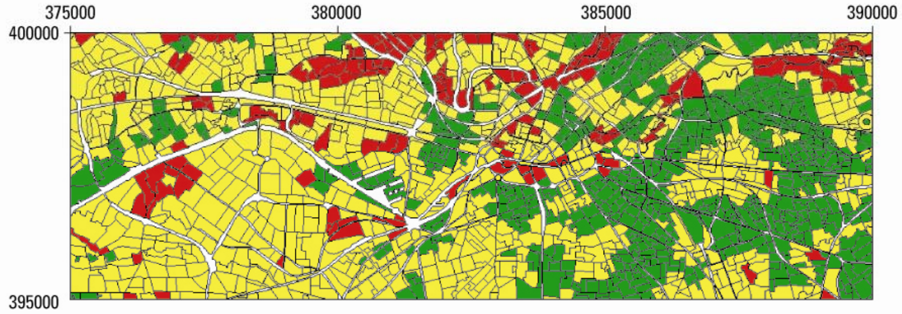


Figure 12. Sewer locations relative to till thickness beneath them in Knowsley, Liverpool, UK. Grid lines are orientated north-south and east-west and are 1 km apart. Utilities locations published with permission of United Utilities. OS topography © Crown Copyright. All rights reserved. 100017897/2008. (After Price *et al.* 2008b).

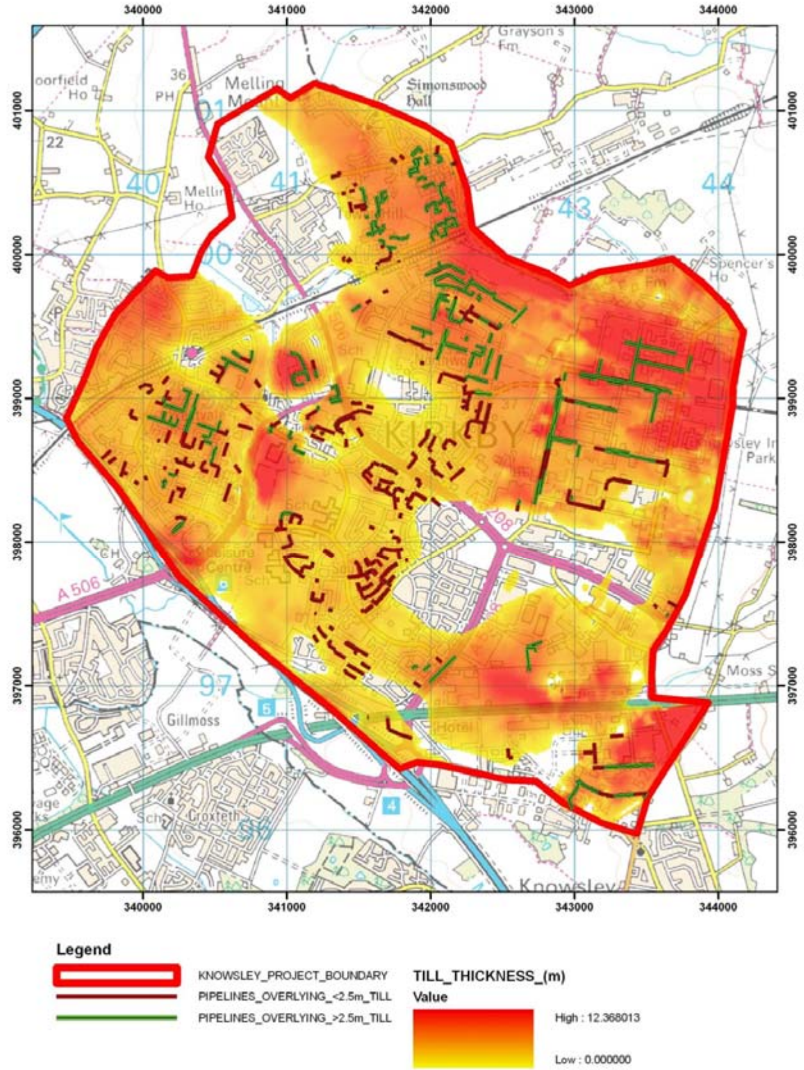
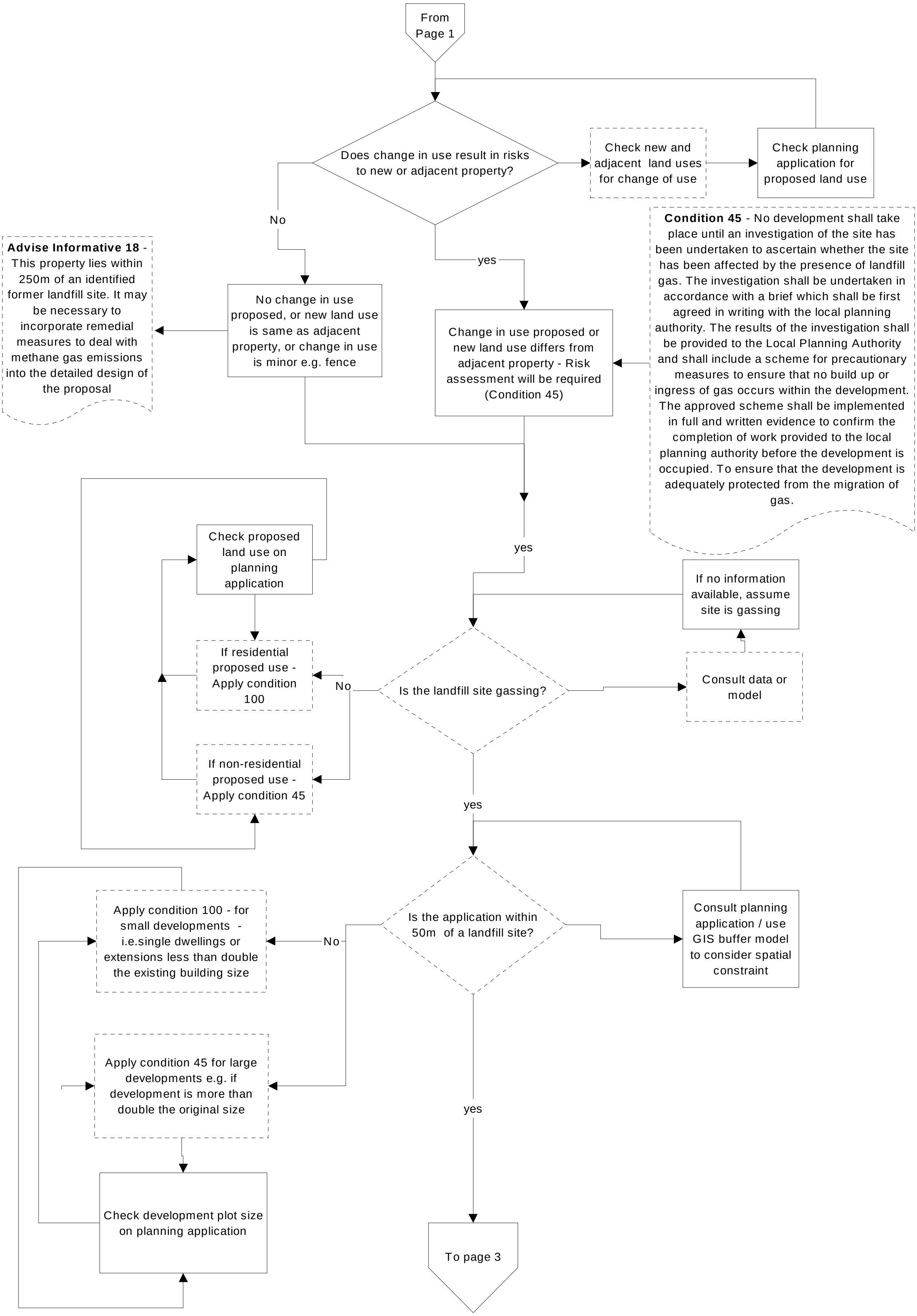


Figure 13. Part of a logical flow diagram (for 'Proximity to landfill') in the EISP. (After Culshaw *et al.* 2006b).


From Page 1
Does change in use result in risks to new or adjacent property?
Check new and adjacent land uses for change of use
Check planning application for proposed land use
No
yes
Condition 45 - No development shall take place until an investigation of the site has been undertaken to ascertain whether the site has been affected by the presence of landfill gas. The investigation shall be undertaken in accordance with a brief which shall be first agreed in writing with the local planning authority. The results of the investigation shall be provided to the Local Planning Authority and shall include a scheme for precautionary measures to ensure that no build up or ingress of gas occurs within the development. The approved scheme shall be implemented in full and written evidence to confirm the completion of work provided to the local planning authority before the development is occupied. To ensure that the development is adequately protected from the migration of gas.
Advise Informative 18 - This property lies within 250m of an identified former landfill site. It may be necessary to incorporate remedial measures to deal with methane gas emissions into the detailed design of the proposal
No change in use proposed, or new land use is same as adjacent property, or change in use is minor e.g. fence
Change in use proposed or new land use differs from adjacent property - Risk assessment will be required (Condition 45)
Check proposed land use on planning application
yes
If no information available, assume site is gassing
If residential proposed use - Apply condition 100
No
Is the landfill site gassing?
Consult data or model
If non-residential proposed use - Apply condition 45
yes
Apply condition 100 - for small developments - i.e.single dwellings or extensions less than double the existing building size
No
Is the application within 50m of a landfill site?
Consult planning application / use GIS buffer model to consider spatial constraint
Apply condition 45 for large developments e.g. if development is more than double the original size
yes
Check development plot size on planning application
To page 3