British Geological Survey
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Ground conditions in central Manchester and Salford: the use of the 3D geoscientific model as a basis for decision support in the built environment

Urban Geoscience Programme
Research Report RR/10/06

BRITISH GEOLOGICAL SURVEY

RESEARCH REPORT RR/10/06

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Keywords

Urban geoscience, 3D modelling, Manchester

Front cover

Construction work on the banks of the Manchester Ship Canal, 2008.

Bibliographical reference

Bridge, D M, Butcher, A, Hough, E, Kessler, H, Lelliott, M, Price, S J, Reeves, H J, Tye, A M, Wildman, G, and Brown, S. 2010. Ground conditions in central Manchester and Salford: the use of the 3D geoscientific model as a basis for decision support in the built environment. *British Geological Survey Research Report*, RR/10/06. 74pp.

ISBN 978 0 85272 670 9

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Ground conditions in central Manchester and Salford: the use of the 3D geoscientific model as a basis for decision support in the built environment

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Keyworth, Nottingham British Geological Survey 2010

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Foreword

This report is the published product of a study by the British Geological Survey (BGS). The report summarises the results of a three-year research programme, established in 2000, to provide up-to-date information on ground-related issues in Central Manchester and Salford. The report is one of a series of thematic studies, each of which deals with specific urban issues. In the case of Manchester, the project is concentrating on the application of 3D modelling to a characterisation of the shallow subsurface. The work builds upon, and extends the scope of, a programme of applied geological research, commissioned during the 1980s and 1990s by the then Department of the Environment. The report includes images and a series of thematic outputs that are best viewed at larger scale in the accompanying Geographical Information System.

Acknowledgements

In addition to the authors of the report, the work could not have been completed without the assistance of many BGS staff including:

Dave Entwhistle (geotechnics)
Marieta Garcia-Bajo (GIS)
Geochemistry soil sampling team
Roy Modgridge (land use)
Kate Rowlands (land use)
Sue Self (geotechnical database)
Margaret Slater (geotechnical database)
Lavinia Nelder (water-strike data)
Caron Simpson (cartography)

Professor Martin Culshaw has provided useful guidance throughout the project and his support is here acknowledged.

Of the many individuals outside BGS who have contributed to the project we would particularly like to thank Hans Georg Sobisch and his team at the University of Cologne for developing a software application appropriate for shallow sub-surface modelling. The research has also benefited from close collaboration with the Environment Agency (North West Region), for whom specific modelling was undertaken in the Trafford Park area.

Thanks also to the following organisations for giving us permission to use their data:

Bovis Land Lease
Costain Group PLC.
Deakin Walters Engineers
Greater Manchester County Records Office
Greater Manchester Geological Unit
John Rylands Library
Trafford Metropolitan Borough Council
Major Highways Consortium (Wigan, Manchester, Salford)
Manchester City Council
Manchester City Libraries
Manchester Engineering Design Consultancy
Manchester Metropolitan University
Mowlem
Nutall Construction
Ove Arup and Partners International Ltd.
Peel Holdings
Salford City Council
Shepherd Construction
Space New Living Ltd.
United Utilities
The University of Manchester
Urban Splash
Waterman BBT

NOTES

Throughout this report the word ‘district’ refers to the area covered by 1:10 000 sheets SJ79NE, SJ89NW, SJ89NE and parts of sheets SJ79SE and SJ89SW (Figures 1; 2).

National Grid references are given in square brackets; all lie within 100 km square SJ, unless otherwise stated.

Summary

In the urban environment, site investigation studies provide a wealth of information about the ground conditions of the shallow subsurface. However, from the developers' perspective, there is generally little incentive to integrate this information beyond the boundaries of the development site. By taking a more holistic view and combining knowledge of the near-surface geology with information on former land use and the groundwater regime across a wider area, it is possible to predict geological scenarios that may better inform ground investigation and reclamation strategies.

As part of its urban research programme, the British Geological Survey has integrated its data holdings across 75 km^2 of central Manchester and Salford. The information has been used to develop an integrated 3D model of the shallow subsurface. By exporting the elements of the model to a Geographical Information System (GIS), there is the capability to produce on demand bespoke maps, cross-sections and other visualisation aids, relevant to regional planning and site appraisal. The value of such a system is illustrated by reference to five topic areas (geology, geotechnical engineering, hydrogeology, geochemistry and land use). A series of thematic maps illustrates the range of outputs.

The approach provides a means of identifying potential problems and opportunities at an early stage in any proposed development and, if implemented over a wider area, it could assist in designing site investigation strategies and reduce costs by ensuring a more focused approach to development planning.

1 Introduction

The role of geo-environmental information is becoming increasingly important as legislative changes have forced developers, planning authorities and regulators to consider more fully the implications and impact on the environment of large-scale development initiatives. To comply with the principles of sustainable development, developers are increasingly required to demonstrate that proposals are based on the best possible scientific information and analysis of risk. Nowhere is this more relevant than in the context of urban regeneration.

The case for using geo-environmental information to underpin preliminary site appraisal and for developing regional strategies has been made elsewhere (e.g. Bobrowsky, 2002 and references therein; Ellison et al., 1998; McKirdy et al., 1998; Thompson, 1998; Culshaw and Ellison, 2002; Ellison et al., 2002). In the UK, studies commissioned by the Department of the Environment in the 1980s and 1990s paved the way by promoting the use of applied geological maps to identify the principal geological factors which should be taken into account in planning for development (e.g. Forster et al., 1995). Since this work was completed, advances in the use of Geographical Information Systems (GIS) and modelling software have meant that there is now far greater opportunity to develop geo-environmental products that take greater account of the third dimension.

This report summarises the results of a three-year research programme aimed at demonstrating the potential that the new technology offers, and illustrates by examples from a major conurbation, the role that the 3D geoscientific model is playing in deriving bespoke thematic products.

1.1 LOCATION

The area chosen for the study covers 75 km^2 of central Manchester and Salford (Figure 1). It is a predominantly urbanised area with a long history of intense, largely unrestrained industrialisation, founded on coal mining, locomotive engineering and the textile industry (including the bleaching and dyeing of cotton). These activities have left a legacy of contaminated land and groundwater pollution in what is one of the most densely populated areas of the UK.

The area includes Trafford Park, the largest industrial estate in Europe, Manchester city centre, still undergoing redevelopment following the 1996 terrorist attack, and east Manchester, an industrially depressed area now undergoing urban renewal aided by £2 bn of public and private investment (Carroll, 2000). Smaller areas of intense redevelopment include the former Bradford Colliery and gasworks, redeveloped as the focal site of the 2002 Commonwealth Games, and Salford Quays, formerly the Manchester Ship Canal docklands, but now home to the Lowry Centre and the Imperial War Museum North.

1.2 SCOPE OF STUDY

This report focuses on the use of the 3D model as a means of presenting geoscience information in a format to suit a variety of user needs. Issues of ground instability, contamination, and urban groundwater management are examined by reference to an attributed 3D model of central Manchester and Salford. The model deals primarily with the shallow subsurface and the difficult site conditions imposed by a variable and heterogeneous cover of Quaternary and artificial deposits.

Separate chapters are devoted to each of five key research topics (Figure 2). The report is accompanied by a set of applied maps derived from the model, which show the versatility of the system.

The model, data layers and associated thematic products are reproduced in digital format (ARC9) on the enclosed CD.

2 Geological setting

This section introduces the main features of the geology and sets the scene for the 3D modelling described in Section 3. Although the bulk of the report is oriented towards understanding the superficial deposits, a section on bedrock geology is included as background to the discussions on hydrogeology.

2.1 BEDROCK GEOLOGY

The cities of Manchester and Salford straddle the southern part of the South Lancashire Coalfield and the north-eastern part of the Permo-Triassic Cheshire Basin. The distribution of rocks present in the district is shown in Figure 3 and the succession is illustrated in the accompanying generalized vertical section. Bedrock exposure is poor throughout the district due to an extensive and often thick cover of superficial deposits. However, mine plans and records dating from the 19th and 20th centuries provide information about the structure and deep geology of the district. The oldest exposed rocks, of Westphalian age (c. 305–298 Ma), are the coal-bearing strata of the South Lancashire Coalfield. Coal was worked from collieries at Patricroft [7629 9914] and Agecroft [SD 7999 0155] until the late 1970s. The smaller Bradford Coalfield forms a structurally isolated inlier, surrounded by Permo-Triassic rocks, and bounded to the east by the Bradford Fault. The inlier was worked from Bradford Colliery [8706 9845] until its closure in 1968.

The Coal Measures are overlain by a sequence of red beds (Etruria Formation) and grey measures (Halesowen Formation) forming part of the Warwickshire Group. These strata subcrop beneath superficial deposits around Alder Forest [SD 750 000], Brindle Heath [806 998], Bradford [865 988] and Medlock Vale [SD 900 000].

Permo-Triassic rocks (298–205 Ma) underlie much of the central, eastern and southern parts of Manchester, where they form the sedimentary fill to the north-eastern part of the Cheshire Basin. This sandstone-dominated sequence, up to 620 m thick, forms the most important groundwater aquifer in north-west England.

A more detailed description of the bedrock formations and geological structure is given in Appendix 1.

2.2 GEOLOGICAL HISTORY

Accounts of the evolution of the area are given in Plant et al. (1999) and Kirby et al. (2000), from which much of this section is summarised.

During the Westphalian, prograding delta systems deposited the Coal Measures of the South Lancashire Coalfield in delta plain, lacustrine and swamp environments. Compression and uplift of the Pennine Basin during the early stages of the Varsican orogeny (Westphalian C/D) led to the regression of the coal swamps and deposition of the alluvial red beds of the Etruria Formation. The fluvial sandstones and lacustrine mudstones and limestones that characterise the Halesowen Formation indicate a return to conditions more typical of the Westphalian and point to a period of fairly low subsidence in an alluvial plain setting. A further period of folding, uplift and widespread subaerial erosion followed, resulting in basin inversion and a partial reversal of movement on some of the basement-controlled faults.

The Permo-Triassic Cheshire Basin developed during a period of east–west regional crustal extension associated with the development of the North Atlantic rift system. The basin is a half graben, with syndepositional normal faults defining its eastern and north-eastern margins.

Deposition of the Permian strata reflects a palaeogeographical change in environment from desert (Collyhurst Sandstone) to marine (Manchester Marls) conditions. Continental deposition was re-established during the Triassic initially in fluvial environments (Chester Pebble Beds) and later with increasing aeolian influence (Wilmslow Sandstone Formation).

2.3 SUPERFICIAL DEPOSITS

Much of the district is covered by extensive spreads of superficial deposits (Figure 4). These can be divided into three major categories: glacial deposits, presumed to be mainly of late-Devensian age about 20 000 to 14 468 BP; postglacial deposits associated with development of the River Irwell, and anthropogenic deposits, recording man's modification of the surface since the Industrial Revolution.

During Late Devensian times, ice streams radiating from centres in the Lake District and the adjoining Irish Sea Basin advanced across the district. The general pattern of movement, based on glacial striae and till fabric (Worsley, 1968), supports ice streams entering the area from a north-westerly or westerly direction, with subsidiary streams constrained to the east by the Pennine escarpment.

The depositional products of the glaciation are dominated by till, which covers all but the most prominent bedrock features. The till is accompanied in the lowlands by sequences of outwash sediments forming multi-layered complexes in places over 40 m thick. Evidence of hummocky moraine on the higher slopes to the east of Manchester (north of the present district) suggests that downwastage of the ice was achieved locally by in situ stagnation. Prominent morainic ridges, such as Buile Hill [800 995], are presumed to be ice-contact in origin, and may represent standstill positions of the ice margin during deglaciation. During this phase large volumes of meltwater deposited subglacial and supraglacial sand and gravel in ice-contact and proglacial settings. At times throughout the wasting process, meltwater was locally impounded to form transient glacial lakes. Silts and laminated clays deposited in these lakes are widely represented in the subsurface but are rarely recorded at outcrop. Subsequent to the retreat of the Late Devensian ice, a local regrowth of permanent snow fields about 11 000 to 10 000 BP provided a source of meltwaters which were channelled down the proto-Irwell and its tributaries to deposit a spread of 'flood gravels' across much of the Manchester embayment.

Postglacial (Holocene) deposits are largely confined to the modern river valleys and include river terrace deposits and tracts of alluvium. A small area of lowland peat is preserved in Trafford Park.

2.4 ARTIFICIAL DEPOSITS

2.4.1 Historical perspective

Although Manchester was the regional centre of south Lancashire prior to the Victorian era, it was little more than a small conurbation at the confluence of the rivers Irwell and Irk. During the 1800s, the population grew to over two million, fuelled by a need for labour to work in industries associated with cotton (weaving, dyeing and distribution), manufacturing and coal mining. The expansion of the city was facilitated by the construction of the Bridgwater Canal in 1763, the Ashton Canal in 1799 and the Rochdale Canal in 1804. In the mid-1800s, the establishment of the rail network through the Manchester area allowed for a more efficient transport of goods. The Manchester Ship Canal, which took eight years to construct, was opened in 1894. The canal provided a direct link between the docks at Salford and the sea, bypassing the need for imported goods to be off-loaded at Liverpool. The 1183-acre Trafford Park Estate, south of the Ship Canal, was sold in 1896, and transformation from a deer park into Europe's largest industrial estate began shortly after. A measure of the importance of the area to the world economy is given by the fact that by 1913 over 65 per cent of the world's cotton was exported from Manchester. During the inter-war period (1918–1939), many heavy industries, including the manufacture of cars, turbines, generators, foodstuffs and chemicals, were based in Trafford Park. The Ship Canal was so successful that at this time Manchester became the fourth largest port in the country. However, in the period following the Second World War there was a contraction of many of the traditional 'heavy' industries and closure of numerous large factory sites. In the 1960s, during a programme of city-wide slum clearance traditional housing was replaced with high-rise residential buildings in Salford, Hulme and east Manchester. It was during this period that the Port of Manchester closed. During the 1980s, under the guardianship of the Trafford Park Development Corporation, Salford Quays was redeveloped, and new light industries were established in Trafford Park. More recent areas of redevelopment include Manchester city centre and the former Bradford Colliery site.

2.4.2 Artificial deposits

The legacy of its industrial past is widespread in the cover of anthropogenic (artificial) deposits in Manchester and Salford. Commonly these show no well defined landform and the boundaries are ill-defined or gradational. Nevertheless, by combining information from a variety of sources, it has proved possible to map out the more significant deposits. Three categories of deposit are recognised (Figure 5):

- **Made Ground**, where material is known to have been placed on the pre-existing land surface
- **Worked Ground**, where the pre-existing land surface is known to have been excavated
- **Infilled Ground**, where the pre-existing land surface has been excavated (Worked Ground) and subsequently partially or wholly backfilled (Worked and Made Ground)

Further details of the distribution and composition of these deposits are given in section 3

The geological model of the Quaternary deposits of the district was constructed using proprietary software developed during the 1990s by Dr Hans-Georg Sobisch specifically for use in Quaternary sequences of northern Germany (Hinz et al., 1999; Sobisch, 2000). Over the past two years further development and testing has been carried out in collaboration with the British Geological Survey, mainly through the Urban Geoscience, Geological Hazards and Integrated Mapping programmes.

3 Building, viewing and interrogating the 3D model

3.1 MODEL OVERVIEW

The modelling process is described in detail by Kessler et al. (2004). The model is built in GSI3D using boreholes and cross-sections as the core of the model (Figure 6). In essence, the Quaternary model is built from a network of cross-sections compiled on-the-fly from coded boreholes displayed graphically on-screen. Lithological and lithostratigraphical horizons are picked, correlated and then gridded. The resulting sequence is stacked and the model calculated automatically according to a predefined order of superposition. Datasets used to build the model are listed in Table 1. One critical task was the selection of a suitable subset of boreholes on which to base the model. Although BGS holds over 6500 records for the area, less than half of this total was considered of sufficient quality to incorporate in the model. The final selection represents a compromise between logs of high reliability (usually from fairly shallow ground investigations) and those that contain more sketchy information but often prove the full Quaternary sequence (for example, water boreholes).

3.2 ESTABLISHING A STRATIGRAPHY

The order in which surfaces are stacked and intersected in the model is determined by a local or regional stratigraphy which is commonly established during field-based mapping and which necessarily relies heavily on the recognition and interpretation of landforms.

In translating the 2D map into a 3D geological model, it was necessary to define additional units to take account of lithofacies unrecognised at surface or only present in the subsurface. The modelled units are listed in Table 2, and their spatial relationships are illustrated schematically in Figure 7. Horizon tags (e.g. [glld]) uniquely identify the base of each of the modelled units and provide the link between the section correlations and the corresponding model surfaces. Lithostratigraphical units with good continuity form the framework of the model and are denoted in upper case in Table 2 (e.g. RIVER CHANNEL DEPOSITS). Other units defined morphologically or occurring as lenticular bodies within major lithostratigraphical units are shown in normal type. Four cross-sections, reproduced from the model, show the spatial relationships of the superficial deposits in different sectors of the district (Figure 8). The geometry and lithological characteristics of the individual units are discussed in the following sections in base-upwards sequence.

3.2.1 Rockhead surface

The rockhead surface [base_quat] is defined for modelling purposes as the base of the superficial deposits, irrespective of the state of weathering of the underlying bedrock. Thus, Permo-Triassic sandstones that have weathered to 'rock sand' beneath superficial cover are here regarded as part of the bedrock sequence.

The elevation of the rockhead surface and the thickness of the overlying superficial deposits are illustrated in a combined plot (Figure 9). The surface is well constrained along the main transport corridors and in areas of major redevelopment but is likely to be less reliable in the older residential areas, particularly in the east around Droylsden, where the borehole density is sparse.

Significant features of the surface are the deeply eroded depressions that skirt the southern and western limits of Trafford Park. These form part of a more extensive system of subparallel buried channels that crosses the Greater Manchester and Merseyside area in a predominantly north-westerly direction (Grayson, 1972; Howell, 1973). Poor quality or incomplete data mean that the continuity of the channels through central Manchester is difficult to demonstrate. However, where the depressions can be mapped out, they appear to have a stepped longitudinal profile falling westwards, which extends in places well below sea level. The greatest depths (38 m below OD) are recorded to the west of Eccles. The depressions are believed to represent former drainage lines that were overdeepened during the Last Glaciation by subglacial meltwaters flowing under hydrostatic pressure (e.g. Johnson, 1985, p. 253). The

Table 1 Datasets used in model construction.

Dataset (3D build)	Source	Comment
Digital Terrain Model (DTM)	Ordnance Survey Profile data	50 m grid created in ArcGIS 8.3 from a Triangular Irregular Network (TIN) based on 5 m digital contours, spot heights and other control points. Converted from a TIN to a grid using ESRI* Natural Neighbours Algorithm.
Digital geological maps	BGS: Digmap10k	1:10 000-scale bedrock, superficial and artificial layers
Borehole databases	BGS: borehole databases (SOBI and BOGE)	6500 records, of which 2600 used to build model surfaces

BOGE Borehole Geology; SOBI Single Onshore Borehole Index; *ESRI®ArcMapTM 8.3

alignment of the troughs probably reflects a combination of structural control and selective erosion of more easily weathered bedrock.

3.2.2 Descriptions of modelled units

3.2.2.1 Basal outwash [gfdu_b]

Sand and gravel deposits of variable thickness occur at the base of the glacigenic sequence (Figure 10). The deposits, which fill depressions in the bedrock surface, are present beneath the Irwell valley to the west of Salford and in the buried valley system that skirts Trafford Park. The deposits are mostly overlain by till but along parts of the River Irwell, where the till sheet has been eroded, they are overlain directly by younger outwash gravels. A proglacial or sub-glacial setting is envisaged.

3.2.2.2 Till [Till_1]

Deposits of till mantle bedrock on the higher ground in the east and occur interstratified with outwash in the Manchester embayment. Typically, much of the till is a poorly sorted, unstratified mixture of rock fragments in a matrix of stiff, greyish brown 'sandy clay'. The sand fraction in the till is generally fine to medium grained. In borehole log descriptions, a distinction can be drawn between deposits described as stiff (presumably overconsolidated) and softer, less highly consolidated deposits, which commonly occur interstratified with, or capping, outwash. The basal till, at outcrop, is typically grey, and contains a predominance of clasts derived from the Coal Measures (Plate 1). In contrast, tills in the upper parts of the sequence tend to be brown, with a higher content of Triassic material.

A study of the engineering properties of borehole material from the Salford area led Worsley (1968) to tentatively conclude that the till sequence may represent the deposits of more than one ice advance. Whilst it has not been possible to confirm this suggestion on geotechnical grounds, there is certainly evidence in the buried valley systems south of Trafford Park for multiple sequences of till, sand and laminated clay that could support this hypothesis.

The thickness of the till sheet including intra-till sands and clays is shown in Figure 11. The sheet thickens to over 30 m against rising ground in the east, and is locally over 40 m thick in the buried channel sequences of the Trafford Park area.

3.2.2.3 Glaciolacustrine deposits

Laminated clays are widely recorded in boreholes, particularly in the west of the district, and are presumed to have accumulated in transient or more long-lived bodies of standing water. For the purposes of description it is useful to group them into two types.

Intra- till deposits [glld_l1-30], [glld_ic]

Glaciolacustrine lenses occur interbedded with other glacigenic deposits, notably in the north of the district and beneath the ice-contact sands at Buile Hill (Figure 12). Similar deposits also occur in association with the moraine complex (3.2.2.6) where borehole records describe laminated clay sequences inclined at 45º to the horizontal.

Laterally extensive (km scale) deposits [glld_1]

The most extensive lake clays occur towards the top of the glacigenic sequence to the south and west of Trafford Park. The unit can be traced over an area of some several square kilometres with a continuation westwards onto the adjoining Wigan district (Figure 13). Although mainly concealed by

Plate 1 Basal till, Whit Brook [883 077] (PXXX).

Table 2 Map and model unit nomenclature.

	Map unit	Model unit	Lithology	Environment (inferred)	Model notation (base of unit)
Holocene	Worked Ground	Worked Ground		Anthropogenic (Artificial deposits)	wgr
	Made Ground	Made Ground	Mixed (see Table 3)		mgr
	Infilled Ground	Infilled Ground	Mixed (see Table 4)		wmgr
	Peat (lowland bog)	Peat	Peat	Organic	peat_1
	Alluvium	Overbank floodplain deposits	Silt, clay, Peat	Fluvial	alv_1
		River channel deposits	Sand, gravel	(may include glaciofluvial element)	alv_2
	River Terraces: Undivided, First Second	River Terrace Deposits (Undivided) (River Irwell, River Medlock)	Sand, gravel	Fluvial/Ice marginal	rtdu,
Pleistocene (Devensian)	Glaciofluvial Sheet Deposits: Sheet deposits (formerly Late Glacial Flood Gravels)	Sheet Deposits (including Late Glacial Flood Gravels)	Sand, gravel	High level terrace	lgfg gfdu_b
	Ice-contact Deposits	Buile Hill deposits Intra-till channel deposits (major) Intra-till lens and sheet deposits (minor)	Loose, fine sand Sand, gravel	Ice-contact glaciofluvial/ glaciolacustrine Subglacial/ supraglacial drainage	glld_s gfdu_1 gfdu_1-25 l
	Glaciolacustrine Deposits	Laterally extensive (km-scale deposits) Intra-till deposits (restricted distribution) Deformed deposits	Laminated silts	Ice-distal Ice-proximal Ice-contact ?push moraine	glld_1 glld_l(1-30) glld_ic
		Moraine complex Till, sand and laminated clay, undivided	Till, sand, gravel	?Push moraine	gfic
	Till	Till	Till, interbedded sands, impersistent laminated clays	Lodgment and melt-out tills, undivided	till_1
Bedrock					base_quat

outwash sands, the deposits were formerly exposed in a brick pit at Crofts Bank [756 958]. The unit is of fairly constant thickness, around 5 m, and is underlain by till. It comprises brown, silty clay, finely laminated with grey silt and sand partings. The upper and lower junctions are both sharp. The maximum height attained by the clays is about 24 m above OD, which is the inferred minimum altitude of the lake surface at time of deposition. More restricted deposits cap the till to the north and east of Manchester city centre.

3.2.2.4 Intra-till sand and gravel deposits (major) [gfdu_1] sheet deposits and lenses (minor) [gfdu_l1-20]

Intra-till channel sands [gfdu_1], up to 7 m thick, occur within the buried channel system (Figure 12). The bodies have only been proved in a few water boreholes and their geometry and lateral connectivity with other (basal) sands is poorly understood. Minor lenses and sheet deposits, of which about twenty five have been identified, occur in other parts of the till sequence (Plate 2).

Plate 2 The Cliff landslip [827 013] (PXXX).

3.2.2.5 Glaciofluvial ice-contact deposits [glld_s]

Buile Hill [800 995] rises to 70 m above OD in the north-western part of the area. The steep south-facing slope is presumed to have formed in direct contact with an ice body that lay to the south of the hill. A borehole drilled by BGS close to the top of the hill [7993 9942] proved 19.5 m of uniform brown, well-sorted, very fine- and fine-grained sand overlying pebbly clay and silt. The sand deposit is interpreted as glaciofluvial/lacustrine in origin, possibly laid down in standing water trapped between ice in the Manchester embayment and rising ground to the north.

3.2.2.6 Moraine complex [gfic]

A low, elongate ridge rises above the outwash plain in the Old Trafford area [800 960]. It comprises a complex of interbedded till, glaciofluvial sand and gravel and deformed lacustrine clays. The origins of this landform remain speculative but one possibility is that it could represent a push moraine. The deposits are laterally impersistent and are included under the umbrella term of moraine complex, pending further work.

3.2.2.7 Outwash sheet deposits [lgfg]

The deposits, formerly mapped as Late Glacial Fluvial Gravels, crop out as a high level terrace which can be traced across the Manchester embayment from a feeder outlet in central Manchester (Figure 14). Thicknesses of 4 to 5 m are typical, increasing to 7 m locally. The base of the terrace falls gently westwards from around 30 m OD in the city centre to 12 m OD at the western margin of the district. The deposits comprise a coarse basal unit of grey-brown, well-graded sand and gravel with some cobbles, and an upper unit of brown, fine- to coarse-grained silty sand. The junction with the underlying glaciolacustrine clays is sharp.

The deposits are interpreted as part of a fluvial or fluvioglacial outwash system fed by streams draining off higher ground to the east, and directed along the valleys of the proto-Irwell and its tributaries. At the time of deposition, the Manchester embayment would have been clear of ice but snowfields must have still existed on the upland areas to feed the outwash system.

3.2.2.8 River Terrace Deposits, undivided [rtdu]

Terrace deposits are present along the valley of the River Irwell, upstream of Salford University, and along the River Medlock. It is probable that these deposits are glaciofluvial in origin and represent the erosional remnants of valley train outwash that once filled the valleys, and through which the modern river systems have become incised.

The terrace deposits of the Irwell Valley are about 3 m thick and consist of silty sand overlying sand and gravel. The base of the deposit is at an elevation of 33 m above OD, where it enters the district, and is cut into till or laminated clay substrate. The Irwell terraces may represent the upstream equivalent of the outwash sheet deposits described in the previous section.

3.2.2.9 Alluvium [alv_1, alv_2]

The River Irwell is flanked by alluvium, typically 6 to 8 m thick and, in places, forming extensive tracts up to 700 m wide particularly in the meander belts around the UMIST University, around Salford Quays and farther downstream at Dumplington (Figure 15). In the intervening tracts, the river is incised in bedrock and the alluvium is poorly developed. The alluvial tract has been extensively modified by industrial and urban development and the natural floodplain is largely obscured by made ground associated with the Manchester Ship Canal and flood defence works. Below the junction with the Ship Canal, the original course of the river is no longer apparent and the canalised section of the river follows a straightened course that by-passes the larger meanders which were infilled at the turn of the century.

The alluvium typically comprises an upper layer of soft grey silty clay [alv_1], underlain by several metres of dense grey or brown coarse sand or pebbly sand and gravel [alv_2]. Thin layers of peat are present locally within, and at the base of, the sequence. The basal coarser sand and gravel layer may include deposits of Devensian age.

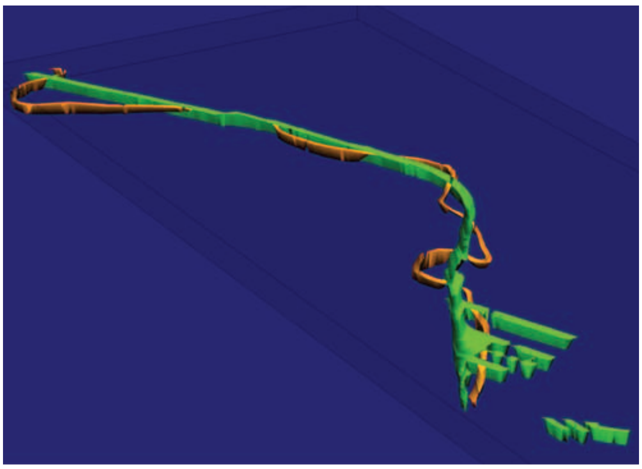

Plate 3 Former course of the River Irwell (orange) in relation to the Manchester Ship Canal (green) (PXXX).

Table 3 Characteristics of Made Ground deposits.

	Category	Thickness in metres	Composition
Made Ground	Undivided 60% coverage of the district	Typically 1 to 2 m, locally 3 to 7 m in Manchester and Salford city centres	Variable mix of construction waste (demolition rubble) and material associated with commercial, industrial and residential infrastructure, processes and waste streams. It is probable that both inert and hazardous material are present.
	River Irwell Meander loops of the River Irwell, infilled during construction of the Manchester Ship Canal	Typically 3 to 7 m but commonly >8 m around Salford Quays	Colliery spoil and material excavated from the main channel of the Manchester Ship Canal. Organic and inorganic domestic refuse also proved by drilling. Infilling of the River Irwell predated the development of Trafford Park, which now extends across the former meander belt. Ground conditions in this complex area of Made Ground are, therefore likely to be highly variable.
	Sewage works and domestic refuse sites (Peel Green Road) Restricted to the west of the district, to the north of Davyhulme	Typically 3 to 7 m thick but reaches 10 m in the area of the southernmost sewage works.	Oily sandy ash with common organic refuse. (60 boreholes).
	Trafford Park Industrial Estate	1 to 2 m but commonly 3 to 7 m. Over 8 m in the eastern part of the Park.	Material associated with extensive industrial development after World War II, which included the establishment of many chemical manufacturing industries. Also, material excavated during the construction of the Manchester Ship Canal used to raise land adjacent to the main navigation.
	Valley infill Medlock river valley	3 to 7 m but commonly 8 to 12 m.	Construction material associated with building into the river valley and also extensive tipping of colliery spoil from the Ashton Branch Railway that ran from Bradford Colliery along the northern slopes of Clayton Vale. Textile works, including bleach and dye works, were common along the length of the Medlock valley and it is probable that waste streams from these works were deposited within the valley. (230 boreholes).
	Valley infill Crofts Bank valley	3 to 7 m	The nature of the fill is unknown. A brickworks with extensive spoil mounds is shown on the 1909 edition of Ordnance Survey map Lancashire103SE, and spoil material may be present in the valley. During a field survey in 2001, numerous gas vents were observed at the margins of the valley and it is interpreted that at least in part, the valley has been infilled with domestic refuse. The material proved in boreholes generally comprises brick, metal and wood fragments with common ash waste. (12 boreholes).
	Valley infill River Irk	Typically 1 to 4 m but locally reaches 7 m, particularly in the south-west of the area.	Railway land of the Manchester, Whitefield and Radcliffe line running out of Victoria Station; numerous textiles factories and dyeworks, and spoil from former brick pits and sandstone quarries. (70 boreholes or trial pits).
	Railway sidings Gorton, east of Manchester city centre	1 to 4 m Borehole control is limited to the central part of this area.	Made Ground related to an extensive network of railway sidings, goods depots and locomotive works associated with Ancoats Junction situated at the junction of the Crewe and Manchester and the Manchester, Sheffield and Lincolnshire lines. The eastern part of the area includes Gorton foundry. The Made Ground is likely to include abundant railway ballast, ash and coal. (over 90 boreholes).
	East Manchester commonwealth site	1 to 4 m but commonly exceeds 7 m, particularly in the north-east of the area.	Material associated with a number of diverse industrial processes and culverting of the River Medlock between 1894 and 1909. In general, the northern part of the site is dominated by material from the infrastructure, processes and waste streams associated with Bradford Road Gas Works. The southern part of the area is dominated by buildings, rail tracks and spoil heaps associated with Bradford Ironworks. Bradford Colliery was sited adjacent to the east of the site and spoil associated with coal mining may also be present. (over 50 boreholes).

Table 4 Characteristics of Worked and Infilled Ground.

	Category	Thickness	Composition
Worked Ground	Manchester Ship Canal		The most extensive area of worked ground in the Salford area is related to excavation and construction of the main Manchester Ship Canal navigation. The canal extends from Pomona Docks in the Old Trafford area, through Salford Quays and westwards towards Liverpool and the River Mersey. Both bedrock and natural superficial deposits were excavated to a depth of approximately 8 m along the length of the canal (Gray, 2000). The main phase of construction took place between 1887 and 1894 with a minor phase in 1901, during construction of Number 9 dock, adjacent to the present-day Lowry Centre. Borehole records within the district show that the base of the canal is excavated mainly in superficial deposits of glacial or postglacial origin, but in places is cut directly into bedrock.
Infilled Ground	Includes all significant pits, quarries and artificial lakes that have been subsequently partially or wholly backfilled. Individual reservoirs, small sand and clay pits and small bedrock quarries have not been considered.		The composition of the material used to backfill these workings is uncertain. Over 90 boreholes prove artificial ground infilling identified former worked ground areas. Most commonly, the fill material comprises redeposited natural material from the workings with common ash, clinker and brick fragments. For example, the fill material of the former Strangeways brick pit, proved in borehole SJ89NW425, comprised over 1 m of sandy clay with ash, clinker and brick was also recorded. The thickness of the fill material is extremely variable across the district, ranging from 1 m to over 15 m in the former Sherwood Sandstone quarry at Little Bolton (SJ784985). Some former brick works and quarries are partially filled while others are completely backfilled. For example, Crofts Bank Brickworks (SJ760958), was operational between 1896 and 1909 (historic map Lancashire103SE) but is shown on the 1930 edition of the same map as being completely backfilled and marked by an area of boggy or marshy ground. In contrast, Little Bolton sandstone quarry (SJ784985) is partially filled. Over 15 m of fill material is proved in the western part of the quarry, while in the central and eastern parts, only thin fill is present and the 5 to 7 m high sandstone face from the former quarry is preserved.

3.2.2.10 Peat [Peat_1, Peat_2]

A formerly extensive area of lowland peat, known as Trafford Moss, lies beneath Trafford Park Industrial Estate. It is one of a number of inland basin peatlands or 'mosses' that accumulated in the Irwell–Mersey catchment following deglaciation. The Trafford Park deposit lies within a shallow, saucer-shaped basin partly coincident with the deepest part of the buried channel system. The deposit comprises fibrous peat with pockets of sand on grey clayey silts. Construction of the Trafford Park industrial complex has led to the removal of much of the peat but an original thickness of 3 m were reported (Tonks et al., 1931). Thin layers of peat are also present locally within the alluvial sequence as noted above.

3.2.2.11 Artificial deposits [mgr, wgr,wmgr]

Two important aims of the modelling process were to provide estimates of the thickness of the artificial deposits and, where possible, to identify their probable composition Both aspects are important to redevelopment, particularly where the deposits may include contaminated material or give rise to unpredictable engineering conditions.

A detailed analysis of all boreholes proving artificial ground was therefore carried out and the results incorporated in the model. The value of such an approach is illustrated by a screen shot from the model which shows the relationship of the former (infilled) course of the River Irwell to the present-day Manchester Ship Canal (Plate 3). The example demonstrates the high level of detail that can be achieved in the model by combining historical land use data, with modern geological linework, and a dense borehole network.

The modelled thickness of artificial ground across the whole district is illustrated in (Figure 16). The deposits are extremely variable in terms of their composition, thickness and geometry. One approach to dealing with this variability is to identify geographical areas where similar historical land use processes have operated. This approach is similar in concept to that of 'domains', more commonly used for subdividing natural Quaternary sequences (e.g. McMillan et al., 2000). By dividing the district in to zones, where specific anthropogenic processes are known to have operated, assumptions about the composition, geometry and thickness of the deposits can be made. In order to establish these zones, an understanding of the historical urban development and industrial archaeology of the city is necessary. For example, the practice of tipping colliery waste and ash from domestic fireplaces into river valleys was commonplace, and occurred widely in the Medlock valley in the Phillips Park area of Bradford. Other river valleys including the Irk, the Irwell and Bent Lanes Brook suffered similar fates, with artificial deposits raising the valley floors above the natural alluvium.

In total, nine areas with significant and identifiable types of artificial ground have been delineated (Figure 17). The characteristics of the deposits in each of the areas are summarised in Tables 3 and 4. Small-scale pits and quarries and areas of made ground (generally less than 100 m^2) were not included in the model but are shown, together with road embankments, road cuttings, and the Bridgewater Canal in Figure 5.

Not all areas lend themselves to this approach, and it is recognised that in some areas of the urban environment, typically where numerous phases of demolition and redevelopment have taken place, precise classification is impractical. However, it is still possible using borehole records to separate Made Ground of unspecified type (greater than 2 m thick) from thinner, patchy deposits (generally less than 2 m thick).

3.3 INTERROGATION OF THE GEOLOGICAL MODEL

The geological model can be interrogated using the proprietary software, GSI3D. Simple tools provide the facility to produce:

- synthetic logs and cross-sections at user-defined locations
- contoured surfaces
- isopachytes of single or combined units
- domain maps
- subcrop and supercrop maps

These outputs can be used for:

- reconstruction of palaeosurfaces (terraces, lake levels)
- checking and revising existing geological models/maps
- process studies

Alternatively, elements of the model can be exported in standard ASCI format for further processing and visualisation in other packages (ARC9, GoCad).

The report includes four thematic maps which illustrate aspects of the modelling process and examples of derivative products:

Thematic map 1: Superficial and bedrock geology

Thematic map 2. Engineering geological classification of soils

Thematic map 3. Hydrogeological pathways

Thematic map 4. Geochemistry of urban soils and land use

4 Engineering geology of Manchester

4.1 INTRODUCTION

Ground conditions in Manchester and Salford vary markedly depending on the local geology and extent of previous development. Variable ground conditions are encountered throughout much of the district, due to the heterogeneous nature of the superficial deposits and a significant thickness of man-made deposits.

Good land for building and construction is a valuable resource and knowledge of ground conditions across the area is important for the identification of land suitable or acceptable for urban regeneration and development. The following sections provide a description of the ground conditions in the district, based on a spatial analysis of geotechnical test data within the 3D environment of the geological model.

4.2 ENGINEERING GEOLOGICAL CLASSIFICATION OF ROCKS AND SOILS

Within the Manchester district, lithologies identified on the geological map were classified for engineering purposes, as either 'engineering rocks' or 'engineering soils' (Tables 5; 6). In general terms, engineering soils can be excavated by digging, and comprise superficial and artificial deposits (Waters et al., 1996). Engineering rocks comprise harder, more competent bedrock strata, which unless highly weathered, usually require a more vigorous means of excavation. The classification of engineering rocks and soils is conventionally based on an assessment of recorded geotechnical parameters for those lithologies identified on the geological map. The resulting engineering divisions may comprise one or more mapped geological units but represent a classification of lithological units with similar geotechnical properties. The distribution of 'engineering soils' and 'engineering rocks' within the Manchester district is summarised in Figure 18. Most of the available geotechnical information relates to 'engineering soils', which are described in detail below. *Engineering rocks* are not considered further in this report.

4.3 GEOTECHNICAL DATABASE

The geotechnical properties of the 'engineering soils' in the district were extracted from a selection of 199 site investigation reports held in the National Geoscience Data Centre. These reports contain data for 9005 geotechnical samples from 2772 boreholes and trial pits. Reports considered suitable to include in the database were selected for:

- the quality of the data
- evidence of accurate levelling of borehole start heights
- stratigraphical coverage (to provide information on changing conditions downhole)
- areal coverage

4.4 ATTRIBUTION OF MODEL WITH GEOTECHNICAL DATA

The development of the 3D geological model (section 3) makes it possible, by attributing the model with geotechnical data, to assess variations in material and physical properties in 3D rather than 2D. This approach offers several advantages over conventional 2D statistical processing:

- data specific to a particular horizon can be selected and analysed
- lateral and vertical trends can be more readily discerned
- engineering properties of different geological units can be more readily compared
- spatial queries of engineering parameters can be rapidly completed

The detailed 3D geotechnical appraisal of the 'engineering soils' in the district was determined from the geotechnical tests listed below:

- Particle size analysis
- Standard penetration test (SPT)
- Moisture content
- Liquid limit
- Plastic limit
- Bulk density
- pH
- Sulphate content
- Triaxial (drained and/or undrained)

The geotechnical (point) test data was integrated with the 3D geological model using standard GIS functionality (ESRI®ArcMap™ 8.3). Data processing involved the following steps:

1. Import engineering test data from the Engineering Access database into a GIS as geo-referenced points.
2. Import 3D geological model as a set of stacked raster grid surfaces (generated using GSI3D).
3. Use automated querying tool (section 9) to select test results between named geological horizons.
4. Apply statistical testing and graphical presentation to validate results.

4.5 GEOTECHNICAL PROPERTIES OF ENGINEERING SOILS

The engineering soils of the study area fall into four broad categories: highly variable artificial deposits, fine soils, coarse soils and organic soils (Table 5).

4.5.1 Highly variable artificial deposits [Made Ground, Infilled Ground]

These deposits comprise materials placed by man on the natural ground surface or as infill within excavations. Descriptions of the distribution, thickness, and composition

Table 5 Engineering characteristics: soils (descriptions based on BS5930; excavatability based on Pettifer and Fookes, 1994).

Engineering Geological Units		Geological Units	Description/ Characteristics	Engineering Considerations			
				Foundations	Excavation	Engineering Fill	Site Investigation
Engineering Soils **Highly Variable Artificial Deposits**		Made Ground (mgr) Infilled Ground (wmgr)	Highly variable composition, thickness and geotechnical properties.	Highly variable. May be unevenly and highly compressible. Hazardous waste may be present causing leachate and methane production	Usually diggable. Hazardous waste may be present at some sites	Highly variable. Some material may be suitable	Essential to determine depth, extent, condition and type of fill. Care needs to be taken as presence of pollution and contaminated ground likely. Essential to follow published guidelines for current best practice
Coarse Soils		Alluvium – River Channel deposits (Alv_2) River Terrace Deposits (rtdu) Glaciofluvial sand and gravel (lgfg, gfdu & gfdu_b)	Medium dense to dense SAND & GRAVEL with some buried channels and lenses of clay, silt & peat	Generally good. Variable thickness of deposit. Thick deposits in buried channels may be significant in foundation design due to differential settlement	Diggable. Support may be required. May be water bearing	Suitable as granular fill	Important to identify the presence and dimension of buried channels and characteristic of infilling deposits. Geophysical methods may be applicable
Coarse Soils		Buile Hill Sands (glld_s)	Loose to medium dense fine to medium SAND	Poor foundation	Easily diggable. Generally poor stability. Running sand conditions possible below the water table and in pockets at perched water tables	Unsuitable as granular fill	Determine the presence, depth and extent of deposit and depth to sound strata
Fine Soils	**Firm**	Till (Till_1)	Firm to very stiff sandy, gravelly CLAY with some channels and lenses of medium dense to dense sand and gravel	Generally good foundation, although sand lenses may cause differential settlement. Possibility of pre-existing slips can also cause a strength reduction	Diggable. Support may be required if sand lenses or pre-existing slips encountered. Ponding of water may cause problems when working	Generally suitable if care taken in selection and extraction. Moisture content must be suitable	Determine the depth and extent of deposit, especially the frequency and extent of lenses and channels. Investigate whether any pre-existing slips and shear planes are present
Fine Soils	**SOFT**	Alluvium (Alv_1)	Soft to firm CLAY some sand, gravel and peat lenses	Poor foundation. Soft highly compressible zones may be present; risk of differential settlement	Easily diggable. Moderate stability, decreasing with increasing moisture content. Running sand conditions possible below the water table and in pockets with perched water tables. Risk of flooding	Generally unsuitable	Determine the presence, depth and extent of soft compressible zones and depth to sound strata
Fine Soils	**SOFT**	Glaciolacustrine Deposits (glld_1, glld_lenses & glld_ic)	Soft to stiff laminated CLAY with some lenses of sand.	Generally poor foundation as long-term consolidation and differential settlement possible	Easily diggable. Support may be required if sand lenses encountered in deep excavations. Ponding of water or exposure to rain may cause softening of formation	Generally suitable if care taken in selection and extraction. Moisture content must be suitable	Determine the depth and extent of deposit, especially the frequency and extent of lenses
Organic Soils		Peat	Very soft to soft brown fiberous or amorphous PEAT	Very poor; very weak; highly compressible foundation. Acidic groundwater	Diggable. Poor stability. Generally wet ground conditions	Generally unsuitable	Determine the depth and extent of deposit and groundwater's acidity

Table 6 Engineering characteristics: rocks (descriptions based on BS5930; excavatability based on Pettifer and Fookes, 1994).

Engineering Geological Units	Geological Units	Description/ Characteristics	Engineering Considerations			
			Foundations	Excavation	Engineering Fill	Site Investigation
Engineering Rocks						
Weak sandstone	Sherwood Sandstone Group Collyhurst Sandstone	Moderately weak to moderately strong yellow, reddish brown fine- to medium-grained poorly to very well sorted; poorly cemented SANDSTONE occasionally gravelly. Weathers to medium dense to very dense sand up to depths of 5m	Generally good provided suitable design is adopted and the depth of weathered rock head is determined	Dependent on discontinuity spacing and degree of weathering. Ripping or pneumatic tools or blasting generally required	Suitable as high grade fill, if care taken in selection and extraction	Essential to determine depth and properties of weathered zone. In situ loading tests advisable to assess bearing strengths at selected sites
Strong sandstone	Holt Town Sandstone Openshaw Sandstone Newton Heath Sandstone	Moderately strong to strong fine to coarse-grained SANDSTONE with mudstone and siltstone interbeds moderately to well jointed thinly to thickly bedded	Generally good provided suitable design is adopted. Possibility strength variability due to fissuring and weathering. Presence of highly weathered zones need to be assessed	Diggable where rocks are weathered. Ripping or pneumatic tools maybe required at depth in fresh rock	Suitable for general fill under controlled compaction conditions. Moisture content must be suitable	Essential to determine depth and extent of strata, the discontinuity spacing and weathering
Weak mudstone	Manchester Marl	Stiff to weak, reddish brown or purple MUDSTONE. Weathers to a soft to stiff clay	Generally good provided suitable design is adopted. Possibility of strength variability due to fissuring and weathering. Presence of highly weathered zones need to be assessed	Diggable where rocks are weathered. Ripping or pneumatic tools maybe required at depth in fresh rock	Suitable for general fill under controlled compaction conditions. Moisture content must be suitable	Essential to determine depth and extent of strata, the discontinuity spacing and weathering
Strong mudstone	Middle Coal Measures	Moderately weak to strong dark grey to grey laminated MUDSTONE, SILTSTONE and SHALE. Weathers to a firm to stiff brown and grey clay	Generally good provided suitable design is adopted. Possibility of strength variability due to fissuring and weathering. Presence of highly weathered zones need to be assessed	Diggable where rocks are weathered. Ripping or pneumatic tools maybe required at depth	Suitable for general fill under controlled compaction conditions. Moisture content must be suitable	Essential to determine depth and extent of strata, the extent of discontinuity spacing and weathering
Interbedded mudstone, siltstone and sandstone	Halesowen Formation Etruria Formation Undifferentiated Upper Coal Measures	Weak to moderately strong grey interbedded MUDSTONE, SILTSTONE and fine to coarse-grained SANDSTONE. Mudstone and siltstone weathers to a very soft to stiff clay	Generally good provided suitable design is adopted and the depth of weathered rock head is determined. Locally high sulphate conditions	Weathered mudstones usually diggable. Ripping or pneumatic tools required at depth in fresh rock	Suitable for general fill under controlled compaction conditions. Moisture content must be suitable	Essential to determine depth and properties of weathered zone. In situ loading tests advisable to assess bearing strengths at selected sites
Limestone	Yard Limestone Half Yard Limestone Great Mine Limestone	Strong to very strong, dark grey to light grey LIMESTONE with some mudstone interbeds	Generally good provided suitable design is adopted. Bed thickness needs to be assessed	Dependent on discontinuity spacing and mudstone interbeds. Ripping or pneumatic tools or blasting generally required	Suitable as high grade fill, if care taken in selection and extraction	Important to identify the presence of locally highly weathered zones and natural cavities. In situ loading tests advisable to assess bearing strengths at selected sites

of the different types of artificial deposits are given in Section 3.2.2.11.

The artificial deposits across the district are highly variable in composition, geotechnical properties and thickness (1 to 2 m thickness is common but 10 to 15 m occur in areas adjacent to the Manchester Ship Canal and along infilled valleys draining to the River Irwell). The nature of the fill is presented in Tables 3 and 4. Infill materials at these sites may consist of chemical and mining waste, construction materials such as brick concrete and rubble, in addition to bulk fill derived from major excavation works such as the Manchester Ship Canal.

Artificial deposits generated by the disposal of domestic and industrial waste in unlicensed tips are potentially the most problematical to construction and land use. The material may include a very wide range of inorganic, organic, inert, reactive, combustible, harmless and toxic substances. In the worst case, these materials may have been tipped without regard to compaction, containment or their potential to react with each other and the environment, and there may be no record of what has been deposited. It is difficult to predict the engineering ground conditions of these sites since they will be highly variable across their area, and with depth.

Detailed assessment of the ground conditions pertaining to the areas of artificial deposits shown on Figure 5 was not feasible but the following points should be borne in mind.

- Where fill has been placed above ground level, as in infilled streams and on low marshy ground, it may rest on soft alluvial clays which may themselves undergo excessive differential settlement when loaded. Therefore the stability of the ground underlying the fill may need to be examined.
- Where the fill is deep, self-weight will often be the principle cause of long-term settlement. Although major compression occurs almost immediately, significant further movements ('creep settlement') may occur under conditions of constant effective stress and moisture content.
- Excessive differential settlements, leading to distortion and damage to buildings, are to be expected in highly variable poorer types of fill, or where the depth of fill changes rapidly.
- At sites in areas of demolished industrial buildings and housing, load-bearing walls may be present at, or close to, the surface of the fill. New foundations built across such walls and the surrounding fill are liable to severe differential settlements.
- Fill comprising industrial waste may be potentially chemically active.
- Domestic refuse will generate methane gas, which is highly combustible in enclosed spaces.
- Colliery spoil may be liable to spontaneous combustion. In addition, pyrite present in colliery spoil is prone to oxidise and produce sulphate-rich, acidic groundwater leachates causing corrosion problems for buried foundations.

4.5.2 Fine soils

The fine soils of the Manchester area are divided into two groups based on their relative density/consistency.

4.5.2.1 Soft/Firm

This subunit is represented by alluvium (overbank deposits) and glaciolacustrine clay.

Alluvial overbank deposits [alv_1] occur extensively on the valley floor of the River Irwell, and are also present in minor tributary valleys. Thicknesses of up to 6 m are commonly recorded in site investigation boreholes. The deposits are comprised of a very soft to firm, brown-grey clay, with partings of silt and fine- to medium- grained sand. Locally, organic peaty horizons are also present. In engineering terms, they are very soft to firm (SPT N-values are consistently below 10; Table 7), with a low density (1.32 Mg/m^3), high moisture content (31%) and low to intermediate plasticity (Figures 19; 20).

Glaciolacustrine deposits *[glld_1, glld_l)* occur at surface only in one small area, although they have been proved from boreholes to occur as impersistent lenses interdigitating with till and as a more laterally persistent unit overlying till in the south-west of the district. The more extensive deposits comprise laminated clay, clay/silt and sandy clay; the lenticular deposits include more sandy material but this may partly be a function of cross-boundary sampling. The glaciolacustrine clays are generally more plastic than the alluvial overbank deposits and possess highly anisotropic shear strengths due to their laminated structure. SPT N-values are in the soft to stiff range.

Design considerations

Foundations

Low bearing capacities, high compressibilities, high groundwater tables and water uplift pressures, and the likelihood of excessive total and differential settlements pose problems for foundations in the alluvium and glaciolacustrine deposits. Site investigations should aim to ascertain the presence, depth and extent of compressible zones and the depth to sound strata. Due to artificial straightening of the river channels (related to development of the Ship Canal), abandoned meanders occur at several locations in the alluvial floodplain of the River Irwell. It is important that these features are identified during site investigations prior to development and construction.

Table 7 Soil classification based on Soil Penetration Test (SPT) (Clayton, 1995).

CLAYS	**SPT N60 — values (blows/300 mm penetration)**	**Term**
	0 to 4	Very soft
	4 to 8	Soft
	8 to 15	Firm
	15 to 30	Stiff
	30 to 60	Very stiff
SAND and GRAVEL	**SPT N — values** (blows/300 mm penetration)	
	0 to 4	Very loose
	4 to 10	Loose
	10 to 30	Medium dense
	30 to 50	Dense
	>50	Very dense

Where limited thicknesses occur, wholesale removal and replacement of alluvium with suitable fill may be an economic option but elsewhere, alternative solutions are required. Of these, piling and raft foundations are the most commonly used. For heavy structures, bored or driven piles should be used to transfer loads to dense basal gravels or into the underlying bedrock. Mini-piles bearing in dense gravels may be suitable for light to moderately loaded structures.

Suitability as engineered fill

Alluvial silts and clays and glaciolacustrine clays are generally unsuitable for use as fill. Glaciolacustrine clays can be used if care taken in selection and extraction, and the deposit has a suitable moisture content.

Excavatability

Alluvial deposits are readily excavated using soft ground excavating machinery but water inflow problems may be encountered.

Stability of cut slopes and excavations

High groundwater levels (usually within 2 m of the surface) mean that excavations in alluvium are subject to water inflow problems and immediate support is required to maintain the stability of trench sides and cut faces. Running sands may also be encountered below the water table.

4.5.2.2 Firm

This unit is represented by till which covers much of the district. The till comprises a firm to very stiff, grey and red-brown slightly gravelly sandy clay with some channels and lenses of sand, gravel and laminated clays, of which only the larger bodies are separately distinguished in the model (see section 3.2.2.2 for details). From the engineering viewpoint, it is important to stress that, 'till' is used as an umbrella term for material, that at the scale of the investigation, cannot be subdivided, but was almost certainly deposited in a range of glacigenic environments, involving lodgement, meltout and mass movement processes. The geotechnical properties can be expected to vary accordingly. Particle size plots for the till (Figure 21) confirm the occurrence of a range in composition that will influence physical properties and may relate to different depositional processes (McGowen and Derbyshire, 1977). Till may be soft in the near-surface, becoming stiffer with increasing depth. A 3D plot of SPT N-values for the till envelope shows this trend (Figure 22). The till matrix consists of clay ranging from generally low to medium, or less commonly high plasticity. Compressibility is generally low but consolidation settlements may be high in softened till adjacent to water-bearing sand and silty layers or lenses.

Design considerations

Foundations

Till should present no major foundation problems providing thickness and lithological variations are determined during the site investigations and accounted for in design. For example, water-bearing sands and gravels below foundation levels may cause softening, due to artesian conditions. Recorded plasticity indices range from about 20 to 50 per cent, indicative of soils with low to moderate potential for shrinkage. Highly shrinkable soils are unlikely to be encountered in the district.

Suitability as engineered fill

The till may be suitable as fill if care is taken in selection and extraction. Because of lithological variations, selection of suitable material will need to be made on a site-specific basis. Laminated clays, which occur locally within the till, are usually unsuitable for use as fill. Clay occurring near water-bearing beds of sand and gravel may be similarly unsuitable.

Excavatability

Till may be machine-dug with the prospect of hard digging in very stiff over-consolidated material. Ponding of surface water in low permeability till may cause problems during working.

Stability of cut slopes and excavations

Temporary cuts or excavations in till should remain stable in the short-medium term, and possibly long-term in low cuts. The presence of layers of laminated silt and clay will reduce stability considerably, as will sand and gravel horizons resulting in perched water tables and increased seepage.

4.5.2.3 Coarse soils

This group of materials consists predominantly of medium dense, fine- to coarse-grained sands and medium dense to dense, fine- to medium-gravels with some cobbles and boulders. Impersistent layers and lenses of clay and silt are developed locally. The materials are associated with alluvial channel, river terrace and glaciofluvial outwash deposits. The distribution of these units within the geological model is shown schematically in Figure 7 and covered in more detail in earlier sections (3.2.2). Particle size distribution curves (Figure 23) show broadly similar gradings except for the Buile Hill Sands, which are remarkable for their fine grain size and good sorting, possibly indicating deposition in standing water. For the granular materials, SPT N-values are in the medium dense to dense range, the highest values being recorded in the basal outwash deposits (mean N-value 36).

Design considerations

Foundations

Provided lithological variations are identified, the terrace and outwash deposits should pose no major problem for most foundations. Recorded groundwater sulphate concentrations generally fall into Class 1 of the BRE classification (British Research Establishment Digest, 2001), indicating that no special precautions are normally required to prevent attack on buried concrete.

Suitability as engineered fill

Most classes of coarse soils should be suitable for use as granular soil fill if care is taken in selection and excavation. However, the Buile Hill Sands are unlikely to be suitable because of their fine grain size.

Excavatability

Surface deposits are easily excavated by mechanical digging. Running conditions may be encountered in sands below the water table.

Stability of cut slopes and excavations

Excavations and cut slopes will normally require immediate support. Casing will be required to prevent collapse of granular material into bores. Water ingress may be a problem if excavations are taken below river/canal level, or in areas where there is a perched water table.

4.5.2.4 Organic soil and peat

Areas of mossland peat occur in Trafford Park, and as impersistent layers and lenses within the Alluvium (section 3). Organic soils and peats result in soft ground conditions and typically possess low densities, high moisture contents and low strengths.

Design considerations

Organic soils and peats offer very poor foundation conditions due to low bearing capacities and high, often uneven settlement. The deposits remaining in Trafford Park are of limited extent, however, if encountered in construction work it is advisable that they are removed prior to development The groundwater in organic soils may be highly acidic and appropriate precautions such as selection of suitably resistant concrete will normally be required to prevent damage and disintegration of foundations (British Research Establishment Digest, 2001).

Use as engineering fill

Organic soils are unsuitable under any circumstances for forming load-bearing fills.

Excavatability

Excavation of peat is easily accomplished by hand digging but machine digging is usually required when encountered at or below foundation levels. Trafficability will vary according to the nature of the material and local groundwater conditions.

Stability of cut slopes and excavations

Very wet peat soils will suffer poor face stability and in extreme cases trench support and dewatering may be required.

4.6 ENGINEERING OUPUTS

Thematic Map 2 shows the distribution in the subsurface of the 'engineering soils' at depths below ground of 2, 5 and 10 m. This type of presentation has clear advantages over the conventional 2D map for illustrating likely foundation conditions for different types of development and also serves as guide to the type of detailed ground investigation required.

Full geotechnical attribution of the model volumes has not yet been achieved but is the subject of on-going research. An example of the type of output that can be expected is illustrated in Figure 24, which shows the variation of SPT N-values throughout the till envelope.

4.7 EXTRAPOLATING GEOTECHNICAL DATA IN 3D

The Manchester case study gives some insights into the benefits of spatial visualisation of geotechnical data; particularly the ease with which detailed spatial relationships can be identified. However, extrapolation of geotechnical data on a regional scale (> 75 km^2), particularly when applied to variable glacial superficial deposits, has to be undertaken with extreme care. Geotechnical data is collected for the purposes of small-scale (< 1 km^2) site appraisals. Applying and extrapolating these data over larger distances will inevitably exceed the scale for which this information was originally intended. In interpreting the information portrayed in the 3D model, it is important, therefore, to understand this limitation on the use of such data.

5 Protection and management of urban groundwater

5.1 INTRODUCTION

One consequence of the European Water Framework Directive is that, as surface and groundwater safeguards become more stringent, there will be a greater need to manage urban water resources in a more sustainable manner. The Environment Agency has taken a pro-active stance in the Manchester region, where as part of a broader study of the Manchester East Cheshire aquifer, one of the objectives has been to examine recharge mechanisms in the drift-covered urban areas of south Manchester and Salford. The research carried out under the 3D modelling project has contributed to this study and led to the development of a conceptual model covering issues of recharge and vulnerability, which are dealt with in section 5.4.

The 3D model has also been used to examine methods for assessing the suitability of sites for installation of sustainable urban drainage systems (section 5.5).

This section starts with an overview of the hydrogeology of the district.

5.2 LOCAL ISSUES

The Permo-Triassic sandstones beneath central Manchester and Salford form part of the Manchester and East Cheshire aquifer which is a significant groundwater resource for both industrial and public water supply. Historically over-abstraction in some parts of the aquifer has resulted in falling groundwater levels and the localised upflow of saline water. Recent changes in patterns of abstraction in response to industrial policy, and the local policies of the Environment Agency have resulted in recovery of water levels in some areas. However, there remains a level of uncertainty as to the sustainable level of abstraction in the aquifer. This is complicated by the abandonment of coal mines to the north of the area, which may potentially affect flow patterns and groundwater quality within the aquifer. In order to fulfill its statutory duties to manage and protect water resources, the Environment Agency is undertaking a regional groundwater study to quantify the sustainable resources of the aquifer. This has involved development of a conceptual model of the aquifer, and will provide the framework for future resource management. The third phase of that project focuses on the complex hydrogeology of Trafford Park.

One of the key areas of research relates to the rate of recharge, which is at present poorly constrained but is an important parameter as it effectively defines the available water resource. It also, to some extent, defines the vulnerability of the aquifer to pollution. Most recharge reaches the sandstone aquifer via the thick superficial deposits that cover much of the region. Understanding the complexities and hydrogeological performance of these superficial deposits is therefore important if estimates of recharge are to be realistic.

A collaborative study between BGS and the Agency has looked at the issue of recharge in the Manchester and Salford area. The work builds on the 3D modelling experience discussed in earlier sections but extends the original project area southwards to the River Mersey (Figure 25).

5.3 HYDROGEOLOGICAL SETTING

The main aquifer in the district is the Triassic Sherwood Sandstone Group. The Permian Collyhurst Sandstone is also a significant aquifer, but is only distinguished in the east of the district where it is separated from the Sherwood Sandstone Group by the Permian Manchester Marls Formation. A number of national studies have shown that flow in the sandstones is by a combination of fissure and intergranular flow (e.g. Ingram et al., 1981; Campbell, 1982; Walthall and Ingram, 1984). The aquifer provides baseflow to the rivers and also groundwater for industrial abstractions. Sandstone bodies within the Coal Measures crop out in the north and east of the district and are also significant water-bearing units.

Most of the rivers rise on high moorland to the north and east of the area and generally have already gained significant flows by the time they reach the Manchester conurbation. All are tributaries of the River Mersey. The Manchester Ship Canal is a significant feature of the local hydrology, receiving flows from the rivers Irwell, Medlock, and Irk. There are also a number of smaller canals such as the Bridgewater Canal.

Existing published studies and reports, prepared as part of the regional groundwater study, provide considerable background information. Some of the key issues related to this study are summarised in the following sections.

5.3.1 Groundwater protection

Much of the area has a long legacy of industrial development with associated soil contamination. This has led to industrial pollutants within the groundwater as well as more serious localised levels of contamination. Contaminated land is a particularly important issue along the corridor of the Manchester Ship Canal (including Trafford Park) and in Central Manchester where redevelopment continues. There are no public water supplies from groundwater sources in the district, but Source Protection Zones (SPZs) have been defined for some of the larger abstractions in Manchester used mainly for brewing.

5.3.2 Groundwater abstraction and groundwater levels

Groundwater abstraction is concentrated around the industrial areas of Trafford Park and the Irwell valley. An embargo on new groundwater abstraction licences in the Trafford Park area was first introduced by the former Mersey and Weaver River Authority in 1973 because of the highly depressed groundwater levels around Trafford Park and the deteriorating quality of the groundwater in the area following heavy industrial abstraction. Groundwater abstraction in the Trafford Park area between 1940 and 1960 averaged 20 Ml/d. In the 1990s this had reduced to about 8 Ml/d. As a result, since the late 1960s, groundwater levels in much of the study area, including Trafford Park, have recovered significantly.

Groundwater level contours in the Sherwood Sandstone Group have been produced for the Agency at five-year intervals (Ruxton and Bennett, 1996–2000). The contours for 2000 are included in Figure 26. In general, groundwater levels decline from a high of approximately 50 m OD in the south and east to a low of 15 m OD in the west. There remains a marked pumping-induced cone of depression around Trafford Park, where groundwater levels are presently depressed to approximately 30 m below OD, which is significantly below their 'natural', pre-abstraction position. Elsewhere in urban Manchester, groundwater levels have generally stabilised and are broadly similar to surface water elevations, suggesting that groundwater is now discharging to surface water either directly or via sewers and drains, although the degree of interaction will depend on the nature of the superficial deposits.

The low groundwater levels of the 1960s and 1970s mean that structures built during these periods (e.g. basements, tunnels and lift shafts) may be at risk as groundwater levels recover. Rising groundwater levels have recently been a feature of the northern part of the aquifer and, in particular, the areas under Manchester and around Trafford Park. Levels in some places are stable but the natural equilibrium position of these groundwater levels is at present unclear as few data are available to indicate the natural position of the water table prior to the start of pumping. Groundwater levels do not fluctuate seasonally by more than 1 m across the aquifer.

Coal mining was abandoned in this part of the Lancashire Coalfield over 30 years ago and this has led to rapidly rising groundwater levels in the Carboniferous strata that underlie and abut the Sherwood Sandstone aquifer. In the north, (Agecroft [SD804 010] especially), the outbreak of mine waters is predicted. Mine water is also currently discharged into the Bridgewater Canal. The abandoned coal mines under Manchester have not yet been studied in any great detail and as a result the potential significance of rising groundwater levels in these units is unclear.

The degree of hydraulic connection between the Coal Measures and the sandstones is poorly constrained by available data, and there is some potential for poor quality water associated with the flooded mines to affect the quality of groundwater in the Permo-Triassic aquifer.

In the north of the area, groundwater levels in the Collyhurst Sandstone at Newton Heath [SD 880 003] have continued to rise steadily over the period of monitoring. This borehole is in an isolated fault block and may reflect local changes in abstraction or rising groundwater levels in the adjacent Coal Measures (Environmental Simulations International Ltd, 2001).

5.3.3 Discharges

Measurements of discharge to surface waters from sewage treatment works for the months of June 2000 to February 2001 indicate that Davyhulme sewage treatment works contributes by far the largest flow at an average rate of 370 Ml/d (ESI, 2001). This is discharged into the Manchester Ship Canal south of Eccles. Two further large discharges are located on the Manchester Ship Canal.

5.3.4 Water quality

Groundwaters within the Permo-Triassic sandstone aquifer are predominantly of Ca-HCO_3 or Ca-Mg-HCO_3 type but show a trend towards Ca-Mg-HCO_3-SO_4 type. There are a significant number of Na-Cl type groundwaters; most have a fairly high hardness, low dissolved oxygen, and a relatively high iron and manganese content.

Analyses associated with the BGS EA Baseline Aquifer Chemistry Project (Griffiths et al., 2003) indicated that some trace element chemistry is a cause for concern. Arsenic has a median value of 1.18 $\mu g\ l^{-1}$, but concentrations in excess of the EU Maximum Admissible Concentration (MAC) drinking water standard of 50 $\mu g\ l^{-1}$ have been recorded. Cadmium has a median value of 0.55 µg/l but some values also exceed the MAC of 5 $\mu g\ l^{-1}$.

The groundwater chemistry implies that the groundwater is relatively old, and that the overall impact of fresh recharge water is low. Low dissolved oxygen and high iron concentrations are indicative of reducing conditions, although the organic content of the aquifer is very low. This water type is dominant in the south of the aquifer and to the west of the Manchester Marls subcrop, with the exception of the Trafford Park [707 961] and Chat Moss areas. Patches of more recently recharged groundwater, especially along lengths of the Manchester Ship Canal, show lower hardness values. To the east, the groundwater chemistry suggests that, although discontinuous, the Manchester Marls compartmentalise groundwater bodies in this area and impede groundwater flow (ESI, 2001).

In the Trafford Park area, there are problems with high Fe concentrations and salinity. Groundwater with high iron concentrations has been identified at shallow depth (< 20 m) in parts of Trafford Park [e.g. 783 981]. Below this depth at c. 40 m, the iron concentrations are much lower. Abstraction in the Trafford Park area has also led to an increase in salinity from upwelling of saline groundwater from depth. There have been a number of studies to investigate the special problems associated with the groundwater chemistry of this area (Pitman, 1981; Tellam and Lloyd, 1986; Tellam et al., 1986; Stansbury, 1994; Tellam, 1995). Electrical conductivity values in the order $10^4 \mu S/cm^{-1}$ are common within the area of Trafford Park. These are mostly associated with elevated concentrations of sodium chloride, although the other major cations (calcium, magnesium and potassium) are also present in elevated concentrations. Tellam (1995) examined the saline waters in detail and stated that the salinity is derived from deep halite brines.

5.4 AQUIFER VULNERABILITY MODEL FOR CENTRAL MANCHESTER AND SALFORD

Aquifer vulnerability is essentially a measure of the susceptibility of the groundwater to pollution and is determined by the intrinsic characteristics of the strata separating the saturated aquifer from the land surface (Foster, 1998). The transport of most groundwater pollutants to saturated aquifers occurs in the aqueous phase (apart from some insoluble hydrocarbons) and forms part of the recharge process. Therefore the vulnerability of an aquifer is intrinsically linked to the recharge mechanisms and pathways.

In England and Wales groundwater protection is administered by the Environment Agency through a two-tier approach. Public water supply abstractions are protected from polluting activities by *Source Protection Zones* (SPZ). Three zones (Inner, Outer and Total catchment) are defined, based on the calculated travel time for a particle of water to reach the abstraction point. Stringent controls are placed on activities that can take place within the Inner SPZ. At a regional scale, *Groundwater vulnerability* maps identify areas vulnerable to groundwater pollution.

The assessment of vulnerability is based on an estimation of:

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

The first generation of these maps, published in the late 1990s, was criticised for their small scale (1:100 000), which makes them less appropriate for site assessment, and for the lack of account taken of superficial deposits. They are also of limited use in urban areas where soils are always assigned a worst-case vulnerability.

The vulnerability model prepared for central Manchester and Salford goes some way to addressing these criticisms. The model, which is derived from the 3D geological model, takes account of the spatial distribution of the main superficial deposits, their interconnectivity and inferred permeability. The model is designed with a resolution capable of supporting broad land use planning decisions, but should be used in conjunction with additional studies (i.e. intrusive site investigation) when dealing with site-scale contaminant issues. The effects of soil cover and the thickness of the unsaturated zone are not considered in this pilot study but will be included in a later iteration through inclusion of soil geochemistry and first-strike water data.

5.4.1 Hydrogeological properties of the superficial deposits

Hydraulic conductivities were assigned to each of the modelled units (Table 8). The figures are taken from published sources (Todd, 1980; Allen et al., 1997; Brassington, 1998) and are based on an assessment of the gross lithology of each unit as summarised in borehole descriptions. The figures assume horizontal flow in a saturated medium, and are not necessarily representative of the unsaturated zone. Additionally, the concept of vulnerability assumes vertical pathways, but it is common for vertical permeability to be lower than horizontal permeability because of sediment stratification.

As a check on the validity of the assigned hydraulic conductivity ranges, values were also determined from particle size data using Hazens empirical formula. Although the method is not strictly applicable to poorly sorted deposits, and the effective grain size is commonly below the stipulated limits of 0.1 to 3 mm (Fetter, 2001), the calculated values fell within the estimated ranges.

It should be stressed that the figures take no account of factors, such as weathering or fracturing, which may increase permeability.

The **alluvial channel** (alv_2) and **river terrace** (rtdu) deposits are assigned the highest hydraulic conductivities but some variation can be expected due to the heterogeneity of the deposits.

The **glaciofluvial outwash sheet deposits** (lgfg) and **basal sand and gravel deposits** (gfdu_b) contain a proportion of clay, notably in their upper parts, and this is reflected in the hydraulic conductivity range.

The **ice-contact sands** (glld_s) of Buile Hill are well-sorted and in consequence are given a relatively narrow hydraulic conductivity range.

The **alluvial overbank deposits** (alv_1) comprise mainly silt and clay, and are interpreted as having a relatively low hydraulic conductivity and are not able to transmit significant quantities of groundwater.

The **laminated lacustrine clays** (glld_1) are homogenous and are assigned the lowest hydraulic conductivity estimate.

The **till** (till_1) is highly heterogeneous and comprises clay to gravel grade material. There is the potential for gravel-rich areas of the deposit to transmit significant volumes of groundwater.

On the basis of the assigned permeabilities, the deposits are classified as either permeable or weakly permeable

5.4.2 Hydrogeological cross-sections

Selected cross-sections derived from the geological model illustrate the superficial-bedrock relationships along key linear features, such as the Manchester Ship Canal (Figure 27). Sections in the Trafford Park area are located in areas of particular interest to the Environment Agency. As an aid to interpretation the bedrock geology has been added manually. Annotations show where potential pathways from ground surface to the underlying aquifer exist, and where pathways are likely to be restricted due to intervening weakly permeable deposits. The annotations identify:

- direct pathways to bedrock (i.e. rockhead at outcrop)
- pathways via permeable superficial strata (as identified in Table 8)
- potential lateral 'drainage' pathways in perched permeable strata and artificial ground

The pathways are drawn on the following assumptions:

- all weakly permeable deposits with a thickness of less than 5 m may still offer a potential pathway due to weathering or discontinuities, and are accordingly classified as permeable
- made ground is highly heterogeneous and of variable thickness, therefore its impact on vulnerability and recharge is difficult to define; consequently it is treated as permeable to give a worst-case scenario
- perched conditions are assumed where permeable strata overlie low permeability strata with a thickness greater than 5 m
- pathways take no account of groundwater head gradients

Groundwater levels within the Permo-Triassic aquifer (Ruxton and Bennet, 2000) have been added to the sections for reference purposes. The cross-sections highlight specific areas where the nature of the superficial deposits is likely to have a significant influence on recharge.

Because groundwater head gradients have not been considered in detail, the potential pathways indicating where 'perched' water may be present should be considered more as 'drainage pathways' in these deposits.

The basal architecture of the outwash sands has been annotated in plan view as an example of potential lateral pathways (Figure 28). These are based solely on the slope of the base of the deposits and do not incorporate groundwater head data as this information is not currently available at suitable resolution or quality. Only lateral pathways are indicated. However it is important to note that there are also likely to be vertical pathways depending on the permeability

Table 8 Hydraulic conductivity of modelled units.

Model unit/notation	Lithology	Inferred permeability	Estimated hydraulic conductivity range (md^{-1})
Alluvium overbank floodplain deposits) (alv_1)	Silt, clay, peat	Weakly permeable	$10^{-5} – 10^{-2}$
Alluvium (river channel deposits) (alv_2_	Sand, gravel, peat	Permeable	$10^{-3} – 10^{4}$
River terrace deposits (rtdu)	Sand, gravel, possibly with a clay-rich upper surface	Permeable	$10^{-3} – 10^{4}$
Outwash sheet deposits (lgfg)	Silty sand, on clayey sand and gravel	Permeable	$10^{-4} – 10^{3}$
Glaciolacustrine deposits (glld_1)	Laminated silt and clay	Weakly permeable	$10^{-6} – 10^{-4}$
Glaciofluvial ice-contact sands (glld_s)	Loose, fine sand overlying laminated silt	Permeable	$10^{-2} – 10^{1}$
Till (till_1)	Till with interbedded sand and impersistent laminated clay	Generally weakly permeable but some permeable lenses	$10^{-4} – 10^{1}$
Basal sand and gravel (gfdu_b)	Clayey sand and gravel	Permeable	$10^{-5} – 10^{3}$

of the underlying strata and the prevailing hydraulic conditions.

Used in conjunction, the cross-sections and plans together provide an indication of those critical areas of the district where the superficial deposits are likely to have a major influence on recharge and where the bedrock aquifer is at its most vulnerable. Identified sites are described in more detail below.

Manchester Ship Canal

A cross-section along the line of the Manchester Ship Canal (Figure 28, section 8) indicates that for most of its length the canal is in contact with Permo-Triassic sandstone, apart from at its western end and near Salford Quays, where thickening till intervenes between the base of the canal and the underlying aquifer. The modelled piezometric surface lies above the base of the canal and it is likely that the canal system and groundwater are hydraulically connected except where the canal base is excessively silted, or where it may have been engineered to reduce leakage. An accurate water level for the canal is required to indicate if the aquifer is recharged by, or discharges to, the canal. This may vary seasonally, be impacted by pumping in Trafford Park, or may have changed due to a decline in overall groundwater abstraction in Manchester.

To the north of the canal, in Eccles, the Permo-Trias comes to crop or is only covered by thin till (Figure 28, section 2), and is likely to be highly vulnerable.

Trafford Park

The superficial deposits beneath Trafford Park show a significant increase in thickness from north to south (Figure 28a, section 2). In the north of the park, a thin sequence of outwash, glaciolacustrine clay and till onlaps against a rockhead high, creating conditions of high vulnerability. Farther south, the vulnerability reduces as till thickens into a deep buried valley system. Several sand and gravel lenses are identified within the till, however the connectivity between these units is uncertain. The large drawdown cone of depression, centred beneath Trafford Park, has the effect of locally making the aquifer unconfined beneath the till, where it would otherwise be naturally confined. This could induce leakage from the overlying strata (depending on vertical head gradients), and could locally increase the aquifer vulnerability. The lack of a cone of depression associated with pumping adjacent to the Manchester Ship Canal (for example at Cerestar No. 2 [7828 9814]) supports the view that there is hydraulic connection between the aquifer and the canal. The actual pumping rate at this location is not accurately known but is believed to be in excess of 3000 m^3/d.

River Medlock

A section drawn along the course of the River Medlock (Figure 28, section 5) shows only a relatively thin superficial drift cover in the middle and upper reaches of the stream where it flows across Collyhurst Sandstone and Carboniferous rocks; aquifer recharge, and vulnerability is likely to be high in parts of this section. Downstream, the superficial deposits thicken as outwash sheet deposits and river terrace deposits develop on till. Hereabouts, the aquifer is less vulnerable, but perched groundwater may be present in the permeable superficial deposits, possibly with lateral flow to the west.

Modelled groundwater levels for the Permo-Triassic sandstone are below the base of the River Medlock indicating that aquifer recharge may occur along this water course. However, the River Medlock is largely culverted downstream of Bradford, which is likely to reduce recharge.

East Manchester

A thickening of the till sheet to the east of Manchester (Figure 28, section 7) is likely to reduce the vulnerability of, and recharge to, the underlying aquifer in this area. Several permeable sand and gravel lenses may act as perched aquifers, however the connectivity of these units from ground surface to bedrock is uncertain.

5.4.3 Hydrogeological domain mapping

The concept of domains has been applied successfully elsewhere to characterise the spatial variability of Quaternary sequences, particularly at catchment scale or larger (e.g. McMillan et al., 2000). A modified approach is adopted in this study to develop a vulnerability map based on a re-attribution of the 3D geological model.

Domains were determined on the basis of four main factors:

- the inferred permeability of the modelled units (Table 8)
- the thickness of the modelled units (5 m is the minimum thickness considered)
- the presence of superposed (multiple) units of differing permeabilities
- the classification of the bedrock (as major, minor, or non-aquifer)

Using the above criteria, nine domains were defined, which are listed in order of decreasing vulnerability in Table 9. The most vulnerable case is where a major aquifer is at outcrop (Domain 1). Lower vulnerability is assumed where one or more weakly permeable units overlie the aquifer. In cases where a permeable unit overlies a thick, weakly permeable unit (for example, sheet outwash on till), the aquifer is defined as perched, and is given a low ranking as there is a less likelihood of a vertical pathway to bedrock. The lowest vulnerabilities are assigned to thick sequences of weakly permeable deposits (e.g. glaciolacustrine clays), and to the non-aquifer domain. Subdomains represent a further refinement, which covers relationships between individual lithofacies. Whether this level of detail is valid has yet to be tested. The schematic diagram (Figure 29) illustrates the vertical relationships within each of the domains. The domain map was created using the spatial analyst extension in Arc-8. Grid-to-grid operations were carried out to determine vertical connectivity between modelled units. Assumptions about potential pathways and permeability are the same as those adopted for the hydrogeological cross-sections (see 5.4.2).

5.4.3.1 Domain Descriptions

The vulnerability model incorporating the nine hydrogeological domains is shown in Figure 30.

Domain1
Major aquifer outcrop

This domain identifies where the Permo-Triassic sandstone aquifer is at outcrop, or covered by less than 5 m of weakly permeable deposits (till, glaciolacustrine clay, or alluvial clay and silt). The aquifer is likely to be most vulnerable, and receive significant recharge (per unit area) under suitable head conditions. This domain covers the Eccles area of Manchester, and includes sections of the Manchester Ship Canal. The water table is above the base of the Manchester Ship Canal and is approximately 10 to 15 m below ground level on higher ground to the north of the canal. The water level within the canal has not been measured as part of this study and no attempt has been made to identify if this feature is recharging to, or being recharged by, the aquifer (see Figure 28, section 8). Further smaller outcrop areas, identified to the east of the city centre, are associated with rockhead highs.

Domains 2 and 3
Major aquifer at outcrop or concealed by permeable superficial deposits

These two domains cover situations where:

- a single permeable unit is in direct contact with, or no more than 5 m above, bedrock (Domain 2), or where
- multiple permeable units (containing no more than 5 m of lower permeability material) are in contact with bedrock (Domain 3)

Domain 2 is associated with the incised alluvial tract of the River Irwell, and with the terrace deposits of the River Medlock. In both cases, bedrock is covered by a relatively thin cover of alluvial [alv_2] or terrace [rtdu] sand and gravel. The domain also includes areas in the north of Trafford Park where outwash sheet deposits [lgfg] overlap less permeable deposits to rest directly on bedrock. Around Manchester City Centre, the domain is defined by the occurrence of outcrops of basal glacigenic sand and gravel [gfdu_b]. Sands within the buried valley system are generally too deep to be included within this category, although some small patches are present adjacent to the River Irwell valley to the north of the city centre.

Multiple permeable deposits (Domain 3) are defined where, for instance, basal sand and gravel [gfdu_b] is overlain directly by river channel deposits (alv_2), as at Salford Quays. This domain has a lower vulnerability ranking because it allows for the presence of up to 5 m of intervening low permeability material, and vertical pathways may be longer.

Domains 4, 5 and 6
Minor aquifer at outcrop or concealed by permeable superficial deposits

These domains are developed above minor aquifers, which in this district are formed by Carboniferous rocks (Coal Measures). The eastern outcrops are generally concealed by a thick cover of till, except along the River Medlock. The aquifer is better exposed in the north-west but again is locally concealed by deposits of till and glaciolacustrine clay.

Domain 7
Perched permeable superficial deposits

This domain identifies areas susceptible to developing a perched water table. This is likely to occur where permeable deposits in the near-surface are underlain by significant thicknesses (>5 m) of less permeable material. The units most likely to be affected are:

- river channel deposits [alv_2]
- river terrace deposits [rtdu]
- outwash sheet deposits [lgfg]
- glaciofluvial sands [glld_s]
- intra-till sheet sands [gfdu_l]

The outwash sheet deposits form the most extensive perched aquifer as they are mostly underlain by glaciolacustrine clay and/or till. Pathways in these relatively flat outwash deposits are not easily defined and are likely to be dependent on groundwater head gradient. The architecture of the deposits implies drainage pathways are likely to be orientated westwards following the regional dip on the base of the deposits, with slight deviations towards the main river valleys (River Mersey, and Bent Lanes Brook).

There are perched aquifers along the River Irwell where till underlies the valley, and in the terrace deposits of both the Irwell and Medlock. The groundwater is likely to form a contiguous surface in connected alluvial bodies regardless

Table 9 Hydrogeological domains.

	Group	Domain		Sub-Domain	
Decreasing potential recharge and aquifer vulnerability	Major Aquifer	1	Outcrop	1a	Bedrock at outcrop
				1b	Bedrock overlain by < 5m of weakly permeable strata
		2	Permeable superficial deposit	2a	River channel deposits
				2b	River terrace deposits
				2c	Outwash sheet deposits (Late Glacial Flood Gravels)
				2d	Basal gravel deposit
				2e	Glaciolacustrine sand and silt
		3	Multiple permeable superficial deposits	3a	River channel deposits, basal gravel deposit
				3b	River terrace deposits, basal gravel deposit
				3c	Outwash sheet deposits, basal gravel deposit
				3d	Glaciolacustrine sand and silt, basal gravel deposit
	Minor Aquifer	4	Outcrop	4a	Bedrock at outcrop
				4b	Bedrock overlain by <5m of weakly permeable strata
		5	Permeable superficial deposit	5a	River terrace deposits
				5b	Outwash sheet deposits
				5c	Basal gravel deposit
				5d	Glaciolacustrine sand and silt
		6	Multiple permeable superficial deposits	6a	Glaciolacustrine sand and silt, basal gravel deposit
	Perched aquifer	7	Perched permeable superficial strata	7a	River channel deposits
				7b	River terrace deposits
				7c	Outwash sheet deposits
				7d	Glaciolacustrine sand and silt
	Aquitard	8	Low permeability superficial strata	8a	Alluvium (overbank deposits)
				8b	Till
				8c	Glaciolacustrine clay
	Non-Aquifer	9	Non-aquifer bedrock strata	9a	Manchester Marls Formation

of whether the alluvial bodies are perched or in direct contact with bedrock.

It should be noted that leakage from sewers, water pipelines and soakaways will form a large proportion of the water balance of perched aquifers and may result in point or line source recharge, for which the model is not currently configured.

Domain 8
Weakly permeable superficial deposits

Overbank alluvium [alv_1], till [till_1], and glaciolacustrine clay [glld_1] deposits have been classified as weakly permeable deposits and are likely to inhibit vertical recharge and promote run-off.

The glaciolacustrine clay deposits comprise laminated, stone-free clays but are generally less than 5 m in thickness and are largely covered by outwash deposits (see Domain 7). Consequently there are only small isolated areas where the glacial lake clay becomes an important element of the model.

Thick overbank alluvial deposits (> 5 m) occur intermittently along the River Irwell valley and in these areas run-off is likely to be directed towards the river (assuming no intervention from land drains).

Till is the single biggest component of the model but its variability poses real uncertainties about its overall hydrogeological behaviour. For the purposes of the model, it is regarded as weakly permeable, and it is assumed that thicknesses greater than 5 m are likely to significantly reduce recharge. However, it is possible that inter-connected sand and gravel lenses within the till may introduce additional local pathways.

Domain 9
Non-aquifer bedrock

The Manchester Marls are classified as a non-aquifer and are preserved as faulted slivers in the eastern, central and north-western parts of the district. Domain 9 has been created to identify areas where the Manchester Marls are at outcrop.

5.4.4 Usage

The model is intended for use at catchment and sub-catchment scale. No quantitative assessment of uncertainty associated with domain delineation has been made but this area of research is currently being examined through use of fishbone/fuzzy logic approaches. A crude assessment of the reliability of the model can be judged from a review of borehole densities. In Table 10 the number of available boreholes used to construct each domain is shown. A distinction is drawn between boreholes that partially penetrate each domain and those that penetrate fully.

The model is also likely to be influenced by the affects of surface sealing, and point or line source recharge as a result of leakage through sewers, water pipelines and soakaways. Both of these factors can be accommodated through additional attribution of the model should there be a need.

5.5 SUSTAINABLE URBAN DRAINAGE SYSTEMS

5.5.1 Introduction

Sustainable Urban Drainage Systems (SUDS) are an alternative approach to conventional drainage systems, which replicate as far as possible the natural drainage and manage runoff where it occurs. The successful implementation of SUDS techniques, including swales, balancing ponds and porous pavements can save money, reduce pollution and alleviate flood risk (CIRIA, 2001). The system design and choice of devices depends on local factors but essentially relies on attenuation, treatment and infiltration techniques to deal with surface run-off.

The applicability of SUDS techniques to a particular geological situation can be assessed by reference to the 3D model. Information critical to the assessment includes:

- the topographical slope angle
- the permeability of the near-surface deposits, and
- the thickness of the unsaturated zone

By combining this information as a simple tri-category map, areas more suited to infiltration techniques can be identified. Additional constraints (potential for contamination, surface sealing) can be incorporated to make the model more robust. The slope angle can be calculated from a digital terrain model, and permeability values for different lithologies are published in the hydrogeological literature (e.g. Allen et al., 1997; McMillan et al., 2000). However, the thickness of the unsaturated zone is more difficult to define because of the transient nature of groundwater levels, which may be affected by seasonal fluctuations or longer term events. To properly determine the variation in thickness of the unsaturated zone requires monitoring of groundwater levels over a significant period of time. Not only is this expensive, but it is not a practical solution over the comparatively short time scale of a typical redevelopment,. An alternative approach examined in this study was to try and derive values for the thickness of the unsaturated zone by careful screening of irst water-strike measurements as recorded in borehole logs. The results of this exercise are discussed below.

5.5.2 First-strike data

From the outset, the question arises as to what constitutes a water-strike. In a 100 m borehole, the driller is unlikely to be concerned about water ingress in the top few metres, whereas all seepages may be recorded in a shallow site investigation hole. There exists, therefore, a large element of uncertainty about how the data should be interpreted or indeed whether it is possible to use it at all in this context. The first step in assessment was therefore to remove obvious sources of uncertainty and carry out a simple statistical analysis.

Water-strike information was extracted from all available borehole logs and loaded to an Excel database. From an original total of 1589 measurements, the data were sorted to remove obvious outliers, including null or positive values

Table 10 Borehole density by domain.

	Number of boreholes that partially penetrate the domain (PP)	Number of boreholes that fully penetrate the domain (FP)	Domain total area (km^2)	Borehole density boreholes/km^2		
				PP	FP	Total
Domain 1	241	0	10.78	22.36		22.36
Domain 2	58	300	12.92	4.49	23.22	27.71
Domain 3	32	19	2.57	12.45	7.39	19.84
Domain 4	23	0	1.14	20.18		20.18
Domain 5	2	7	1.98	1.01	3.54	4.55
Domain 6	0	0	0.003	0.00	0.00	0.00
Domain 7	26	302	22.43	1.16	13.46	14.62
Domain 8	418	292	39.89	10.48	7.32	17.80

(above DTM), and values showing large changes over very short distances. A further screening was carried out to remove all water-strike data prior to 1980 to try and reduce fluctuations caused by over-abstraction and changing water levels in the 1970s and 1980s (5.3.2). A total of 1026 water-strike values remained after this round of filtering. Simple histogram analysis of the sorted data indicated that approximately 90 per cent of first water strikes were between two and six metres below ground surface (Figure 31), suggesting the regular occurrence of a shallow water table within the superficial deposits.

As a check on the overall validity of the dataset, first-strike depths were plotted against ground height. In an ideal situation, the relationship between surface elevation and the depth to first strike should be approximately linear as the groundwater surface usually follows a subdued representation of the topography (Salama, 1996). The cross-plot (Figure 32) shows that in practice the first-strike data is poorly correlated with ground height. This may be due in part to the inadequacies of the data but may also reflect the complexity of the superficial geology where a range of sediments of varying thickness and permeability are unlikely to conform to the ideal of a single continuous groundwater surface.

5.5.3 First-strike data analysis by domain

To assess the first-strike data in a more controlled hydrogeological setting, first-strike results were analysed spatially using the domain map as a basis for sub-setting the data. Geologically, one of the simplest domains to test the data against is the perched outwash sheet domain (Domain 7, Table 9). This domain has the advantage of being of relatively large aerial extent, and comprises a simple vertical profile of outwash deposits above glaciolacustrine clays or till. It is inferred that the outwash sand and gravels will support a perched water table, which is unlikely to be in direct continuity (vertically) with groundwater in the Permo-Triassic sandstone aquifer and can, therefore, be treated as generally having an independent water table surface.

A plot of the first-strike data for this domain shows a weak trend, with depth to first strike increasing eastwards beneath rising ground (Figures 33; 34). However, within this overall trend, there are clusters of data points which show significant variations in depth to first strike for sites of similar elevation; this is illustrated by two clusters at elevations of between 21.3 to 23.5 m OD and 24.8 to 26.6 m OD.

From this preliminary analysis, it can be concluded that

- at a broad scale there does appear to be a relationship between depth to first strike and topography if the data are properly screened; however, within this overall trend measurements may range over several metres. This may be attributable to the time between measurements (months to years), to variations in classification of a water strike, or may be natural (i.e. a perched lens, or localised variations in water table possibly influenced by drainage)
- the depth to water strike generally does not vary rapidly between adjacent boreholes and increases the likely reliability of the measurements
- the method is highly reliant on rigorous data assessment and processing and there is a danger that the data could be over-processed to fit the desired results

In summary, it seems that the first-strike method offers a crude means of assessing the thickness of the unsaturated zone, which may be applicable to SUDS. However, given the limitations of the methodology, it is recommended that where first-strike data is used as a surrogate for depth to water table, it must be checked carefully for consistency, and any groundwater surfaces created should be validated against surface water features and actual groundwater monitoring measurements.

6 Land use

Land use studies were undertaken to assist in the interpretation of the geochemistry (section 7) and to provide information on surface sealing for intended future use in connection with on-going aquifer vulnerability studies (5.4.3).

6.1 PRESENT-DAY LAND USE

The district was split into land parcels and classified according to the National Land Use Database 'Previously Developed Land' (NLUD-PDL) Scheme version 3.2 (www.nlud.org.uk). The scheme is hierarchical and based on 13 main land use types, or 'divisions' but allows for a further 51 'classes' and 431 'subclasses'. The Manchester district was classified to division level, but further subdivided into two classes (recreation, and industrial and commercial) to aid interpretation of other related data (Table 11).

Land use divisions were assigned by one of three methods:

- from 1:10 000 scale OS base-maps (dated 1993–1994), A–Z encyclopaedia (Geographers' A–Z Map Co. Ltd, 2000) and Manchester City Centre land use map
- from airphotographs dating from 1998
- from local knowledge, primarily derived from fieldwork carried out in 2001

Land parcel digitisation and polygon attribution was carried out in Arcview 3.2. A minimum land parcel size of 0.25 ha (50 × 50 m) was used to enable effective coverage of the area. Capture of specific features was limited as follow:

- watercourses : only those watercourses indicated on OS 1:50 000 base-maps by a double line with a water fill
- roadways: motorways or A-roads only
- railways: to include the full extent of the embankment and/or cutting

The present-day land use map of the district (Figure 35) shows a concentration of industrial and commercial land in the Trafford Park, Weaste, Manchester city, Strangeways, Bradford and Openshaw districts. Residential areas are for the most part restricted to the periphery of the district. Larger recreational areas are present along the Medlock at Clayton Vale, the Irwell at Salford, along Worsley Brook at Winton, and Bent Lanes Brook; smaller areas are scattered mainly in the north-west and south-east parts of the area.

6.2 PAST POTENTIALLY CONTAMINATIVE LAND USE

The past potentially contaminative land use caters for three eras, with snapshots covering the late Victorian period (1890s), the 1920s and the 1950s (Figure 36). The survey involved a trawl of legacy 1:1250 scale and 1:2500 scale Ordnance Survey maps, and subsequent digitisation at 1:10 560 scale. Past potentially contaminative land use was categorised using an enhanced version of the DoE Classification of Contaminative Industries (DoE, 1991). This classification splits land uses into 20 categories and 57 subcategories (Table 12). In addition to a land use category and subcategory, all identified sites were assigned a name, address, details of activity (such as type of mill), any additional notes and a unique reference number.

The past potentially contaminative land use map for 1890 shows that industry was closely associated with the main transport corridors of the time, including rivers and canals, as well as the rail routes. The western part of the area, including Eccles and Trafford Park remained undeveloped at this time, as did much of the area around Abbey Hey and Debdale in the east. By the 1920s, Trafford Park had begun to develop, along with the Ordsall and Weaste in response to the opening of the Ship Canal. To the north of the city, the Strangeways area was also becoming industrialised. In the south-west, the Davyhulme Sewage Works complex was opened in 1894, at the same time as the Manchester Ship Canal. The 1950s map shows a general expansion in industries across the area, but with concentrations in Eccles, Pendleton and the St George's–Hulme areas.

Table 11 Land use classification scheme based on the National Land Use Database (NLUD).

NLUD Division	NLUD Class/Subclass
Agriculture	
Woodland	
Water and Wetland	
Minerals and Landfill	
Recreation	Outdoor
	Indoor
	Allotments
Transport	
Residential	
Community buildings	
Industrial and Commercial	Undifferentiated
	Graveyard
	Cemetery
Vacant land and buildings	

Table 12 Classification of past potentially contaminative industries.

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

7 Soil geochemistry

7.1 INTRODUCTION

This section describes the results of a geochemical soil sampling programme undertaken in central Manchester and Salford in the summer of 2002. It forms part of a national programme of urban sampling which, to date, provides coverage of 21 cities. The data have a range of applications in relation to land use planning, urban regeneration and assessing the extent of urban contamination. Full integration of the data with the 3D groundwater model has still to be completed but the data are included here for completeness.

The Manchester soil survey was based upon the collection of 315 surface (0.15 m depth) and profile (0.45 m depth) soil samples collected on a grid pattern at a sampling density of 4 per km^2. Following air drying, surface soil samples were sieved to < 2 mm before analysis by X–ray Fluorescence Spectrometry (XRF) for total concentrations of approximately 25 elements; pH and loss-on-ignition (LOI), as a measure of organic content, were also determined. A detailed description of the sampling methodologies employed is given in the Technical Appendix.

7.2 POTENTIAL SOURCES OF CONTAMINATION IN URBAN SOILS

The chemistry of urban soils is determined by three main factors:

- the chemistry of the parent material
- the source of any imported material used as fill, and
- contamination from varied anthropogenic sources

Major sources of elevated metal concentrations in urban areas are well documented in the literature and include materials associated with building, waste disposal, industrial and manufacturing processes and use of fossil fuels. The types of contaminants commonly associated with these activities are summarised in Table 13.

7.3 SURFACE SOIL GEOCHEMISTRY

Proportional symbol maps (e.g. Figure 37) show the distribution of individual element concentrations across the study area, and summary statistics for the entire dataset are given in Table 14. To help set the data in a wider geographical context, median elemental concentrations are also quoted from the Geochemical Atlas of England and Wales (McGrath and Loveland, 1992) or, where these are not available, from estimated world topsoil values (Reimann and Caritat, 1998).

7.3.1 Analysis of results

Elements with concentrations that exceed the reference median values for topsoil include Ag, As, Ba, Br, Cd, Cr, Cu, Ge, Ni, Pb, Sb, Sn, W and Zn. This group is typically found in elevated concentrations in urban areas, where metallurgical industries and coal mining have been important historically.

Other elements with elevated concentrations are not as widely known. For example, the median value of germanium (Ge) is considerably higher than the given reference median values. Germanium is commonly associated with Pb and Zn sulphide ores and is invariably associated with Zn in nature, being frequently recovered as a by-product of Zn smelting (Reimann and Caritat, 1998).

The median value of bromine (Br) is twice as high as the reference median value. Although the most common environmental pathway for Br deposition is in sea-salt, its enhanced concentrations in Manchester topsoil may be attributed to road salting practice or it may be a result of traffic pollution. In the past, ethylene dibromide (1, 2-dibromoethane) was used as a lead scavenger in petrol anti-knock compounds (Reimann and Caritat, 1998).

7.3.2 Comparison of Manchester soil geochemistry with rural soils

To try and gauge the extent to which soils in the Manchester urban area have been affected by anthropogenic activities, it is instructive to compare metal concentrations of the urban soils with those found in samples from surrounding rural areas. Results from the rural G-BASE survey of 2060 samples from North-west England and North Wales (British Geological Survey, 1997) are given in Table 15 for comparison. Although no account has been taken of the more varied bedrock of the rural areas, it is evident that the mean and median values of Cd, Cu, Pb, Mo, Sn, V and Zn are higher in the urban area, reflecting the influence of anthropogenic deposition. Interestingly, values for Ba, Cr and Ni are either similar to, or lower than their rural counterparts.

7.3.3 Statistical analysis to determine element associations

Spatial relationships between elements were examined by calculating correlation coefficients. Elements that are strongly correlated (r>0.6) are shown highlighted in the matrix (Table 16). Cluster analysis was also performed to identify element groupings. The graphic output is a dendrogram where the degree of association is strong between members of the same cluster and weak between members of different clusters (Figure 39). The results produced by these statistical techniques are discussed below.

Alumino-silicate and clay minerals

A group of elements related to Al (Al_2O_3), is positively correlated including Ti, K, Rb, Nb and Ga. These elements are typically found in alumino-silicates, and form a large part of the < 0.2 μm or clay mineral fraction of the soil. Silicon (Si), the other major component of alumino-silicate minerals, was found to have highly negative correlations with many of the elements associated with Fe oxides (Fe, Sc, V, Co, Ni, La, Ce and Nd).

Fe and Mn oxides with associated trace elements

Elements Mn, Fe, V, Ni, Co, Ba and Sr form a group typical of soils developed over iron or steel works. A second group

Table 13 Typical sources of metal contamination found in urban soils.

Contaminant Source	Likely contaminants	Elements	References
Buildings, households and waste disposal	Paints Fossil fuel residues Refuse disposal Sewage disposal	Ag, As, Cd, Co, Cr, Cu, Ni, Pb, Se, Hg, Sb, Sn, W, Zn.	Kelly and Thornton, 1996 Meyer et al., 1999
Urban Surface Runoff and transport corridors	Petrol Diesel Tyres Blown dust from transport of goods or railway sidings	Pb from old petrol Ba to reduce soot emissions Zn from hardener used in tyres Ag, As, Cd, Co, Cr, Cu, Ni, Pb, Se, Hg, Sb, Sn, W, Zn from coal or metal related dusts	Kelly and Thornton, 1996 Monaci and Bargagli, 1997 Ge et al., 2002
Metal smelting	Ore materials; atmospheric emissions; transport of materials	Zn, Cd, Pb, As, Sb, Cu, Mo, Fe, Tl, Sn and Bi	Kelly and Thornton, 1996 Rieuwerts and Farago, 1996 Rawlins et al., 2002
Extraction and combustion of fossil fuels		Ag, As, Cd, Co, Cr, Cu, Ni, Pb, Se, Hg, Sb, Sn, W, Zn. Fly ash may also contain B, Be, V, Mo, Mn and Te	Kelly and Thornton, 1996
Manufacturing industries	Metal related Battery manufacture Chemicals (inc. agro-chemicals Oil and oil-related industries Textiles and leather Glass and ceramics	Cr, Ni, Cu, Zn, Cd Ni, Cd, Zn, Sb, Hg, Pb P, N, As, Cr, Cu, Zn, Cd, Sn, Hg, Pb Cr, Ni, V, Co, Cu, Zn, Cd, Mo, As, Pb Cr Cr, Pb, Co, Se, Cu, Mo, Ti, Fe	Kelly and Thornton, 1996 Pichtel et al., 2000.

of linked elements includes Ge, Mo, As, Se and Tl. It is likely that these two groups are related because they are naturally associated in sulphide deposits and metal ores (Reimann and Caritat, 1992).

Rare-earth elements (REE)

Fe and Mn oxides are associated with a range of trace elements and rare earth elements (REE) including Zn, Ga, Sc, Ge, Sr, Se, Y, Mo, Th, Sn, La, Ce and Nd, all with r values > 0.6. Sequential extraction analysis has shown that rare earth elements are related to Fe and Mn oxides in soils (Land et al., 1999).

Mining and related activities

On the dendrogram a group of seven elements (Cr, Cu, Zn, Pb, Sn, Sb and W) are commonly associated with mining or metallurgical industries. Some of these elements, such as Zn and Pb, co-exist in ore deposits such as galena (PbS) and sphalerite (ZnS). Arsenic is highly correlated with Cr (0.77) and Cu (0.81). Arsenic and copper are often found together in ore materials such as copper arsenic sulphide (Brocardo, 1982).

Other correlations

Other correlations highlighted in the correlation matrix include:

Pb and Tl (0.86) These two elements are often found in sulphide deposits.

Soil pH and Ca (0.62) Ca is reported as CaO in the XRF analysis. However, it is likely that much of the Ca occurs as $CaCO_3$, which if present naturally or applied to soils as limestone will be important in determining soil pH.

LOI and Br This association has been reported in a survey of Austrian soils (Gerzabek et al., 1999) and could be due to Br being present in soil organic matter (Müller, 2003). In addition, a strong correlation between LOI and P probably results from P being present in plant and soil microbial biomass.

Zr and Hf Zirconium sand is used in foundry cores, welding rod coatings and abrasive cleaning and contains Hf as an impurity (Reimann and Caritat, 1998).

7.3.4 A comparison of surface soil metal concentrations with CLEA Soil Guideline Values (SGVs)

Metal with published Soil Guideline Values

DEFRA Soil Guideline Values (SGVs) are intended to assist local authorities in making decisions relating to the remediation and sustainable re-use of contaminated land (DEFRA, 2002a). They are a tool that can be used to assess the risks posed to human health from exposure to contaminated soil. Values have been derived for three typical land uses (Table 17) (DEFRA 2002 b, c, d, e, f, g, h):

- residential (with/without plant uptake)
- allotments
- commercial/industrial

Where applied appropriately, metal concentrations exceeding a Soil Guideline Value may suggest the need for either further investigation and/or remediation. In the context of the published Soil Guideline Values, the main findings of the Manchester soil survey are:

- maximum concentrations of As, Cd, Cr, Pb and Ni exceed the SGVs for the two most sensitive categories — 'residential' and 'allotments' (Table 18)

Table 14 Summary statistics for total soil element concentrations and other soil parameters (n = 300 unless stated). Median values are given for the UK, where available (McGrath and Loveland, 1982), or from an estimated world average* (Reimann and Caritat, 1998).

Element	Min	Max	Median	Mean	Std Dev	Skew	Median England and Wales (mg kg^{-1}) unless stated (*)
Soil pH	3.9	7.98	6.28	6.11	0.86	-0.56	
LOI							
Ag	0.3	7.9	0.6	0.8	0.8	4.97	0.07*
Al_2O_3 (%)	5.2	23.6	9.8	10.12	2.28	1.61	
As	2.5	1001	20.1	27.9	58.41	15.61	5*
Ba	287	5476	511	583	370.3	8.44	121
Bi (n=299)	0.1	34.3	0.2	0.82	2.6	9.2	0.3*
Br	1.6	38.7	14.8	15.20	5.46	0.59	10
CaO (%)	0.13	8.81	1.18	1.42	1.13	2.85	
Cd	0.3	80.3	0.9	1.4	4.7	16.0	0.7
Ce	14	112	46.0	48.4	13.9	1.43	65
Co	3	44	9	9.9	4.4	3.22	9.8
Cr	30	1238	76	92.3	92.4	8.65	39.3
Cs (n=237)	2	8	2	2.33	1.04	3.32	3
Cu	7.2	2073	85.9	120.5	176.2	2.81	18.1
Fe_2O_3	1.27	20.26	4.55	4.91	1.88	2.93	
Ga	4.8	32.1	9.7	10.2	3.21	2.52	
Ge	1.6	31.8	3.9	4.7	3.21	30.4	2.1*
Hf	1.1	12	3.4	3.5	1.1	2.4	5*
I	1	10	2	2.05	1.2	2.1	2
K_2O (%)	1.11	3.6	1.62	1.66	0.34	1.87	
La	6	76	25.5	26.9	9.5	1.5	35
MgO (%)	0.2	2.7	0.9	0.98	0.39	1.57	
MnO (%)	0.02	0.63	0.07	0.07	0.05	7.02	
Mo	0.1	21.9	2.5	3.1	2.8	15.2	1.2
Na_2O (%)	0.3	0.8	0.5	0.519	0.06	0.69	
Nb	2.1	15.9	7.6	7.8	1.9	1.3	12
Nd	8	52	21	21.7	6.8	1.4	
Ni	4.5	148.3	29.4	33.54	17.8	2.9	22.6
P_2O_5 (%)	0.08	1.3	0.29	0.33	0.17	2.19	
Pb	19.5	2758	218.3	276.3	268.2	5.37	40
Rb	35.8	165.9	57.2	59.1	14.8	2.72	65
Sb (n=299)	1.9	48.7	5.4	7.55	6.6	3.2	0.5*
Sc	3	29	10	10.49	3.09	1.76	12*
Se	0.1	3.2	0.4	0.52	0.43	2.06	0.3*
SiO_2 (%)	35.5	86.2	66.95	66.22	7.05	-0.80	
Sm	1	17	4	4.8	3.4	0.7	6.1*
Sn	3.3	365.1	18.15	29.6	36.8	4.73	4*
Sr	43.3	336.4	69.9	76.8	30.5	3.73	27
Ta	0.1	2.1	0.2	0.42	0.4	1.4	1.1*
Te	0.5	4.1	0.5	0.54	0.25	10.6	
Th	2.3	20.9	6	6.24	1.9	2.5	9.4*
TiO_2 (%)	0.12	0.93	0.44	0.46	0.11	0.68	
Tl	0.1	4.1	0.3	0.45	0.46	3.5	0.5*
U	0.1	4.5	2.1	2.1	0.67	0.49	2.7*
V	26	234	82	86.8	26.8	2.0	90*
W	1	33.2	2.3	2.9	2.8	7.06	1.5*
Y	6.1	43.6	17.6	18.2	50.2	4.9	20*
Zn	25	1363	168	222	176.2	2.82	82
Zr	62	500	154	157.6	39.6	19.7	230*

Table 15 Comparison of mean and median values for selected metals from the Manchester urban survey (n = 300) and rural values (n = ~2060) collated from the G-BASE survey of north-west England and north Wales (BGS, 1997).

Element	Mean Manchester (mg kg^{-1})	Median Manchester (mg kg^{-1})	Mean NW England and N Wales (mg kg^{-1})	Median NW England and N Wales (mg kg^{-1})
Barium	583	511	646	551
Cadmium	1.4	0.9	0.7	<0.6
Chromium	92	76	114	104
Cobalt	9.9	9	12	11
Copper	120	86	43	21
Lead	276	218	117	43
Molybdenum	3.1	2.5	< 1	<1
Nickel	34	29	35	32
Tin	30	18	8.4	2
Vanadium	87	82	79	77
Zinc	222	168	147	105

- mean and median concentrations of As exceed the SGVs for two categories — ‘residential with plant uptake’ and ‘allotments’
- the mean and median concentrations of Cd are just below, and just above, the respective SGVs (for a pH value of 6)
- Mean and median values for Pb, Ni and Cr are below the SGV values
- For commercial/residential land the highest As and Pb concentrations exceed the SGVs for that land
- Concentrations of Se throughout the dataset are very low (mean = 0.52, median = 0.4) and do not approach the SGVs for any of the categories

Other metals

It should also be noted that high metal concentrations occur for other elements where SGVs are still to be published.

- The elements Cu and Zn have maximum concentrations of 2072 and 1363 mg kg^{-1} respectively. As an indication of the possible degree of spatial soil contamination from these two elements, 24 per cent of Cu and 18 per cent of Zn analyses exceed the DEFRA sludge limits for Potentially Toxic Elements in agricultural land (MAFF, 1995) (where pH > 6)
- Antimony and its compounds are a priority interest for the USEPA and EU (Filella et al., 2002). Typical concentrations in uncontaminated world topsoils are generally < 5 mg kg^{-1} (Filella et al., 2002). Results from the Manchester survey indicate that 55 per cent of soil samples have concentrations > 5 mg kg^{-1}

7.3.5 Urban soil geochemistry in relation to land use

The relationship between soil geochemistry and land use was investigated by reference to a modified version of the National Landuse Database scheme presented earlier (Tables 11; 19). A comparison of mean and median results for eight metals from each of the present day land use categories (Table 20). surprisingly, shows only minor differences across the different land use categories. One exception is the water (canal side) category where soils are relatively enhanced in a wide range of elements including As, Cu, Cr, Ni, Pb and Se. Historically, the canals were major transport routes for bulk minerals, and elevated element concentrations may derive from wind-blown dust from these shipments or from the redistribution of canal dredgings. Plots (Figure 39) show a similar pattern of elevated concentrations for Ba, Br, Ce, Co, Ge, La, Mo, Sb, Sn, Sr, V, W and Y. In addition, higher mean and median concentrations of per cent LOI, Ca and Fe along the canal path suggest significant redistribution of contaminated material in this part of the city.

The degree of consistency of metal concentrations across the remaining seven categories is unexpected, given the range of potentially contaminative processes that once operated. It may be that, at a sampling density of only four samples per km^2, many contaminated areas were excluded from the sampling programme or the sites were already built over. Evidence that this may have been the case, is seen when the sample locations are plotted against the land use map for 1950, which shows that the majority of sample points fall outside designated industrial areas (Figure 40).

7.3.6 The distribution of metal contamination

Overall, the geochemical results show few well-defined trends, however, there are a number of locations where adjacent soil samples show elevated concentrations of metals (Thematic Map 4). In some cases, these ‘hot spots’ probably relate to former metallurgical and chemical industries present in 1950, with some dating back as far as 1890. For example metal works, extraction and mineral processing industries have long been a feature of the River Irwell near Lower Broughton and Charlestown, Strangeways and Bradford (Map 4; Land use inset, areas 5, 8, and 10).

Elevated concentrations of some metals are present along the Cheshire Ring Canal in Trafford Park (Map 4, area 4). Dust from transported goods can produce areas of linear pollution along transport routes and this may have contributed to the concentrations in this area. Elsewhere in Trafford Park, the survey picked up little evidence for widespread contamination.

Table 16 Correlation coefficients (r) between elements in Manchester topsoil.

	pH	LOI	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	Fe2O3	Sc	V	Cr	Co	Ba	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Rb	Sr	Y	Zr	Nb	Mo	Hf	W	Tl	Pb	Bi	Th	U	Ag	Cd	Sn	Sb	La	Ce	Nd
pH	1																																											
LOI	-0.27	1																																										
Na2O	0.05	0.07	1																																									
MgO	0.33	-0.16	0.05	1																																								
Al2O3	0.03	0.11	-0.06	0.54	1																																							
SiO2	-0.05	-0.63	-0.14	-0.23	-0.52	1																																						
P2O5	-0.31	0.54	0.12	-0.2	-0.08	-0.35	1																																					
K2O	0.22	-0.13	-0.17	0.66	0.8	-0.32	-0.22	1																																				
CaO	0.62	0.06	0.13	0.24	-0.02	-0.41	-0.02	0.08	1																																			
TiO2	-0.05	0.25	0.06	0.52	0.95	-0.55	0.01	0.7	-0.04	1																																		
MnO	0.01	0.21	0.12	0.09	0.18	-0.36	0.22	0.11	0.1	0.19	1																																	
Fe2O3	0	0.53	0.12	0.14	0.51	-0.77	0.28	0.32	0.22	0.51	0.37	1																															
Sc	0.04	0.51	0.09	0.32	0.71	-0.83	0.25	0.5	0.28	0.7	0.33	0.85	1																														
V	-0.08	0.59	0.08	0.17	0.59	-0.83	0.3	0.37	0.2	0.59	0.36	0.87	0.91	1																													
Cr	0.08	0.21	0	0.07	0.11	-0.32	0.22	0.09	0.29	0.11	0.14	0.29	0.25	0.25	1																												
Co	0	0.52	0.13	0.11	0.46	-0.75	0.29	0.29	0.27	0.45	0.35	0.92	0.85	0.89	0.27	1																											
Ba	-0.05	0.33	0.05	0.04	0.33	-0.43	0.27	0.23	0.11	0.31	0.14	0.49	0.47	0.5	0.23	0.46	1																										
Ni	0.03	0.56	0.16	0.12	0.44	-0.8	0.3	0.27	0.33	0.43	0.37	0.9	0.86	0.92	0.31	0.94	0.5	1																									
Cu	0.04	0.31	0.05	-0.08	0.08	-0.42	0.23	-0.02	0.34	0.09	0.32	0.46	0.33	0.39	0.72	0.45	0.28	0.5	1																								
Zn	0.07	0.47	0.26	-0.04	0.12	-0.52	0.39	0.02	0.27	0.16	0.41	0.65	0.48	0.54	0.48	0.63	0.47	0.66	0.64	1																							
Ga	-0.02	0.3	-0.05	0.42	0.92	-0.64	0.06	0.73	0.04	0.87	0.25	0.71	0.84	0.77	0.19	0.67	0.41	0.65	0.19	0.3	1																						
Ge	-0.2	0.62	0.19	-0.15	0.17	-0.58	0.43	-0.02	0.09	0.2	0.27	0.79	0.66	0.76	0.22	0.81	0.46	0.83	0.41	0.65	0.46	1																					
As	-0.01	0.16	-0.07	-0.07	-0.03	-0.22	0.11	0	0.27	-0.02	0.15	0.23	0.13	0.17	0.77	0.21	0.12	0.23	0.81	0.39	0.08	0.19	1																				
Se	-0.3	0.6	0.05	-0.14	0.34	-0.6	0.53	0.12	0.03	0.36	0.29	0.68	0.67	0.75	0.22	0.69	0.45	0.7	0.33	0.48	0.57	0.73	0.16	1																				
Br	-0.5	0.76	0.1	-0.3	-0.01	-0.39	0.52	-0.25	-0.15	0.11	0.17	0.31	0.31	0.46	0.09	0.32	0.19	0.37	0.18	0.28	0.18	0.53	0.13	0.64	1																			
Rb	0.11	-0.08	-0.18	0.56	0.89	-0.36	-0.16	0.95	0.01	0.8	0.13	0.38	0.58	0.45	0.1	0.34	0.26	0.32	0.01	0.03	0.84	0.04	0	0.25	-0.14	1																		
Sr	0.25	0.29	0.1	0.21	0.43	-0.68	0.17	0.38	0.57	0.39	0.25	0.67	0.73	0.73	0.37	0.75	0.55	0.79	0.52	0.48	0.53	0.48	0.32	0.48	0.12	0.4	1																	
Y	0.01	0.45	0.17	0.3	0.72	-0.77	0.24	0.5	0.21	0.73	0.34	0.87	0.92	0.89	0.27	0.87	0.5	0.87	0.38	0.52	0.83	0.68	0.14	0.67	0.27	0.58	0.77	1																
Zr	-0.03	-0.1	0.29	0.21	0.5	-0.03	-0.14	0.25	-0.13	0.58	0	0.02	0.14	0.03	0.05	-0.04	0.02	-0.05	0.03	-0.05	0.3	-0.13	-0.1	-0.02	-0.1	0.33	0.01	0.25	1															
Nb	0.04	0.18	0.1	0.53	0.93	-0.55	-0.03	0.71	0.07	0.96	0.2	0.55	0.73	0.63	0.17	0.51	0.34	0.51	0.17	0.21	0.87	0.24	0.03	0.37	0.05	0.8	0.52	0.79	0.59	1														
Mo	-0.13	0.62	0.14	-0.16	0.17	-0.64	0.38	-0.01	0.17	0.2	0.34	0.84	0.67	0.77	0.28	0.84	0.45	0.85	0.5	0.67	0.44	0.9	0.27	0.69	0.45	0.05	0.56	0.7	-0.15	0.24	1													
Hf	-0.04	0.08	0.25	0.21	0.41	-0.16	-0.06	0.22	-0.03	0.48	0.03	0.11	0.21	0.14	0.18	0.08	0.09	0.09	0.21	0.11	0.29	-0.03	0.08	0.04	0.01	0.27	0.13	0.28	0.74	0.51	-0.02	1												
W	-0.09	0.2	0.07	-0.01	0.1	-0.26	0.16	0.04	0.09	0.15	0.16	0.2	0.17	0.23	0.21	0.21	0.1	0.25	0.28	0.31	0.13	0.15	0.19	0.09	0.14	0.07	0.2	0.18	0.04	0.16	0.26	0.11	1											
Tl	-0.11	0.38	0.16	-0.05	0.12	-0.37	0.47	0	0.07	0.15	0.24	0.46	0.38	0.45	0.25	0.45	0.4	0.46	0.28	0.5	0.3	0.56	0.11	0.59	0.37	0.07	0.29	0.47	-0.05	0.17	0.5	-0.02	0.06	1										
Pb	-0.02	0.37	0.24	-0.11	0	-0.31	0.51	-0.12	0.13	0.05	0.23	0.44	0.31	0.36	0.33	0.41	0.42	0.43	0.34	0.59	0.17	0.55	0.14	0.49	0.31	-0.06	0.27	0.41	-0.04	0.08	0.51	-0.02	0.09	0.86	1									
Bi	-0.16	0.16	-0.03	-0.02	0.04	-0.16	0.5	-0.01	-0.01	0.05	0.04	0.08	0.08	0.07	0.29	0.06	0.22	0.09	0.2	0.17	0.05	0.1	0.12	0.22	0.08	0	0.04	0.1	-0.01	0.02	0.07	0	0.01	0.33	0.32	1								
Th	0.06	0.27	0.08	0.35	0.83	-0.66	0.11	0.6	0.16	0.8	0.27	0.68	0.8	0.73	0.35	0.66	0.44	0.67	0.45	0.4	0.85	0.42	0.2	0.53	0.12	0.71	0.66	0.85	0.47	0.85	0.45	0.47	0.22	0.37	0.31	0.12	1							
U	-0.08	0.28	0	0.17	0.61	-0.41	-0.06	0.42	0.03	0.63	0.07	0.42	0.58	0.52	-0.03	0.43	0.18	0.42	0.05	0.05	0.6	0.25	-0.05	0.31	0.14	0.5	0.44	0.56	0.37	0.65	0.27	0.3	0.24	-0.12	-0.25	-0.2	0.57	1						
Ag	-0.12	0.4	0.08	-0.05	0.13	-0.39	0.6	0.02	0.08	0.15	0.15	0.49	0.38	0.39	0.3	0.45	0.51	0.45	0.34	0.53	0.27	0.5	0.13	0.47	0.21	0.04	0.3	0.4	-0.04	0.14	0.48	0.04	0.09	0.54	0.56	0.73	0.32	-0.03	1					
Cd	-0.04	0.08	0.01	0.01	0.07	-0.06	0.11	0.04	-0.01	0.07	0.05	0.09	0.07	0.06	0.1	0.08	0.09	0.11	0.07	0.11	0.06	0.07	0.02	0.17	0.01	0.06	0.05	0.08	0.03	0.07	0.04	0.03	0	0.05	0.07	0.18	0.08	0.02	0.11	1				
Sn	-0.02	0.48	0.15	-0.09	0.1	-0.46	0.35	-0.01	0.2	0.13	0.2	0.69	0.45	0.5	0.26	0.62	0.42	0.63	0.5	0.69	0.3	0.7	0.22	0.48	0.26	0	0.4	0.48	-0.11	0.15	0.7	0.01	0.22	0.44	0.49	0.22	0.32	0.1	0.62	0.09	1			
Sb	-0.05	0.41	0.17	-0.13	0.05	-0.41	0.33	-0.05	0.16	0.09	0.31	0.49	0.37	0.46	0.22	0.47	0.35	0.51	0.4	0.61	0.21	0.54	0.2	0.44	0.3	-0.01	0.37	0.41	-0.09	0.12	0.55	0.06	0.33	0.44	0.46	0.14	0.27	0.08	0.37	0.3	0.5	1		
La	-0.06	0.46	0.04	0.3	0.8	-0.75	0.19	0.54	0.1	0.8	0.31	0.8	0.9	0.86	0.2	0.79	0.44	0.8	0.32	0.42	0.88	0.59	0.1	0.62	0.28	0.64	0.67	0.92	0.29	0.82	0.61	0.31	0.19	0.33	0.23	0.07	0.85	0.64	0.33	0.05	0.41	0.32	1	
Ce	-0.02	0.41	0.08	0.34	0.83	-0.76	0.14	0.57	0.14	0.82	0.31	0.79	0.9	0.85	0.25	0.79	0.45	0.79	0.36	0.4	0.89	0.56	0.13	0.61	0.24	0.67	0.71	0.94	0.35	0.86	0.57	0.34	0.19	0.34	0.26	0.07	0.89	0.63	0.31	0.09	0.39	0.3	0.95	1	
Nd	-0.01	0.41	0.05	0.31	0.76	-0.73	0.16	0.54	0.12	0.75	0.31	0.76	0.87	0.83	0.15	0.78	0.42	0.77	0.26	0.36	0.84	0.55	0.07	0.58	0.24	0.63	0.67	0.89	0.23	0.78	0.57	0.22	0.2	0.28	0.19	0.09	0.79	0.62	0.3	0.09	0.36	0.29	0.89	0.9	1

Table 17 DEFRA soil guideline values for assessed metals. Units are all mg kg-1 based on total metal concentrations.

Metal	Residential with plant uptake		Residential without plant uptake	Allotments	Commercial/ industrial	Manchester soil statistics (mean, median, max)
arsenic	20		20	20	500	28, 20, 1001
cadmium	pH 6 = 1 pH 7 = 2 pH 8 = 8		30	pH 6 = 1 pH 7 = 2 pH 8 = 8	1400	1.4, 0.9, 80.3
chromium	130		200	130	5000	92,76, 1238
inorganic mercury	8		8	15	480	
lead	450		450	450	750	275, 218, 2758
nickel	50		75	50	5000	34, 29, 148
selenium	35		260	35	8000	0.52, 0.4, 3.2

Contaminated soils are also commonly found in association with railway depots and sidings, due to storage of coal and other materials (Ge et al., 2000). Areas 8 and 11 probably fall into this category.

There are a number of areas where elevated metal concentrations are clearly associated with the redistribution of waste products. The sewage works at Crofts Bank (Map 4; Land use inset, area 2) and Medlock Vale (area 11) are examples. Medlock Vale is also an area where the enhanced geochemical concentrations reflect extensive spoil and landfill operations.

7.3.7 How does Manchester compare with other urban areas?

By comparing metal concentrations in soils from surveys conducted in other urban centres, it is possible to draw comparisons between cities and towns that have similar industrial legacies. The histogram (Figure 41) shows median values of selected metals from the Manchester survey alongside results for Swansea (Morley and Ferguson, 2001), Telford (Brown, **in prep**), Cardiff (Brown, 2000) and Stoke (Fordyce and Ander, 2003). All these urban areas are similar in that they have historical associations with coal and metal processing industries that are known to cause anthropogenic inputs of metals. Median concentrations of Cr, Ni and As from the Manchester survey are similar to those found in the other urban areas, with the exception of Swansea, where the median value of As is higher. However, median values of Cu and Pb are higher in Manchester than Telford, Cardiff and Stoke. In all these urban areas the median concentrations of As, Cr, Cu, Ni, Pb and Zn exceed the median values of 5, 39, 18, 22, 40 and 82 mg kg^{-1} respectively, for typical top soils as noted in Table 14.

7.3.8 Relating soil geochemical data to environmental issues

Concerns relating to human and ecosystem health are posed where metal concentrations are known to be elevated. In these situations, it is important to consider the 'bio-availability' or 'bio-accessibility' of the metal and the potential exposure routes to the receptor organism. Assessing these factors may require more specialised measurements. However, the following points may be considered as a guide to potential routes of exposure.

The 'bio-availability' and uptake of heavy metals by plants and soil biota is dependent on the solubility of the metal in question. Soil pH is the major determinant controlling the solubility of heavy metals and metalloids in soils. For metals such as Pb, Cu, Zn, Cd and Ni, a low soil pH will potentially increase the solubility of these metals (Sauvé et al., 1997a; b; Tye et al., 2003), possibly leading to increased uptake in plants (Parker et al., 2001; Hough et al., 2004).

Table 18 Percentile value at which Soil Guideline Value (SGV) is exceeded for surface soils (0–15cm).

Metal	Residential with plant uptake	Residential without plant uptake	Commercial/Industrial
Arsenic	48	48	No soils exceed SGV
Cadmium	pH 6 = 58 pH 7 = 91 pH 8 = No soils exceed SGV	No soils exceed SGV	No soils exceed SGV
Chromium	97.2	No soils exceed SGV	No soils exceed SGV
Lead	86.4	86.4	No soils exceed SGV
Nickel	90.5	97.2	No soils exceed SGV
Selenium	No soils exceed SGV	No soils exceed SGV	No soils exceed SGV

Table 19 Land use in areas with elevated metal concentrations.

Area	Land use 1950	Land use present day
1	Industrial (iron and brass)	Residential; recreation; transport
2	Sewage treatment and works	Residential; vacant land
3	Oil and petrol storage; garage facilities	Residential; recreational; transport; industrial
4	Chemical works – dye, paint, varnish, roofing felt; engineering	Industrial and vacant land
5	Dockyard and council depots; textiles (waterproofing); chemical works; petrol filling and bulk storage	Industrial; residential; wetland
6	Pulp and paper works; engineering (switchgear and die casting)	Industrial; residential; transport
7	MOD land; hospitals and cemetery; electricity substation	Residential; commercial; industrial
8	Works, metal works, railway land and landfill (unspecified)	Residential and community buildings; industrial and commercial; vacant land
9	Metal works; textile and engineering works (unspecified)	Community buildings; recreation; transport; industrial and commercial
10	Engineering, gas and coke works; pulp and paper works; textiles	Industrial and commercial; vacant land and buildings; recreation and transport
11	Allotments; hospitals and cemetery; spoil and landfill (unspecified); railway sidings; sewage treatment; slagheap; oil refineries	recreation

Therefore, one potential route of exposure may be the uptake of metals in vegetables grown in gardens and allotments.

Unlike the metals listed previously, the behaviour of arsenic differs. In aerobic soils, the predominant arsenic species in soil pore water is arsenate (As^{V}). Arsenate is least available at low soil pH, but increases in availability as soil pH reaches circum-neutral pH values, in a manner analogous to phosphate (Peryea et al., 1997). However, plant uptake of arsenic is generally low, but contamination of watercourses may pose a problem. The recommended guideline value for total dissolved As in drinking water is 10 $\mu g\ l^{-1}$ (WHO, 1993). This survey located many areas where there were elevated As concentrations in soils close to water courses.

A further possible route of transfer to humans is direct soil ingestion or through the inhalation of dusts. This may be particularly important for arsenic and lead (Ruby et al., 1996). In the Manchester area, a considerable proportion of the soils exceed the Soil Guideline Values for As in residential and allotment ground of 20 mg kg^{-1}. Assays such as the Physiologically Based Extraction Test (PBET), developed around the functioning of the human gut, could be used to examine the proportion of As that is available through ingestion (Ruby et al., 1996). It is also apparent from the Manchester survey that many public access areas have high As levels (e.g. Medlock valley area). These are therefore areas where transfer to the receptor may occur, especially for 'at risk' population groups such as small children (Hough et al., 2004). Dust inhalation in these areas may also be a possible concern (Meyer et al., 1999).

Table 20 Mean and median concentrations of selected metals.

a Median concentrations of selected metals

	Community Buildings n=13	Industrial n=59	Residential n=77	Recreational n=106	Transport n=23	Vacant land n=16	Water n=4	Woodland n=2
Arsenic	21	18.2	20.8	22.4	18.1	24.1	32.5	22.6
Cadmium	1	0.8	0.9	0.85	1	0.75	0.95	0.45
Copper	83	70.1	84.6	91.9	88.6	90.8	175.4	72.2
Chromium	79	73	72	78.5	83	80	101	67.5
Nickel	27.7	28	28.7	31.65	24.6	34.6	82.6	27.8
Lead	233.3	206.6	233.8	200.7	219.4	181.3	412.1	352.7
Selenium	0.5	0.4	0.4	0.4	0.2	0.4	0.95	0.5
Zinc	193	160	187.5	167.5	193	134	172	130.5

b Mean concentrations of selected metals

	Community Buildings n=13	Industrial n=59	Residential n=77	Recreational n=106	Transport n=23	Vacant land n=16	Water n=4	Woodland n=2
Arsenic	22.6	20.4	22.8	37.64	21.92	26.32	33.35	22.6
Cadmium	1.04	1.03	1.06	1.87	1.11	1.64	1.15	0.45
Copper	86.3	98.7	102.3	147.3	109.9	126.1	253.6	72.2
Chromium	90.9	86.03	76.06	110.6	86.8	81.81	100.75	67.5
Nickel	28.6	29.3	32.3	35.7	31.4	36.7	78.9	27.8
Lead	281.3	224.6	308.7	280.2	250.6	273.1	415.4	352.7
Selenium	0.48	0.40	0.51	0.58	0.4	0.63	1	0.5
Zinc	208.2	203.0	200.2	240.6	284.13	204.6	224.0	130.5

8 Conclusions and recommendations

In areas experiencing rapid regeneration, currently available information on geoscience issues is often at a scale that is too small to aid decision makers or is at a level of complexity that is not easily interpreted by non-geologists. The move towards 3D modelling of the shallow subsurface will provide greater flexibility in meeting user needs particularly in relation to land use planning and sustainable development.

At present, use of the 3D model by key users (local authorities, regional development agencies, developers and regulators) remains at a low level, although increasing interest is being shown by the water sector and by some of the larger city councils.

The 3D subsurface model of central Manchester and Salford and derivative products featured in this report illustrate the potential of the geological model to deliver information in formats relevant to a wide range of planning issues (ground stability, contaminated land, groundwater management). The challenge is to move from a research-based programme of 3D modelling to a more systematic approach which will ultimately provide geographical coverage in key user-defined areas, and at appropriate scale(s) of resolution. This will require a commitment to update and digitise the underpinning borehole databases, and to include provision for maintenance of the models, particularly those constructed in data-rich regeneration areas.

There are several areas where research needs to continue including voxel-based property modelling, estimation of uncertainty, and inter-operability with other software applications (e.g. MODFLOW).

Modelling practice in the US and Canada has shown the value of ground truthing. Gathering property information at first hand rather then by proxy must remain an important part of the overall modelling process. In Canada, purpose drilled 'golden spike' boreholes are recognised as essential for deposit characterization and model validation.

The benefits of the 3D model are unlikely to be recognised unless the information contained within the model is supplied in a user-friendly and GIS-compatible format. In the near future, all models will be enhanced by inclusion of a simple viewer-browser supplied with basic analytical functions enabling the constructed model to be viewed, rotated, tilted, or sliced, and with in-built functionality to export data in GIS format.

Finally, if use of the 3D model in environmental assessment is to become a reality, then outputs will need to be seen to be relevant and link directly into land use planning regulations and guidance.

9 Technical appendices

BEDROCK GEOLOGY

Lower Coal Measures

Strata belonging to the Lower Coal Measures have been proved in underground workings but do not come to crop in the area. The Lower Coal Measures are composed of a mudstone-dominated sequence with subordinate beds of coal and thin beds of sandstone. Four named coals have been proved:

Coal	Thickness (m)
Doe	2.8 (in leaves)
Five Quarters	0.9 (in leaves)
Hell Hole (Victoria)	1.7 (in leaves)
Oldham Great (Trencherbone)	1.5 (in leaves)

The oldest strata are recorded in the central part of the district, where mudstones beneath the Oldham Great (Trencherbone) Coal have been proved.

Middle Coal Measures (Westphalian B)

The Middle Coal Measures conformably succeed the Lower Coal Measures. They comprise a mudstone-dominated sequence with subordinate beds of sandstone, coal and ironstone. The base of the sequence is taken at the base of the Vanderbeckei (Sutton Manor) Marine Band. The correlation between the Middle Coal Measures of the Bradford Coalfield and the equivalent sequence in the main coalfield is not well understood, and it is simplest to consider the two successions separately.

The South Lancashire succession in the west of the district is known from boreholes drilled to prove the concealed coalfield around Patricroft [e.g.75407 9856] and Brindle Heath [e.g. 8018 9941]. Seven main coals have been proved:

Coal	Maximum thickness (m)
Worsley Four Foot	1.4 (in leaves)
Major (Binn; Bin)	1.1 (in leaves)
Shuttle (Crombouke)	1.1 (in leaves)
Roger (Crombouke; Brassey)	1.4 (in leaves)
Rams	1.7
Little Rams	0.75
White	0.7 (in leaves)

Several laterally persistent sandstones are well developed in this area. Two of the thicker named units are the Peel Hall Rock, a fine-grained, grey or white cross-bedded sandstone, up to 48 m thick, which occurs towards the base of the succession; and the Newton Heath Sandstone, up to 24 m thick and coarse-grained, lying between the Worsley Four Foot Coal and the top of the Middle Coal Measures.

The Middle Coal Measures also come to crop in the extreme north-eastern part of the Bradford Inlier around Newton Heath [8680 9980]. Information comes mainly from provings associated with Bradford Colliery [8706 9845], where the sequence of coal seams is as follows:

Coal	Maximum thickness (m)
?Worsley Four Foot	0.6
Parker	0.8
Radley	0.7
New Jet Amber	0.7
Pottery	1.0 (in leaves)
Major (Bradford Top)	1.1 (in leaves)
Bland (Bradford Middle)	0.4–2.3 (in leaves)
Ashton Great (Bradford Deep)	1.1
Roger	1.8–2.4 (in leaves)
Top Furnace	1.0
Bottom Furnace	0.9
Stubbs & Fairbottom (Moston Mary)	1.4 (in leaves)
Foxholes (Ashton Mary)	0.7
Town Lane	0.6
Top Shuttles	0.7 (in leaves)

The upper and lower parts of the Middle Coal Measures in the Bradford Fault Block are generally coarser grained than the intervening part. Two named sandstones from the lower part of the sequence are the Foxholes (Huncliffe) Rock (below) and the Bardsley Rock (above). A third, coarse-grained sandstone, the Newton Heath Sandstone, up to 36 m thick, occurs approximately 90 m below the top of the Middle Coal Measures.

Upper Coal Measures (Westphalian C)

The Upper Coal Measures crop out around Brindle Heath [8060 9990] (bounded to the east by the Pendleton Fault), and in the Bradford Inlier between Newton Heath [8670 9970] and Beswick [8650 9850]. The strata are best developed within the latter area, which preserves a maximum thickness of approximately 360 m of mudstone with subordinate beds of sandstone, coal and limestone. Coals proved within the Upper Coal Measures at Bradford Colliery are as follows:

Coal	Thickness (m)
Openshaw	0.8
Charlotte	0.5
Bradford Threequarters	0.5
Bradford Four Foot	1.4
Yard	0.5–1.2
New (Smut)	0.3
Doctor	0.6
Two Foot	0.6

Only the Bradford Four Foot Coal has been identified with any degree of certainty in both the Bradford Fault Block and the central Manchester area. Farther west, none of the coals present in the Bradford Fault Block has been identified, and the Slack Lane Coal is the only coal recorded within this part of the succession. This seam comes to crop between Alder Forest [7500 9955] and Monton [7685 9940], where it terminates against the Worsley Fault.

Within the Bradford Fault Block, a 0.38 m-thick S*pirorbis* limestone bed occurs between the Bradford Four-Foot and

Bradford Three-Quarters coals (Gerrard, 1904). This bed has been proved in mine workings but it is not known if it comes to crop in the Bradford area. Limestones are not known from the Upper Coal Measures in the area to the west.

The Worsley Delf Rock occurs approximately 8 to 20 m above the base of the Upper Coal Measures in the central and western parts of the area. It is a brown, yellow and purple, medium-grained sandstone, cross-bedded with numerous mudstone interbeds, and up to 84 m thick. The sandstone is exposed at the base of a disused quarry at Collyhurst [853 001], immediately to the north of the district, where it is a purple medium-grained sandstone with rare sandstone pebbles reworked from older Coal

Warwickshire Group (Westphalian C-D)

The Coal Measures pass up by transition into red beds of the Etruria Formation, which in turn are overlain by predominantly grey measures of the Halesowen Formation.

The **Etruria Formation** (formerly 'Ardwick Marls', and the lower part of the 'Ardwick group') comprises a sequence dominated by mottled brown, red, purple, green and grey, poorly bedded mudstone. The unit is thickest (92 m) within the Bradford Fault Block; farther west up to 80 m is preserved. In many areas, much of the formation has been removed by erosion during Permian times. The top of the formation is taken at the base of the Twelfth Limestone of the overlying Halesowen Formation. Faunas recovered from the Etruria Formation suggest that the Westphalian C–D boundary lies at, or near, the top of the formation.

The **Halesowen Formation** comprises the upper part of the former 'Ardwick group', and represents a return to Coal Measures-type sedimentation. The boundary with the underlying Etruria Formation is difficult to identify, especially where the Halesowen Formation is reddened; but is taken at the base of the Twelfth Limestone (see below) or where this is absent approximately 120 m below the Great Mine Limestone, which is laterally continuous throughout the Bradford Fault Block. The Halesowen Formation is composed dominantly of red and grey mudstones. A reddened and poorly cemented sandstone, the Holt Town Sandstone, has been proved in the Bradford Fault Block. The sandstone is up to 24 m thick and occurs approximately 4 m above the base of the formation. It comes to crop between Holt Town [8560 9870] and Beswick [8640 9800]. Up to twelve thin limestone beds are present within the formation (Roeder, 1890). Sections along the River Medlock formerly exposed these beds dipping at 20º to 22º to the south-west. The beds have yielded *Spirorbis*, ostracods and fish debris (Jones, 1938). The more important limestones within the sequence have been named:

Limestone	Thickness (m)
Yard Mine	1.1
Half Yard	0.8
Great Mine	1.5–2.7
Twelfth	0.6

Of these, the Great Mine Limestone has been worked from a series of shafts in the Beswick area, where extraction continued until at least the late 1860s.

Collyhurst Sandstone Formation

The Collyhurst Sandstone rests unconformably on Carboniferous strata. The thickness of the formation varies between 60 and 220 m. At least some of this variation can be ascribed to synsedimentary faulting (Tonks, 1931; Aitkenhead et al., 2002). The formation comes to crop in the north-eastern part of the district around Droylesden [8950 9850], and in a series of faulted blocks to the west of the Bradford Coalfield. The sandstone is red and orange, fine to medium grained, and has been interpreted as being dominantly aeolian (Plant et al., 1999) or of mixed aeolian and fluvial origin (Aitkenhead et al., 2002).

Manchester Marls Formation

The Manchester Marls are preserved in fault blocks in the east (Clayton–Reddish), centre (Strangeways–Rusholme) and north-west (Alder Forest–Pendleton) of the district. A maximum thickness of 60 m is recorded in the eastern part of the area. The formation is conformable on the Collyhurst Sandstone, or locally oversteps this unit to rest unconformably on the Halesowen Formation (e.g. in the Pendleton to Ellesmere Park area). The base is lithologically well defined, being taken at the first red-brown mudstone above the sandstones of the Collyhurst Formation or older rocks. The Manchester Marls comprise red mudstone with subordinate siltstone and limestone beds. The lower part of the formation is fossiliferous, and has yielded a limited marine fauna (Aitkenhead et al., 2002).

Sherwood Sandstone Group

The **Sherwood Sandstone Group** comprises red-brown, orange and buff coloured sandstone with subordinate beds of red-brown mudstone. Sandstone units within the Sherwood Sandstone may be strongly cross-bedded or massive (structureless). The group is divided into three formations in the Cheshire Basin, of which only the lower two–the **Chester Pebble Beds** and the overlying **Wilmslow Sandstone —** are present within the Manchester district. Sediment was supplied by broad fluvial systems, sourced from the Varsican foldbelt to the south.

The Chester Pebble Beds in this more distal location contain sparse pebbles, and are not readily distinguishable from the Wilmslow Sandstone from log descriptions. Consequently, the mapped junction between the two formations is conjectural, and is based on an inferred dip and estimates of thickness of strata from the Stockport district.

The Chester Pebble Beds are conformable on the Manchester Marls, and attain a maximum thickness estimated to be in the region of 300 m. There are numerous exposures in Manchester city centre, with particularly good sections preserved along the Irwell [8335 9837] and at Castlefield [8321 9755]. Outside the city centre, exposure is restricted to Little Bolton Quarry [788 985], east of Eccles. The western part of the quarry exposes a thinly laminated aeolian sandstone, overlain by a trough cross-bedded fluvial sandstone. Faces in the eastern part of the quarry [7887 9842] show a lower sandstone unit overlain by a thin, weathered red-brown mudstone. Strata in the quarry dip 5º to 10º towards the south-south-east.

The overlying Wilmslow Sandstone Formation is not exposed but crops out beneath drift in the southern part of the area. It is estimated to reach a maximum thickness of 275 m around Davyhulme [750 950]. Typically, it comprises a well-sorted fine- to medium-grained, orange and pale buff sandstone with large-scale, low-angle cross-bedding. The unit was deposited as large aeolian dunes that formed on the interfluves of a major braided river system.

Structure

The regional dip recorded underground in the Coal Measures varies between 10º and 20º to the south-west. Somewhat lower dips (about 10º), also towards the south or south-west, are recorded in the Permo-Triassic rocks, though large thickness variations in some of the sandstone units make accurate dip determination difficult.

A series of major north- and north-west-trending faults divide the district into a system of tilted fault blocks, with throws on the larger faults commonly in excess of 500 m. Some of the structures are interpreted as having been active prior to the deposition of the Permian rocks (Tonks et al., 1931). The faults are associated with local oversteeping of bedding and minor folding (Jones, 1938).

Nine named faults have been mapped within the Manchester and Salford area. From west to east they are as follows.

The **Worsley Fault** trends north-westwards from Walkden [SD 743 025], to the north of the area, to Eccles [776 989]. The fault throws approximately 500 m down to the north-east, and brings Chester Pebble Beds against Upper Coal Measures.

The **Pendleton Fault,** mapped from Brindle Heath [SD 810 005] to the Macclesfield district in the south, is a splay of the Irwell Valley Fault, with a throw in the northern part of the district of approximately 630 m. The fault throws the Chester Pebble Beds against the Upper Coal Measures and Wilmslow Sandstone.

The **Irwell Valley Fault** is one of the main structural features of the South Lancashire Coalfield. To the north of the district, the fault has a throw of approximately 1500 m down to the north-east, but the throw is likely to be much less within the Lower Broughton area [834 995], where the fault splits into the West and East Manchester faults.

The **West Manchester Fault** throws down 480 m to the north-east, bringing the Halesowen Formation against the Chester Pebble Beds. The **East Manchester Fault**, with an estimated throw of 160 m, juxtaposes the Collyhurst Sandstone against the Chester Pebble Beds. Both faults terminate against the Ardwick Fault. An electrical tomography survey carried out by Sub-Terra Surveys in 2003 proved a minor, unnamed splay of the West Manchester Fault in the central Manchester area (Figure 42), based on the contrasting electrical responses of the Manchester Marls and Chester Pebble Beds.

The **Ardwick Fault** can be traced from the coalfield, to Norbury Moor [918 863], and south to Stockport. The fault throws approximately 160 m down to the north-east, and brings the Collyhurst Sandstone against the Chester Pebble Beds.

The **St Georges Fault** defines the north-western margin of the Bradford Fault Block, and has an estimated throw of approximately 920 m down to the west.

The **Bradford Fault** has an arcuate fault plane trace from Whitefield [797 072] in the north, to Levenshulme [872 949] in the south, where it terminates against the Ardwick Fault. Within the district, the fault throws approximately 920 m to the east, and defines the northern and eastern margins of the Bradford Fault Block.

The **Ashton Moss Fault** present in the extreme north-eastern part of the district, trends north-westerly to Haughton Green [933 846]. The throw of the fault is approximately 960 m down to the north-east, throwing Chester Pebble Beds against Upper Coal Measures.

Variations in thickness of the Permo-Trias and the Warwickshire Group in the western part of the district suggest that several large faults, in addition to those noted above, affect the sequence to the south-west of the Pendleton Fault. However, there is insufficient borehole or geophysical evidence to delineate them.

BESPOKE GIS TOOLS

Several bespoke tools have been developed specifically for the Manchester project to assist in validation and interrogation of the 3D model. Each tool has been developed using Visual Basic for Applications (VBA) within ArcGIS 8.3. VBA is the programming interface that sits behind ArcGIS, and this uses the ESRI ArcObjects Library to define each Arc element (e.g. shapefile, raster image) and to specify how to deal with it.

Borehole Composition tool
Analysis of downhole borehole lithology within a designated area of the model stack

The tool takes, as its primary inputs, information held in the Single Onshore Borehole Index (SOBI) and Borehole Geology (BOGE). Borehole records are selected by either drawing a digital envelope around the desired records, or by selecting an existing geological polygon and analysing all records within it (e.g. a DiGMap polygon).

The programme works by calculating from BOGE, the total length in metres of each lithology recorded above rockhead for boreholes within the designated area. There are separate options to search between surface and rockhead, or between specified stacked surfaces within the model.

The programme was designed to help validate units created in GSI3D, but it also provides an indication of lithological variability.

The schematic cross-section (Figure 43a) illustrates the search option where intervals are calculated between two surfaces. By extracting all of the borehole geology records that lie between, say, the base and top of a unit, and analysing their composition, the tool provides a means of validating the model.

The programme outputs summary statistics and a pie chart detailing the cumulative borehole length of each lithology within the search area. It also creates a shapefile containing information on the lithological thicknesses and depths down each borehole.

Additionally this tool can be used to analyse the thickness of the drift cover and create basic shapes highlighting where the thickness is greater than a specified value.

Point data selection tool
Analysis of downhole data held as point shape files (e.g. geotechnical data)

This tool allows selection of downhole test data held as a point shapefile. It is designed to be used in conjunction with the 3D model. The user selects two or more model surfaces and data points falling within the specified interval are selected automatically for processing.

GEOCHEMICAL SURVEY PROTOCOLS

Methodology

Soil sampling

Sample sites are arranged on a regular grid pattern at a density of four samples per km^2. Sample spacing is kept as regular as possible (500 m interval) within the limitations of the available open space. Care is taken to avoid contamination

Table 21 Land use in areas with elevated metal concentration.

Area	Landuse 1950	Landuse present day
1	Industrial (iron and brass)	Residential; recreation; transport
2	Sewage treatment and works	Residential; vacant land
3	Oil and petrol storage; garage facilities	Residential; recreational; transport; industrial
4	Chemical works — dye, paint, varnish, roofing felt; engineering	Industrial and vacant land
5	Dockyard and council depots; textiles (waterproofing); chemical works; petrol filling and bulk storage	Industrial; residential; wetland
6	Pulp and paper works; engineering (switchgear and die casting)	Industrial; residential; transport
7	MOD land; hospitals and cemetery; electricity substation	Residential; commercial; industrial
8	Works, metal works, railway land and landfill (unspecified)	Residential and community buildings; industrial and commercial; vacant land
9	Metal works; textile and engineering works (unspecified)	Community buildings; recreation; transport; industrial and commercial
10	Engineering, gas and coke works; pulp and paper works; textiles	Industrial and commercial; vacant land and buildings; recreation and transport
11	Allotments; hospitals and cemetery; spoil and landfill (unspecified); railway sidings; sewage treatment; slagheap; oil refineries	recreation

from roads, buildings, fences, pylon lines, etc, an ideal sample being collected at least 50 m from any of these contaminating sources. In urban areas it is often difficult to find sample sites that meet these stringent conditions, but wherever possible samples are taken so as to preserve as near as possible the regular sampling grid.

Soil samples are collected using a Dutch style hand auger with a 3 cm bore. Two samples are collected at each site, a surface soil 0 to 15 cm depth and a profile soil 40 to 50 cm depth. Each sample is made of a composite of material from auger flights taken from five holes distributed within an area of approximately 20 × 20 m (see below). Over terrains where only thin soils (< 40 cm) have developed then the profile soils are collected from as deep as possible and the depth noted.

Sample preparation

Samples are dried in an oven at temperatures below 20ºC and then sieved. Surface soils and profile soils are sieved to obtain a –2 mm fraction. A 10g split of the < 2 mm fraction of the surface soil is taken for pH analysis. The sieved material is coned and quartered and a split of the sample ground using an agate ball mill until 95 per cent is finer than 53 µm. A 12 g split of the ground material is combined with 3 g of wax binder and pressed into a pellet for analysis by X-Ray Fluorescence Spectrometry analysis (XRFS). A 5 g split of the ground material is also taken for Loss on Ignition at 450ºC, to give an estimation of the organic content of the soil. Excess sieved and ground sample material is retained in the National Geoscience Records Centre at the BGS.

Analytical procedures

WD-XRFS

All samples were analysed at the BGS laboratories for a range of elements by Wavelength Dispersive X-ray Fluorescence Spectrometry (Wd-XRFS) (Ingham and Vrebos, 1994). Two Philips PW2400 WD-XRF spectrometers fitted with 102 position sample changers and with 3 kW/60 kV rhodium anode x-ray tubes were used to determine TiO_2, MnO, Fe_2O_3, V, Cr, Co, and Ba in one suite and Ni, Cu, Zn, As, Mo, Pb, and U in another. The Philips spectrometers were controlled using Philips SuperQ application software package, version 3.0H, running under MicroSoft™ Windows2000 operating system.

The elements determined, lower limits of detection (LLD), and upper and lower reporting limits (URL and LLR) for each analyte are shown in Table 22. The quoted LLDs are theoretical values for the concentration equivalent to three standard deviations above the background count rate for the analyte in a pure silica matrix. High instrumental stability results in practical values for these materials approaching the theoretical.

ED-XRFS

A Spectro X-LAB2000 energy-dispersive, polarised, X-Ray fluorescence spectrometer fitted with a palladium-anode X-ray tube (400 W 54 kV) was used for Ag, Cd, Sn, Sb, Te and I. The Spectro X-LAB2000 was controlled using X-LABPRO application software package, version 2.4, running under MicroSoft ™ Windows2000 operating system.

Soil pH

Soil pH was measured in surface soils by adding 10 g of each sample (> 2mm fraction) to 25 ml of 0.01M $CaCl_2.2H_2O$. The mixture was shaken to form a slurry prior to analysis by pH electrode (Rowell, 1994). This method of soil pH determination generally gives lower results (0.5 pH units) than water-based methods.

Loss on Ignition

Loss on ignition (LOI) was used as a measure of soil organic matter. LOI was determined for surface soil samples on 1g of oven dried < 2 mm material heated in a furnace and kept at 450°C for a minimum of four hours. Organic matter is burnt off at this temperature and the LOI (difference in weight of the sample prior to and after heating at 450°C) can be calculated. Rowell (1994) reports that LOI is similar to organic matter content in sandy soils but may be up to twice the organic matter content in heavy textured soils because clays and sesquioxides lose ‘structural’ water between temperatures of 105° to 500°C. An estimate of organic C can be made from the per cent LOI result by multiplying the result by 0.58. This is based on the assumption that organic matter contains 58 per cent C (Rowell, 1994).

Table 22 XRFS analysis of urban soil samples: values for lower limit of detection (LLD), lower limit of reporting (LLR) and upper reporting limit (URL).

Analyte	LLD (ppm)	LLR (%)	URL (ppm)	URL (%)
TiO_2*	-	0.010	-	100.0
MnO	-	0.010	-	10.0
Fe_2O_3	-	0.01	-	100.0
V	2	-	20 000	-
Cr	3	-	250 000	-
Co	2	-	10 000	-
Ni	1	-	4000	-
Cu	1	-	6500	-
Zn	1	-	10 000	-
As	1	-	10 000	-
Mo	1	-	1000	-
Cd	1	-	500	-
Sn	1	-	10 000	-
Sb	1	-	10 000	-
Ba	3	-	600 000	-
Pb	1	-	10 000	-
U	1	-	650	-

*A horizon only.

Data interpretation

Once full error control and data quality procedures were completed, the Manchester geochemical and location data were loaded into Arcview© GIS software package. Proportional symbol geochemical maps for surface and profile soils were then generated.

Random numbering of samples

Samples were allocated numbers according to a random numbering system (Plant, 1973), but were analysed in numerical order. This allows any systematic error in either sampling or analytical methodologies to be identified and attributed to the appropriate process.

Duplicate and subsamples

Within each batch of one hundred samples, a pair of sample numbers were assigned to a sampling duplicate, resulting in a duplicate pair for both A and S samples. Duplicate samples were collected using identical sampling methodology adjacent to the original sample. At the sample preparation stage each of the duplicate samples were split to obtain a subsample. Each subsample was assigned a different number and treated as a separate sample for analytical purposes.

The collection of duplicate samples enables the sampling error, or sampling variation, to be estimated, thus providing a measure of the between-sample variance. Subsampling allows the analytical error or variance to be estimated. The variation in the results between original and sub-sample gives an indication of the variation introduced by sample preparation and analysis.

The components of variance were estimated using analysis of variance (ANOVA). This statistical technique is used to determine the residual variance introduced by sub-sampling, sample preparation and chemical analysis; the between-sample variance, attributed to within-site variation and variability introduced during sample collection; and between-site variance, representing the natural variation in element concentrations across the survey area. All of the analyses considered were part of a single randomised dataset and therefore a random nested model of ANOVA was used. The results of the ANOVA indicate that for all elements, with the exception of uranium, the between-site variance is greater than 90 per cent of the total variance. Variations in the distribution of element concentrations can thus be attributed principally to the inherent variability in the environment rather than to variation introduced by the sampling and analytical procedures. In the case of uranium the between-site variance is approximately 70 per cent indicating probable analytical variation, which may be attributed to the overall low concentrations of uranium being very close to the analytical detection limits.

Standards

Standards were included in the analytical runs to monitor the accuracy of the results. These were assigned a unique number at the sample preparation stage and were treated identically to the other samples. The inclusion of standards allows the data to be normalised to the G-BASE regional data set for North-West England and North Wales (British Geological Survey, 1997).

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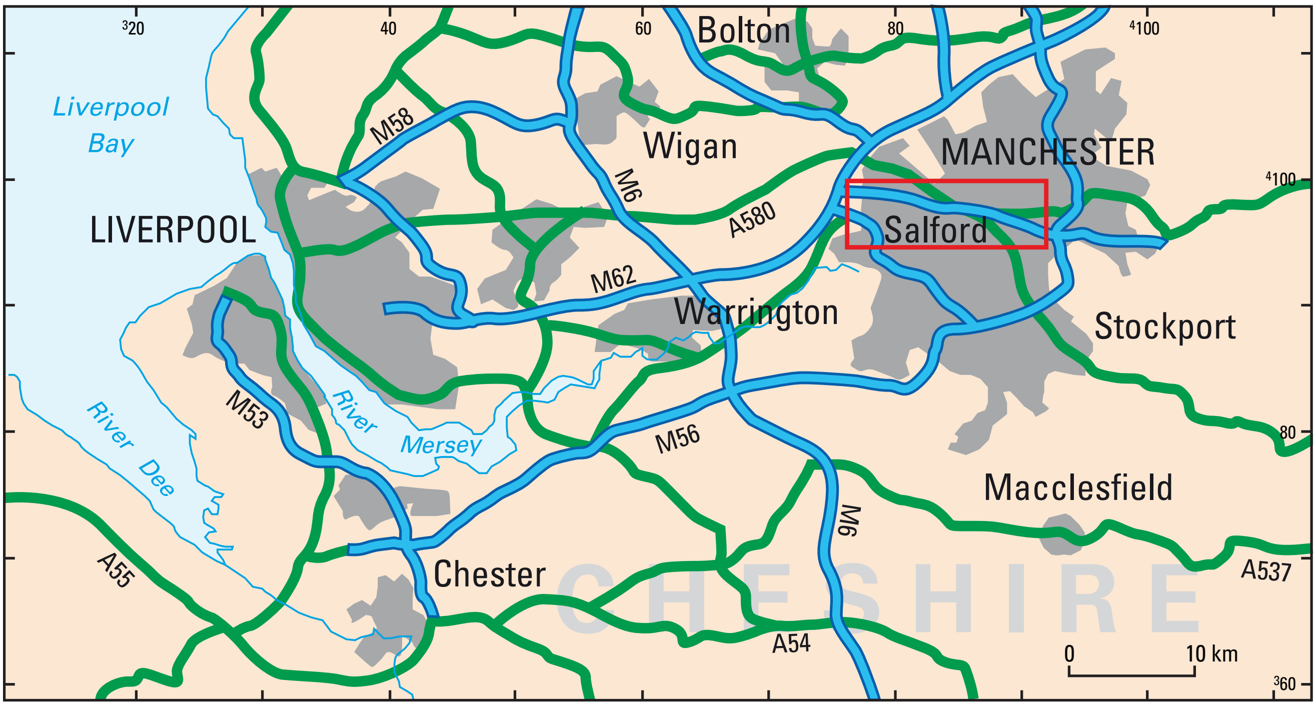


Figure 1 Location of the Manchester-Salford district.

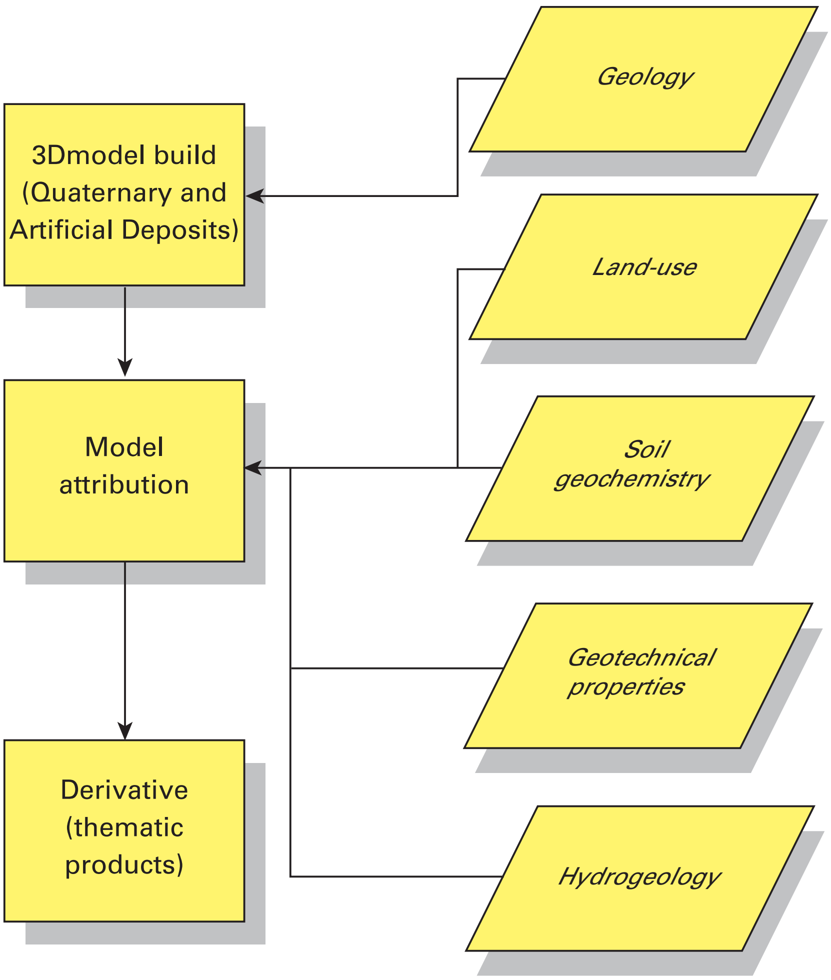
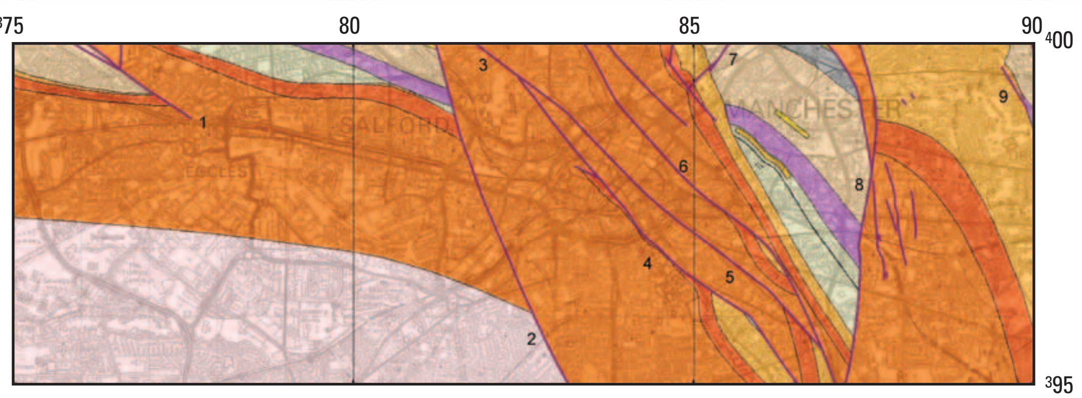


Figure 2 Component elements and research topics.

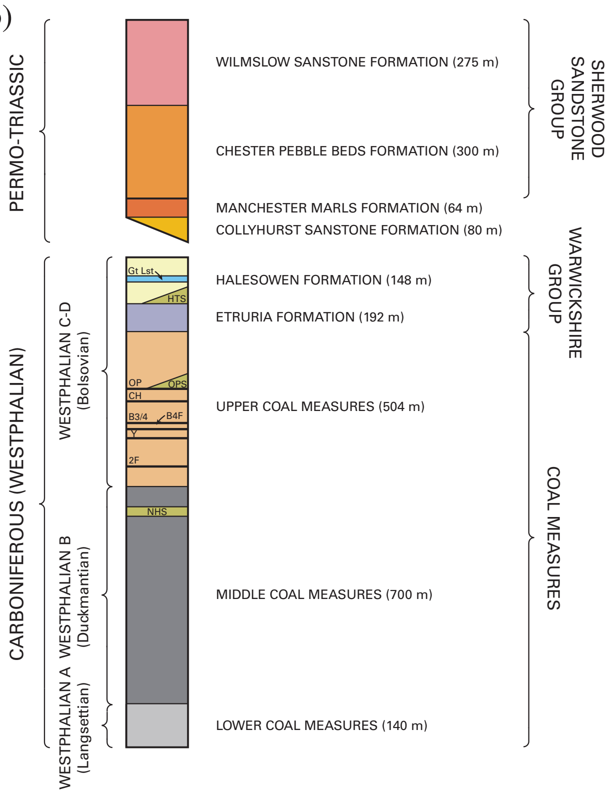
a)



Faults numbered

1 Worsley Fault
2 Pendleton Fault
3 Irwell Valley Fault
4 West Manchester Fault
5 East Manchester Fault
6 Ardwick Fault
7 St Georges Fault
8 Bradford Fault
9 Moss Fault

b)



c)

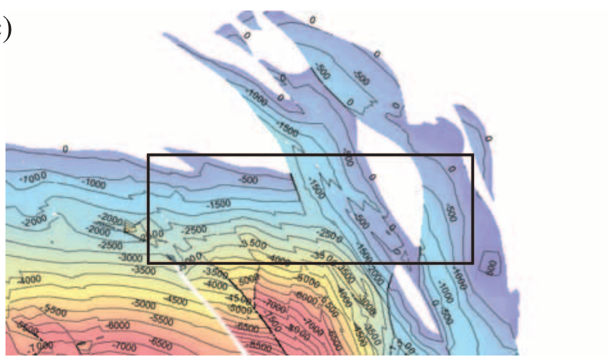


Figure 3 Geology of the district.

a Bedrock
b Generalized vertical section
c Structure contours on the base of the Permo-Triassic

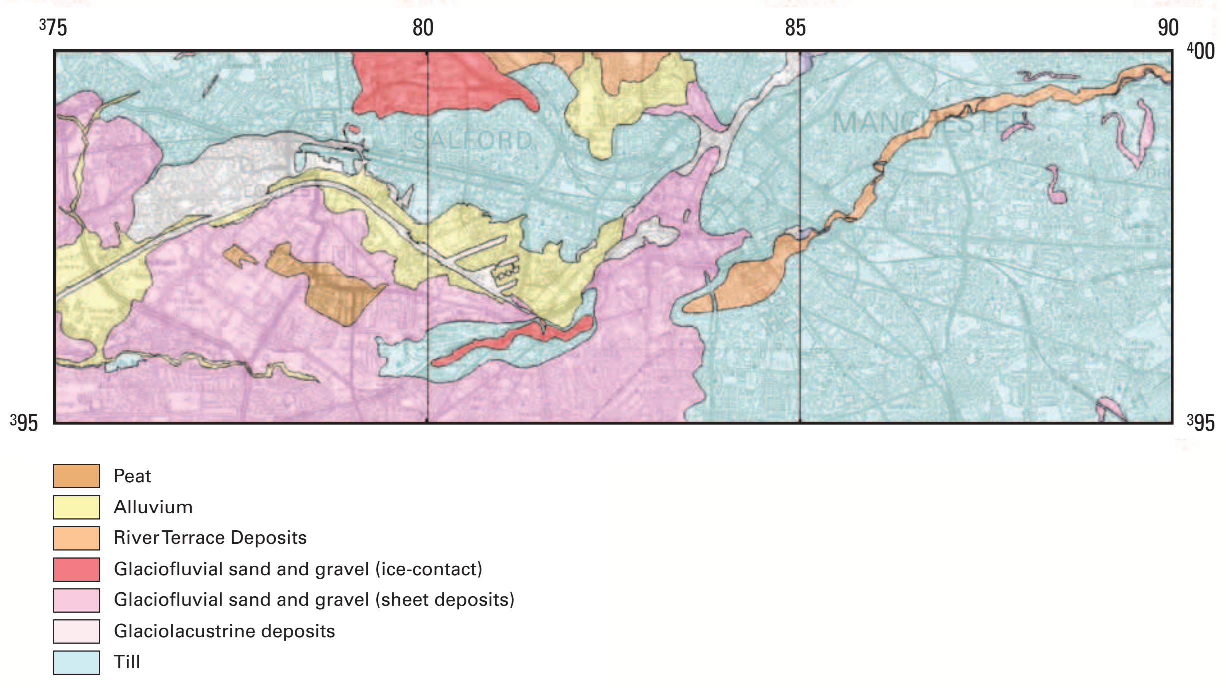


Figure 4 Superficial deposits.

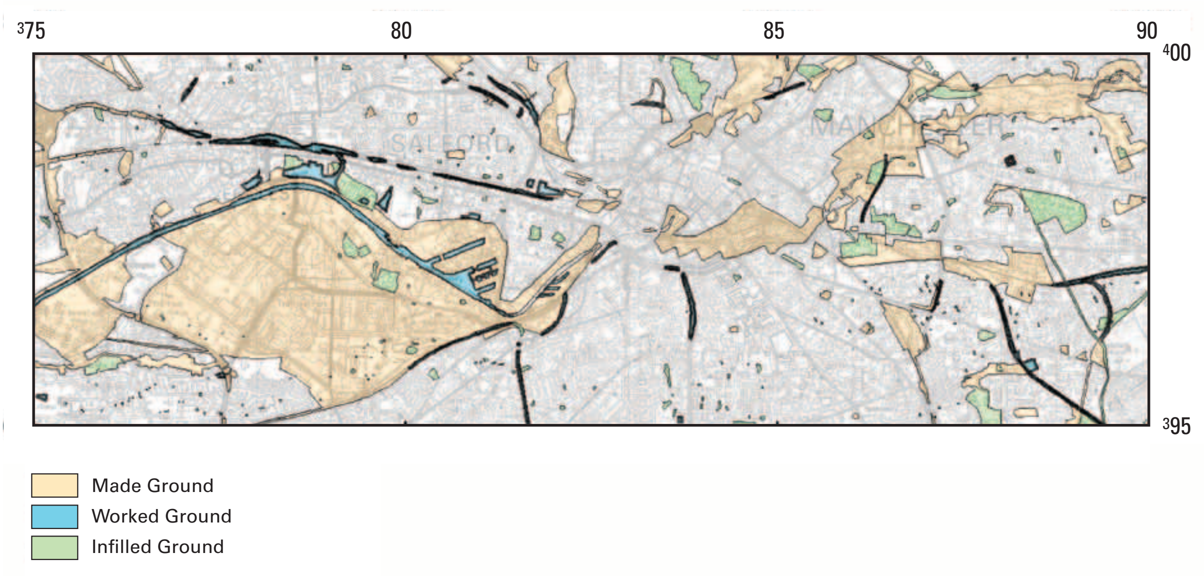


Figure 5 Distribution of artificial ground.

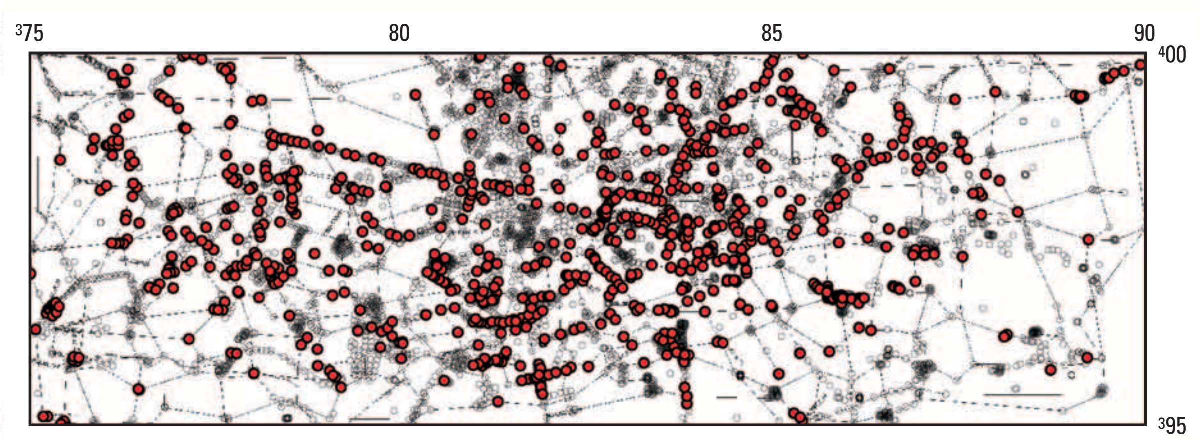


Figure 6 Stages in the modelling process. Distribution of boreholes and cross-sections within GSI3D.

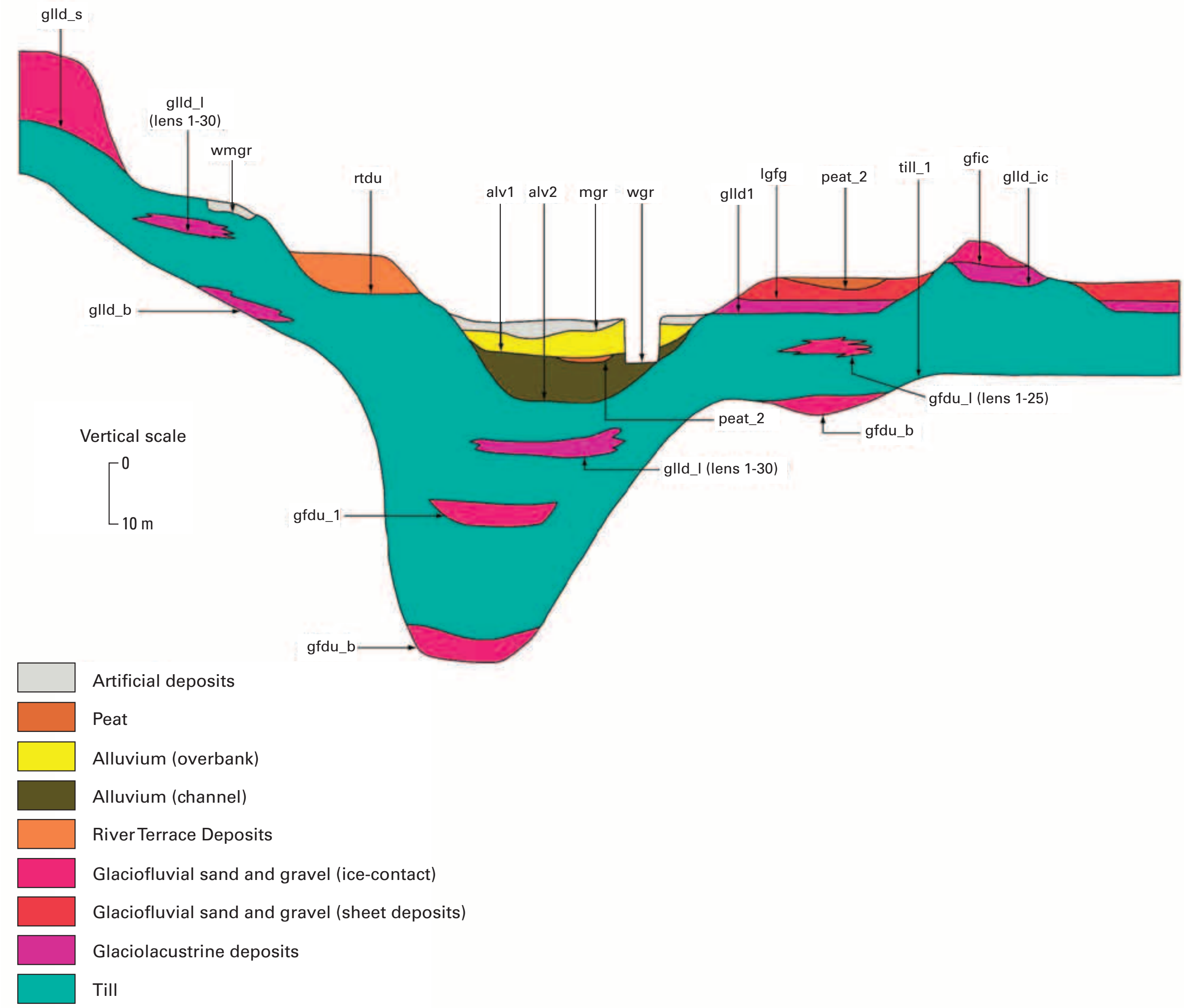


Figure 7 Schematic diagram showing relationships between modelled units.

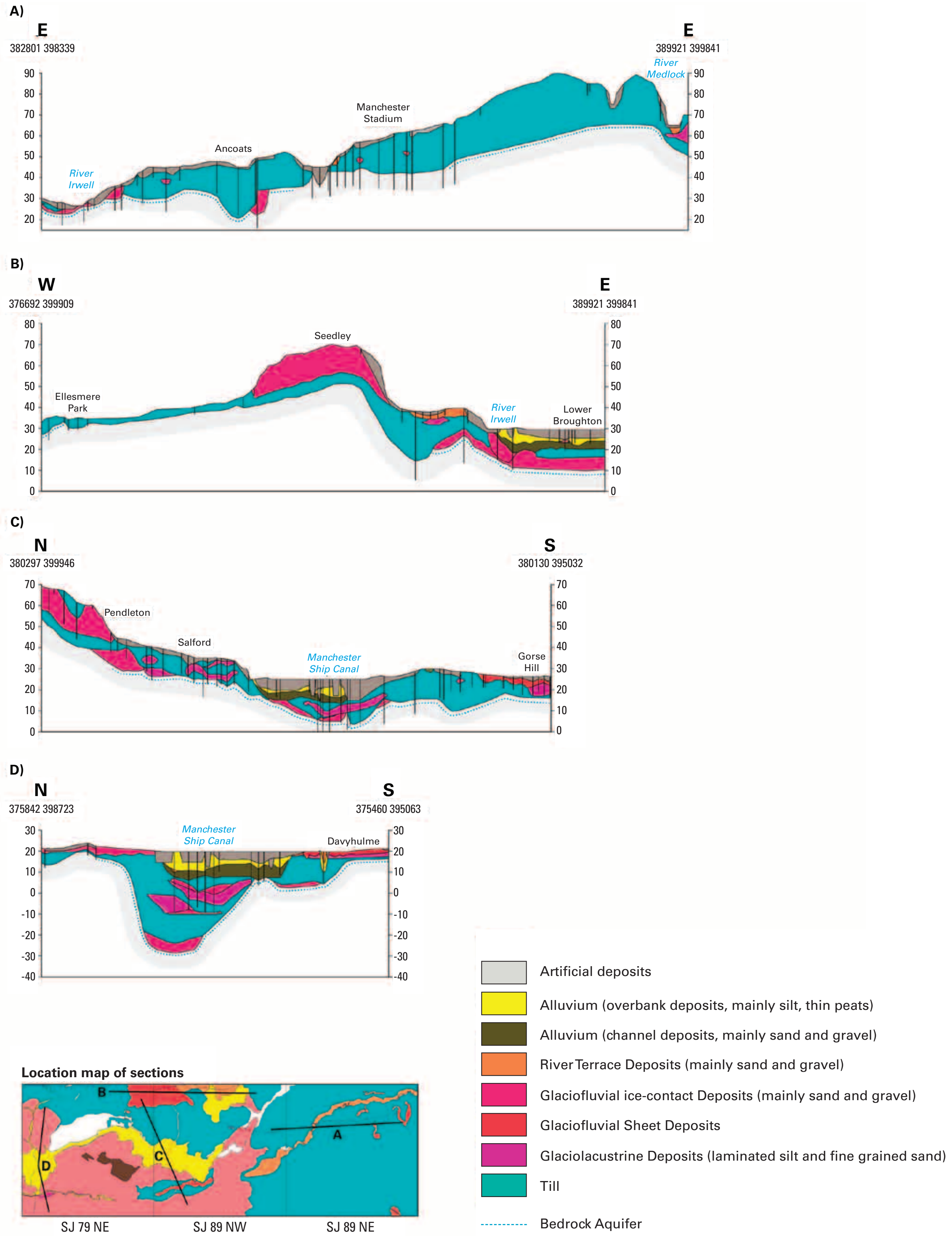


Figure 8 Selected cross-sections to illustrate the variability of the superficial deposits.

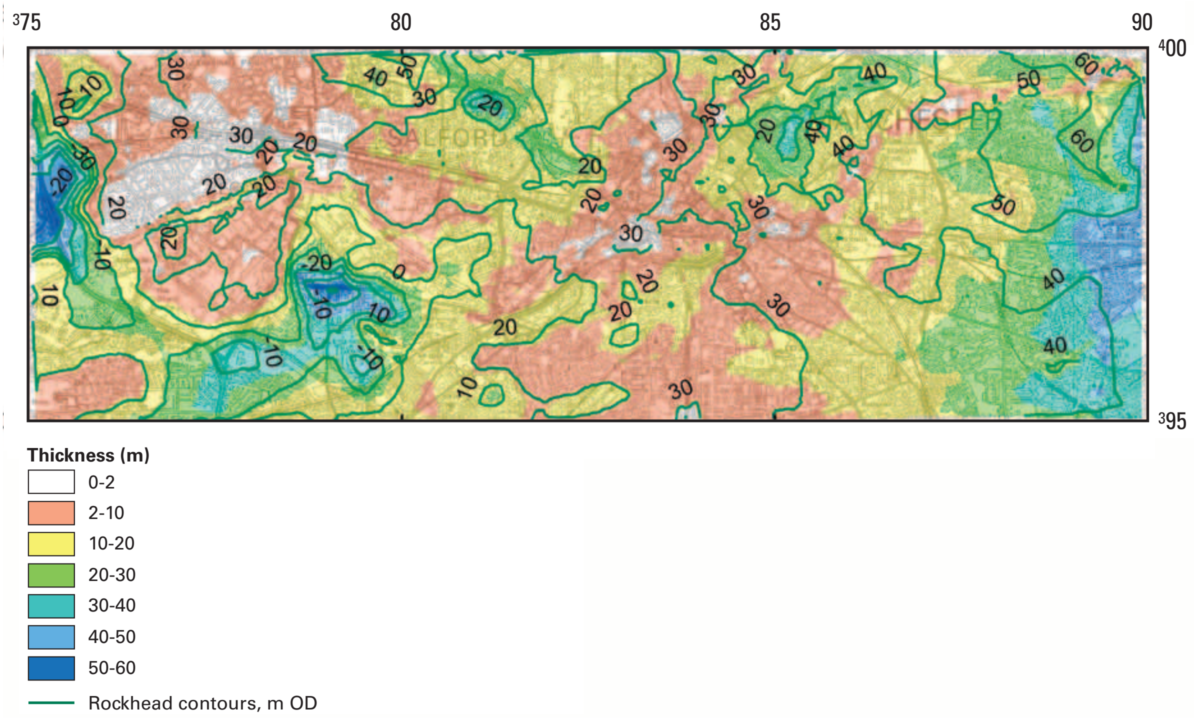


Figure 9 Rockhead elevation and thickness of superficial deposits.

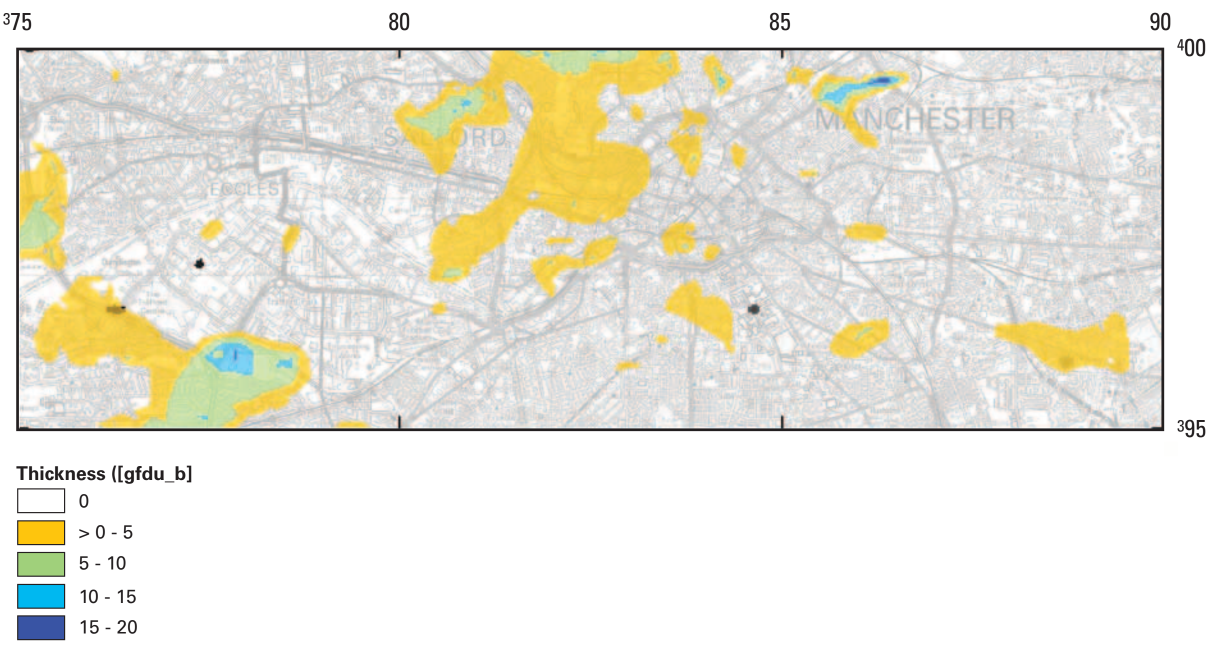


Figure 10 Thickness and base elevation of basal outwash sand and gravel [gfdu_b].

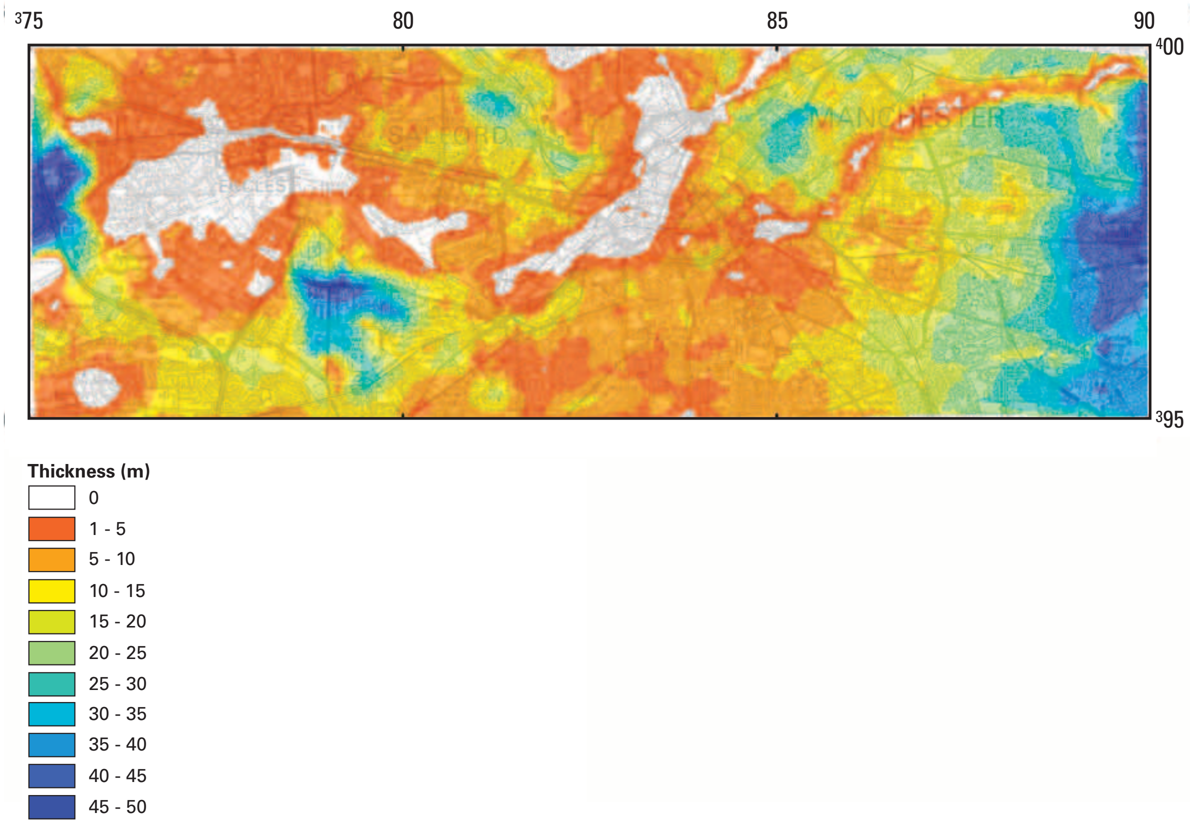


Figure 11 Thickness of till.

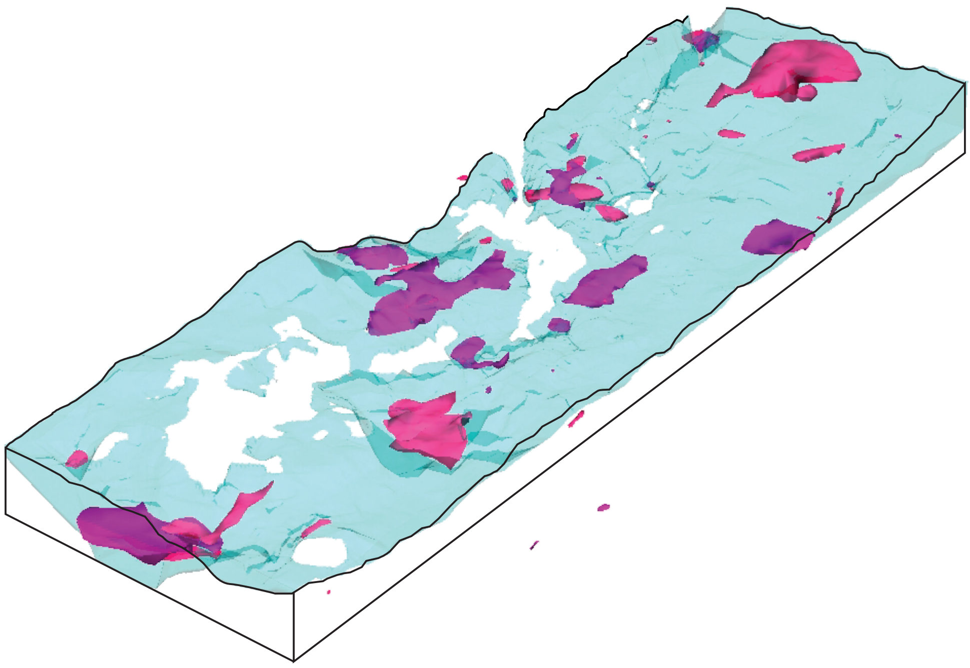
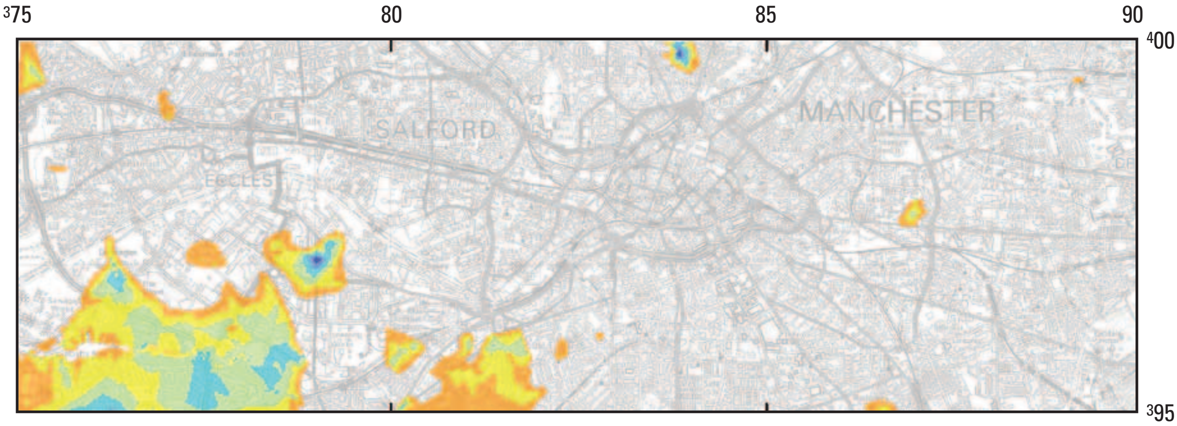
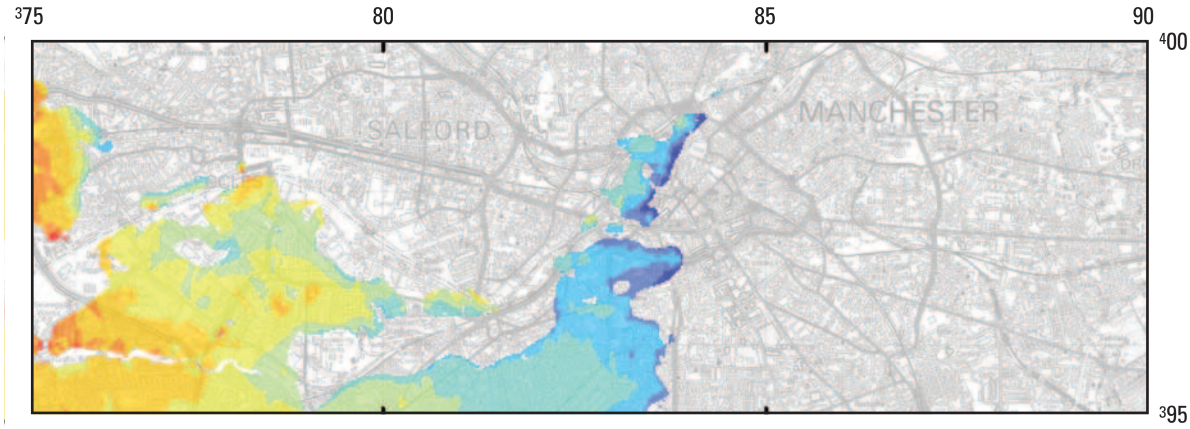


Figure 12 Intra-till glaciolacustrine (purple) and outwash (red) deposits.



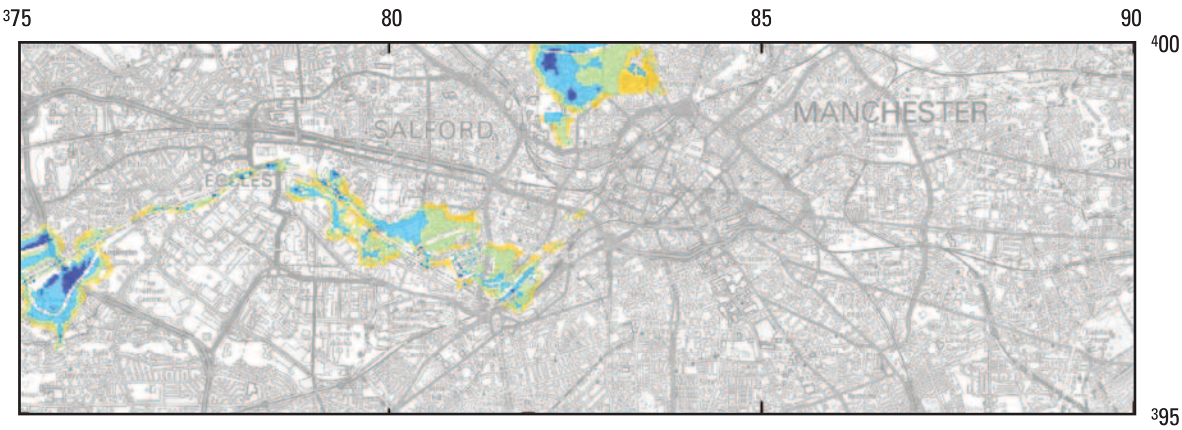
Thickness (m)
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12

Figure 13 Thickness and base elevation of major glaciolacustrine deposits [glld_1].



0 - 2
2 - 4
4 - 6

Figure 14 Thickness (m) and base elevation of outwash sheet deposits [lgfg].



2 - 3
4 - 6
7 - 9
10 - 15

Figure 15 Thickness (m) and base elevation of alluvial deposits [alv_1, alv_2].

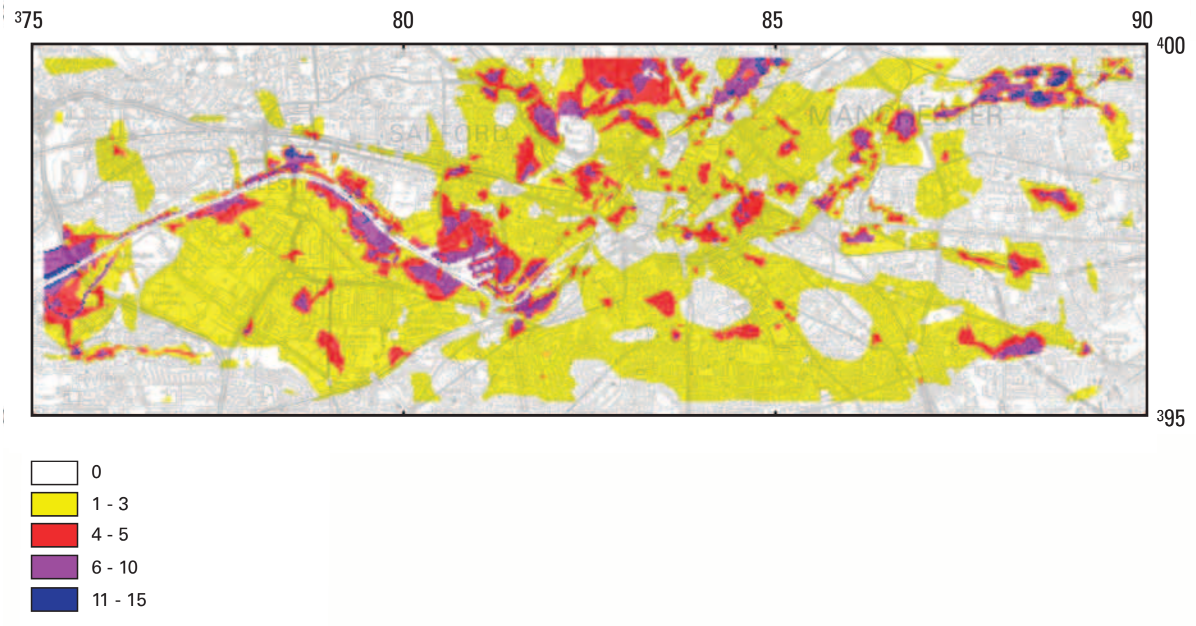


Figure 16 Thickness (m) of artificial ground.

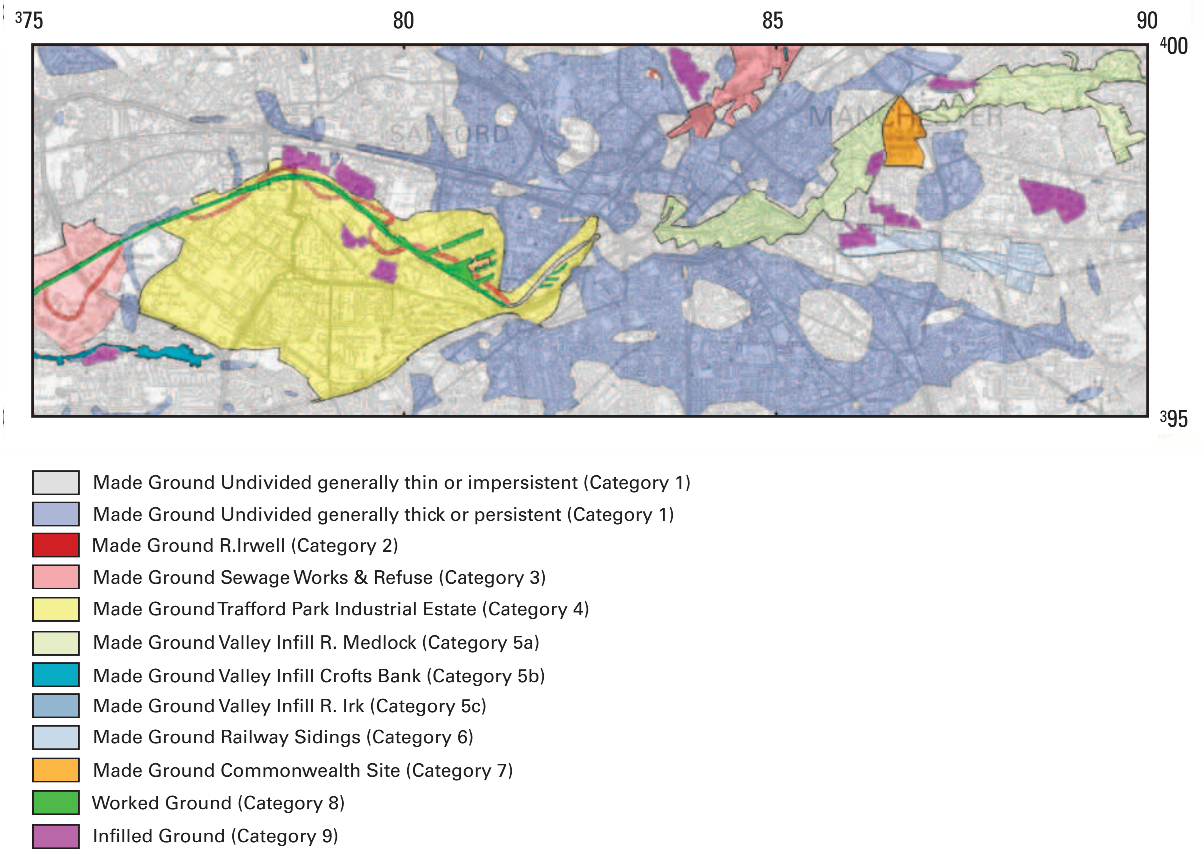
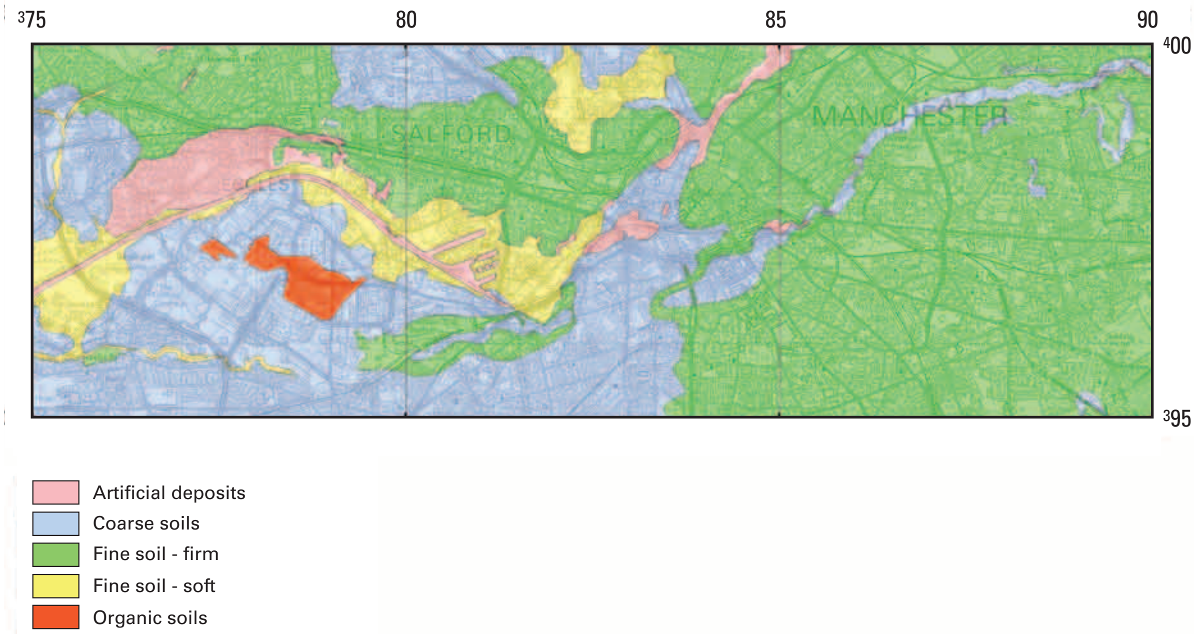


Figure 17 Types of artificial deposit found in the district.

a) Engineering Soils



b) Engineering Rocks

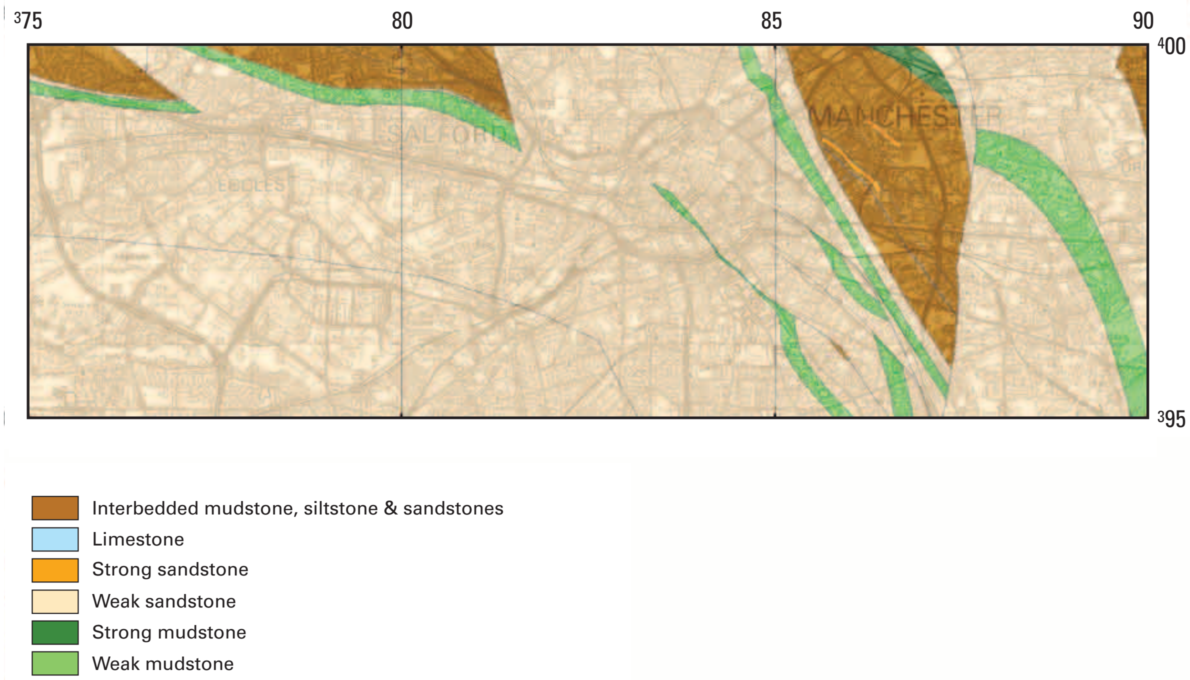
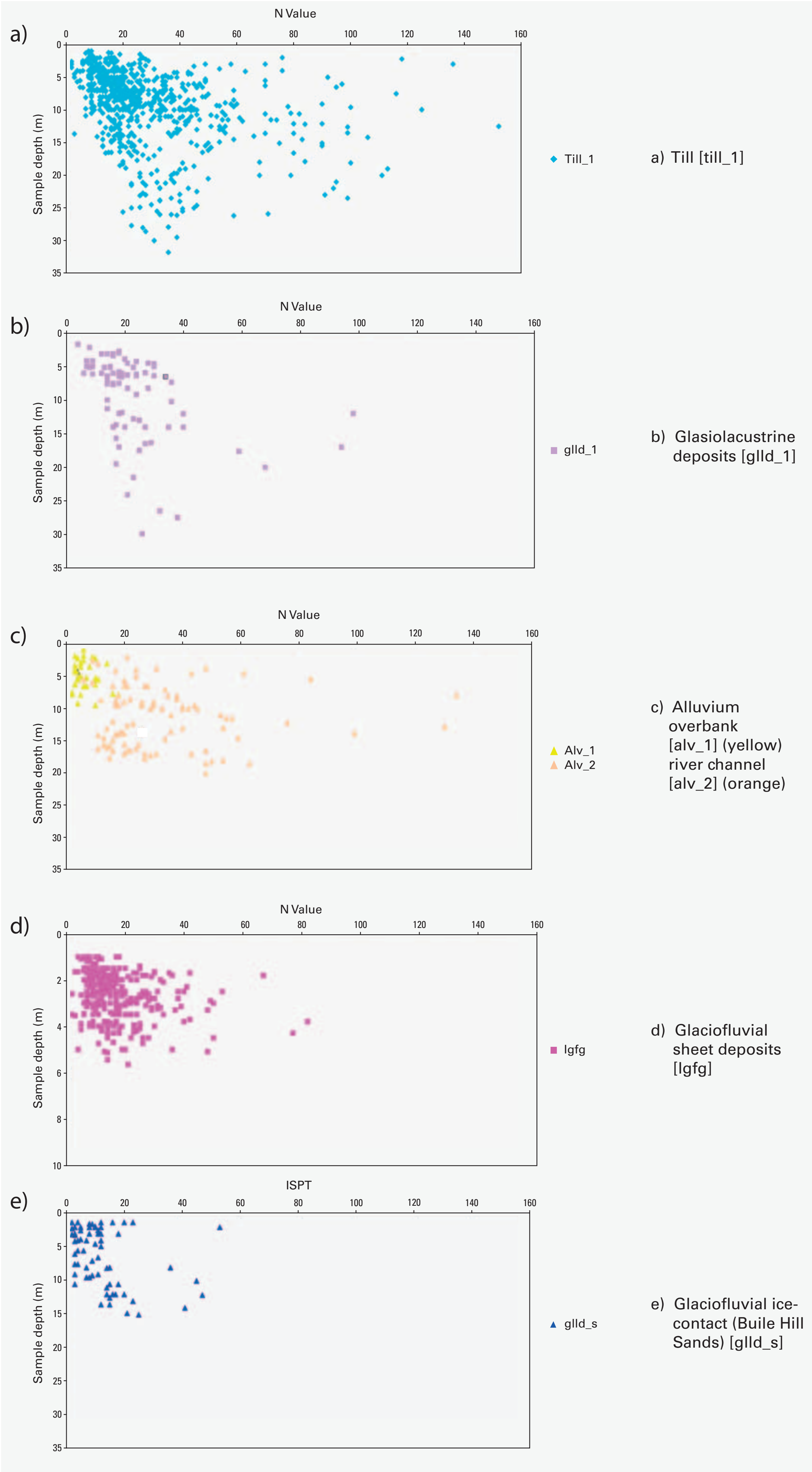


Figure 18 Distribution of engineering soils.

Figure 19 Plot of Standard penetration Test (SPT) values against depth for principal engineering units.

a Till [till_1]
b Glaciolacustrine deposits [glld_1]
c Alluvium overbank [alv_1](yellow); river channel [alv_2] (orange)
d Glaciofluvial sheet deposits [lgfg]
e Glaciofluvial ice-contact (Buile Hill Sands) [glld_s]



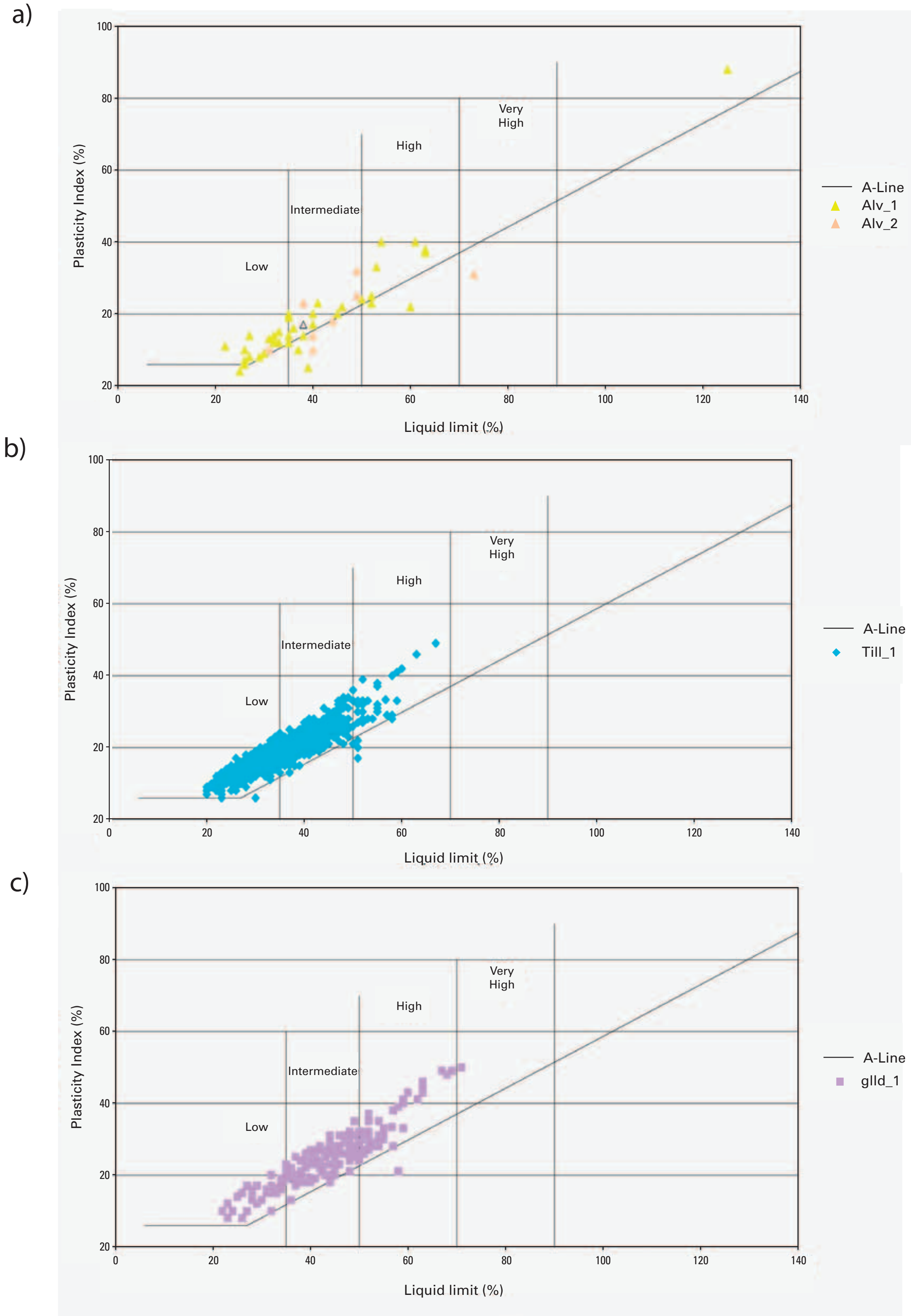


Figure 20 Plasticity charts.

a Alluvium
b Till
c Glaciolacustrine clays

Figure 21 Summary ternary plot of the mean gradings for till samples. Till classification from McGowen and Derbyshire (1977).

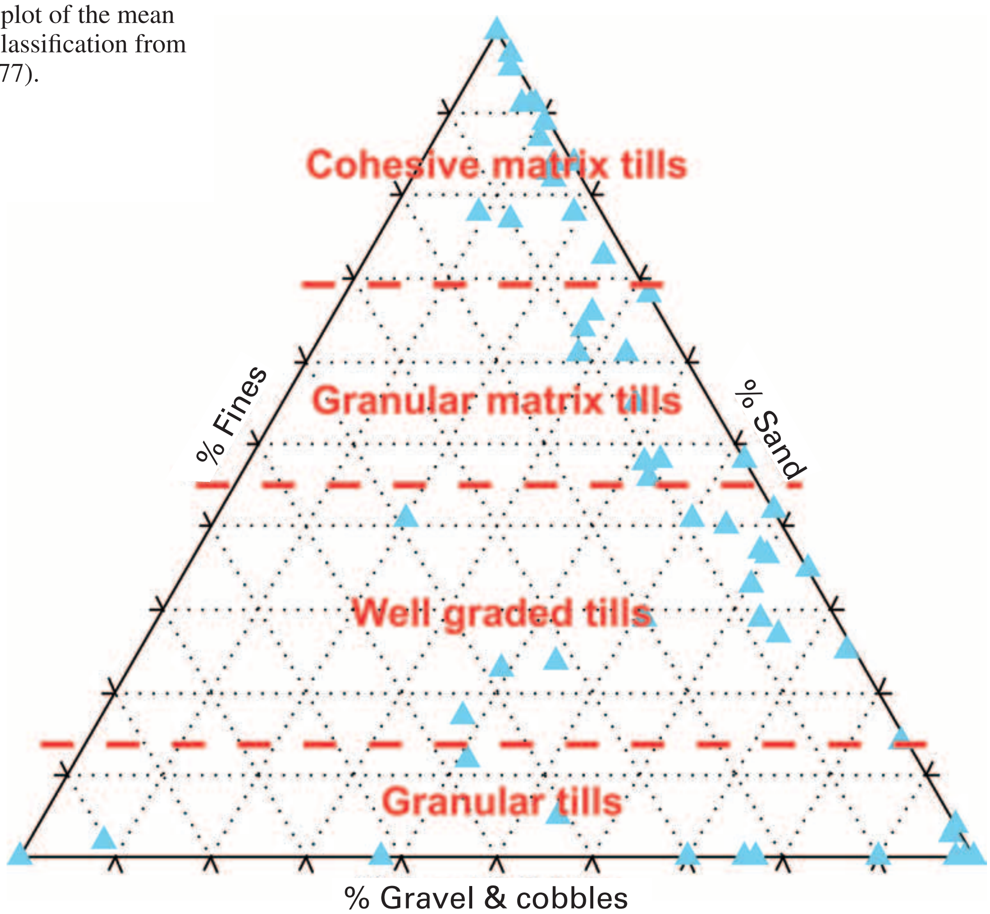


Figure 22 Standard Penetration Test (SPT) N-values for till displayed on a digital terrain model of ground surface (SPT classification from Clayton, 1995).

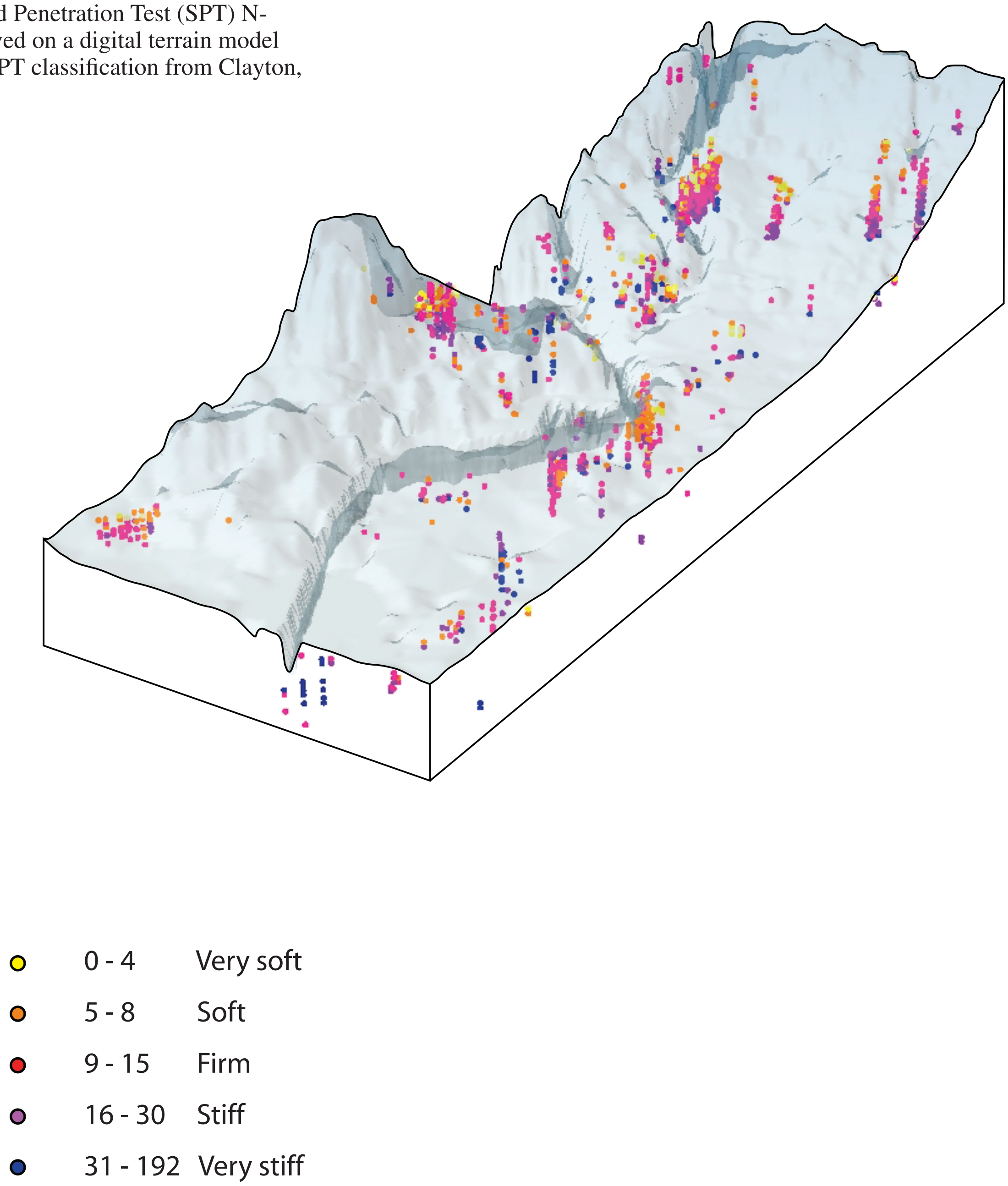
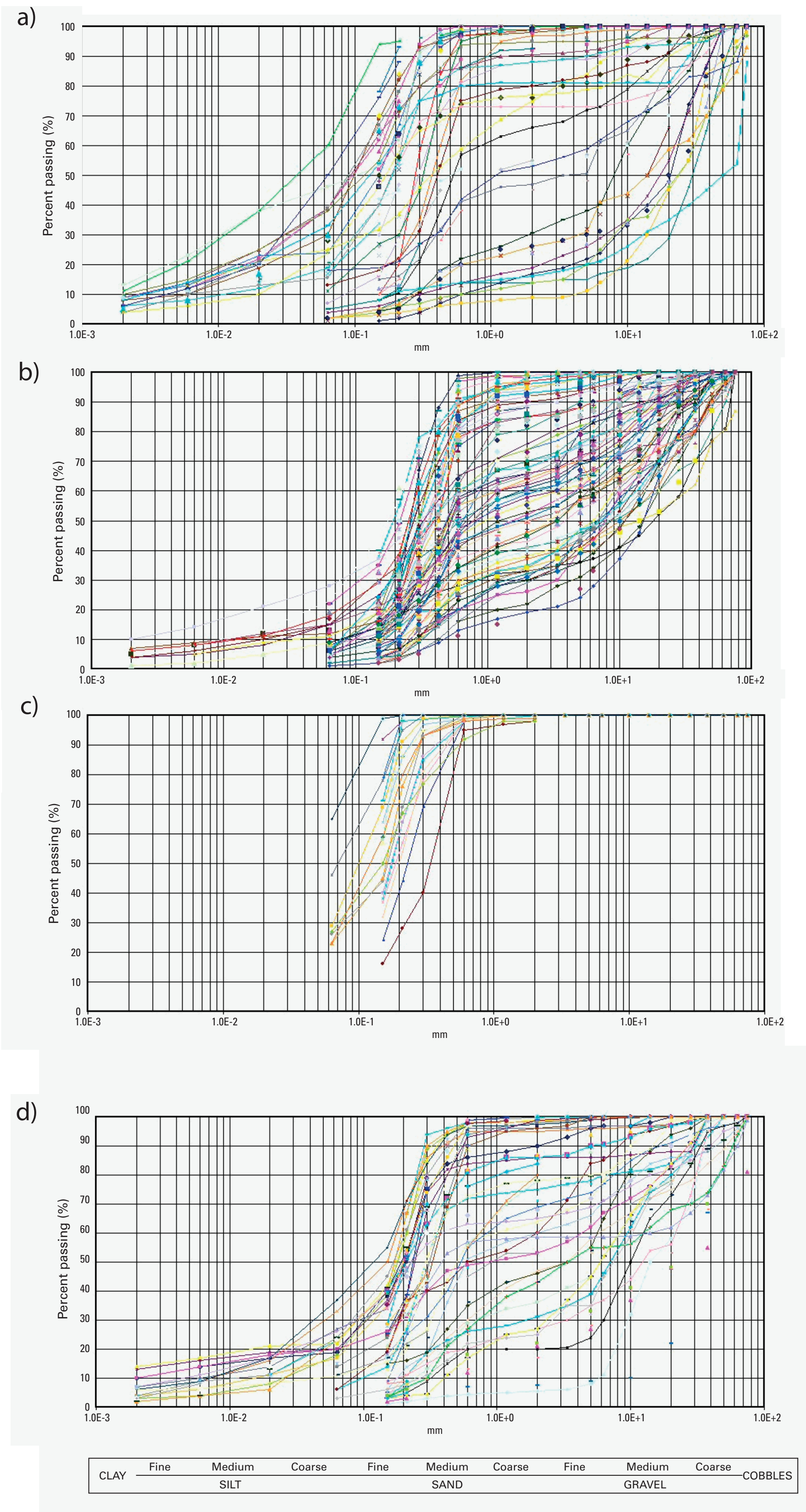


Figure 23 Particle size analysis for selected coarse soils.

a Alluvium (river channel deposits) [alv_2]
b Glaciofluvial sheet deposits [lgfg]
c Glaciofluvial ice contact deposits [glld_s]
d Glaciofluvial deposits, basal [gfdu_b]



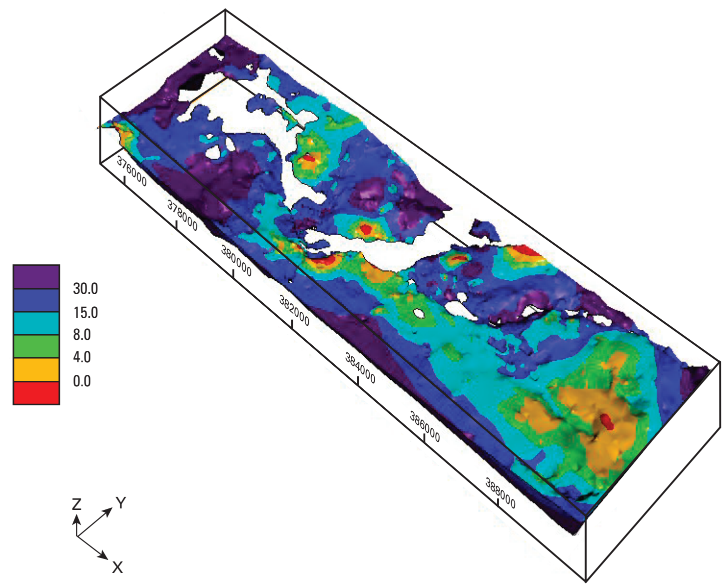


Figure 24 Variation of Standard Penetration Test (SPT) within the till envelope.

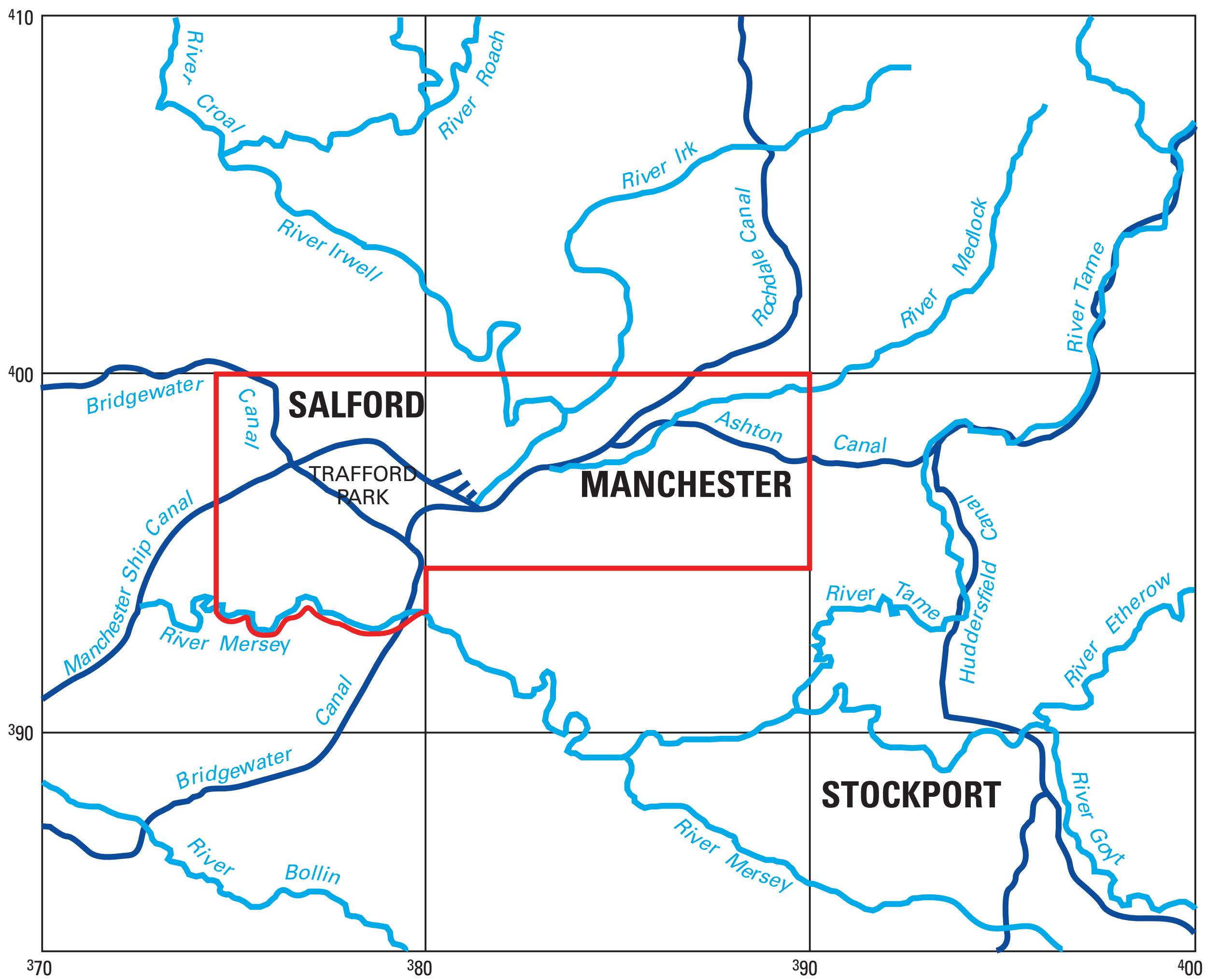


Figure 25 Principal rivers and canals.

AQUIFER UNIT 118.07 MANCHESTER AND EAST CHESHIRE GROUNDWATER LEVEL CONTOURS YEAR:2000 SHEET 1 OF 2

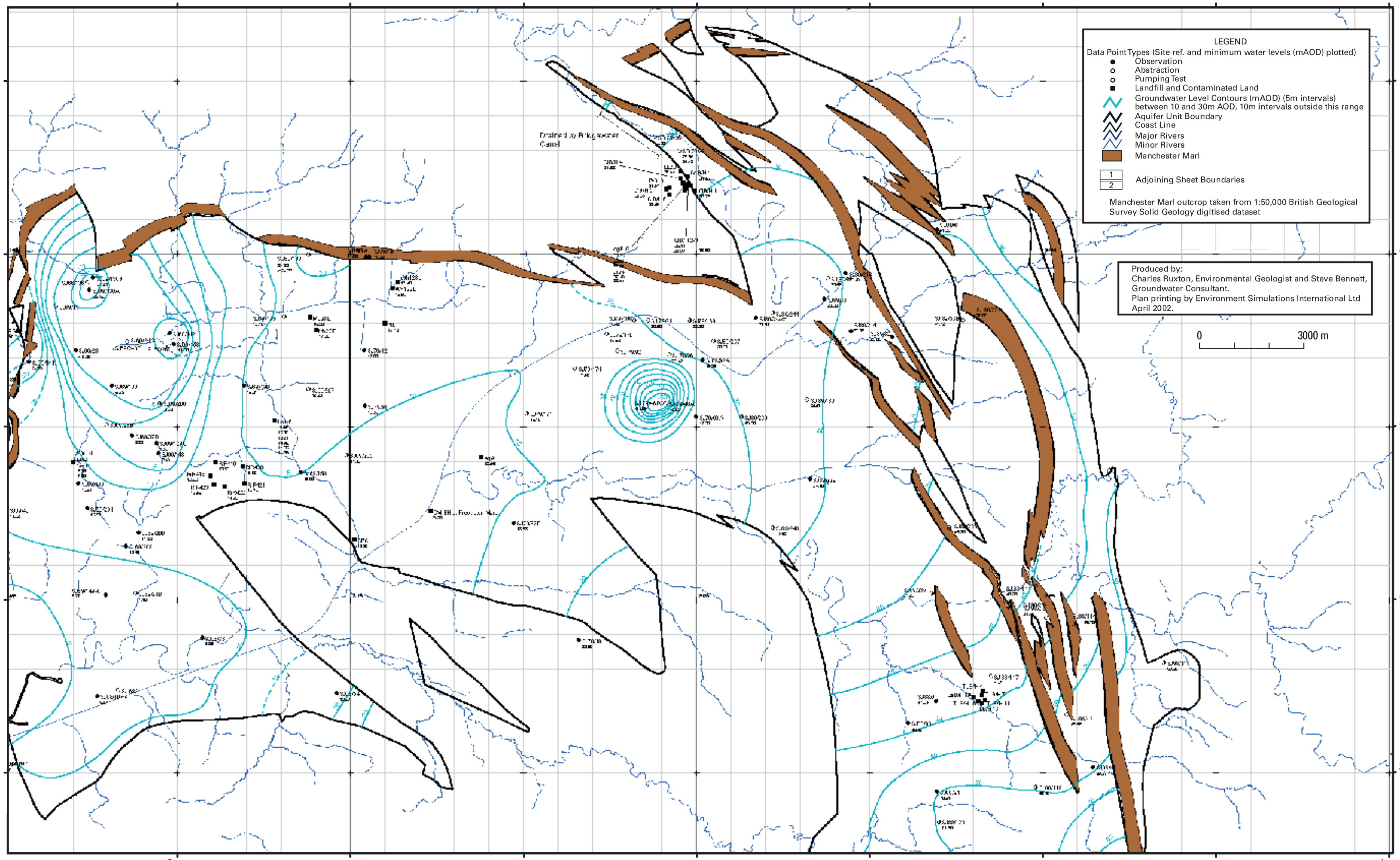
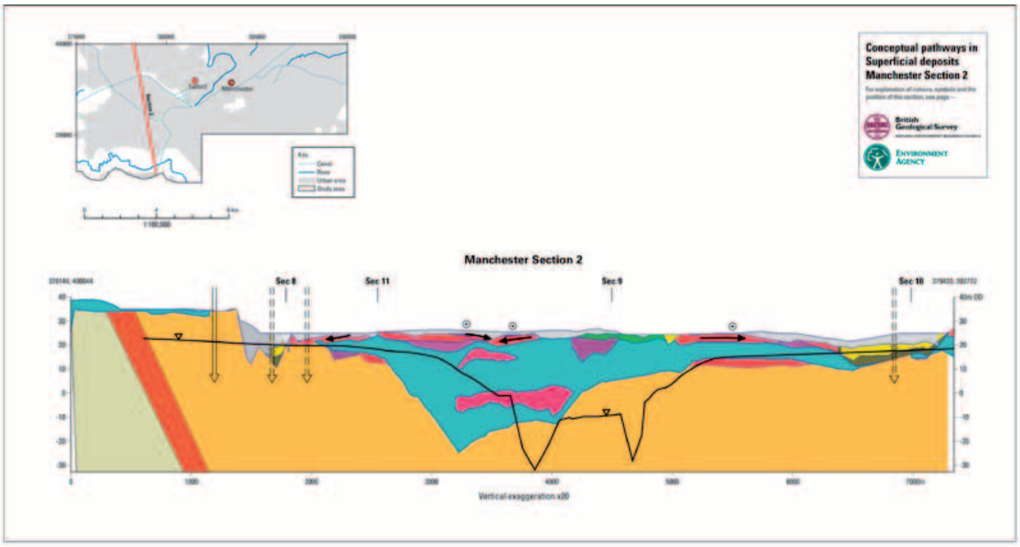
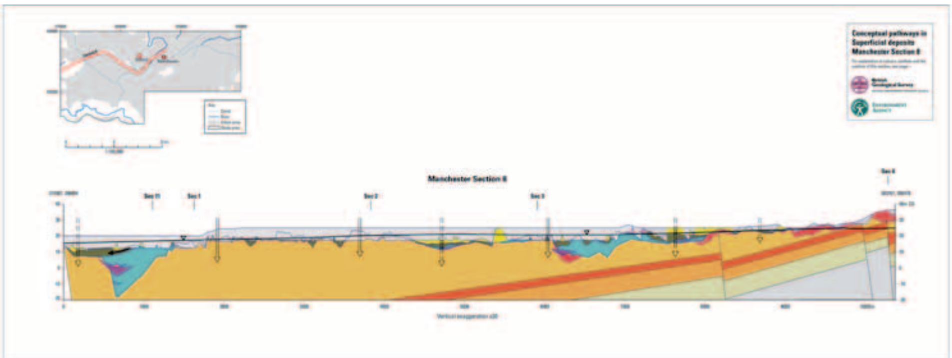
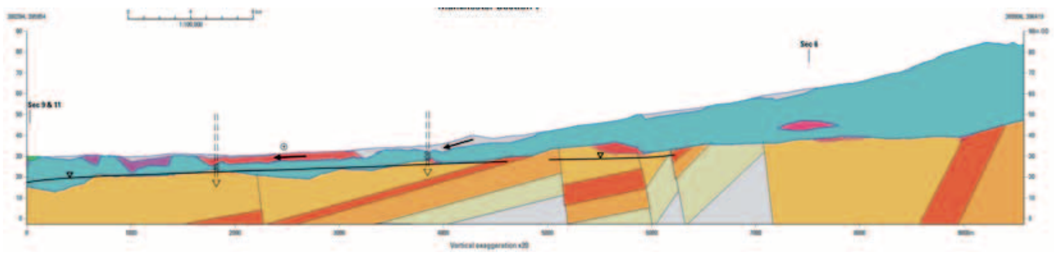


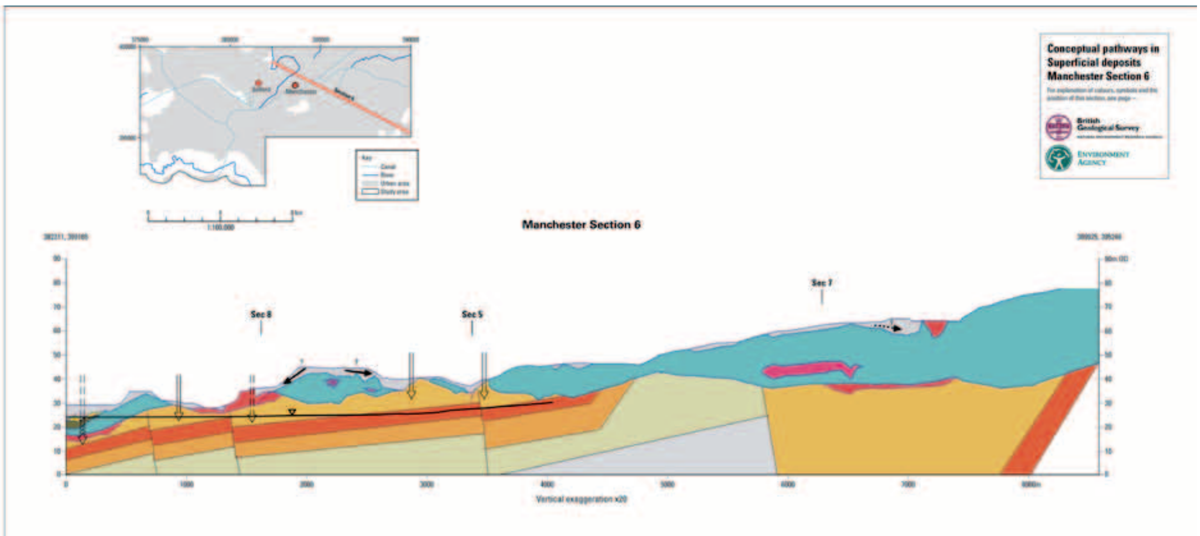
Figure 26 Groundwater level contours for Manchester and east Cheshire, 2000 (Ruxton and Bennet, 2000).

Figure 27 Cross-sections showing potential recharge pathways.









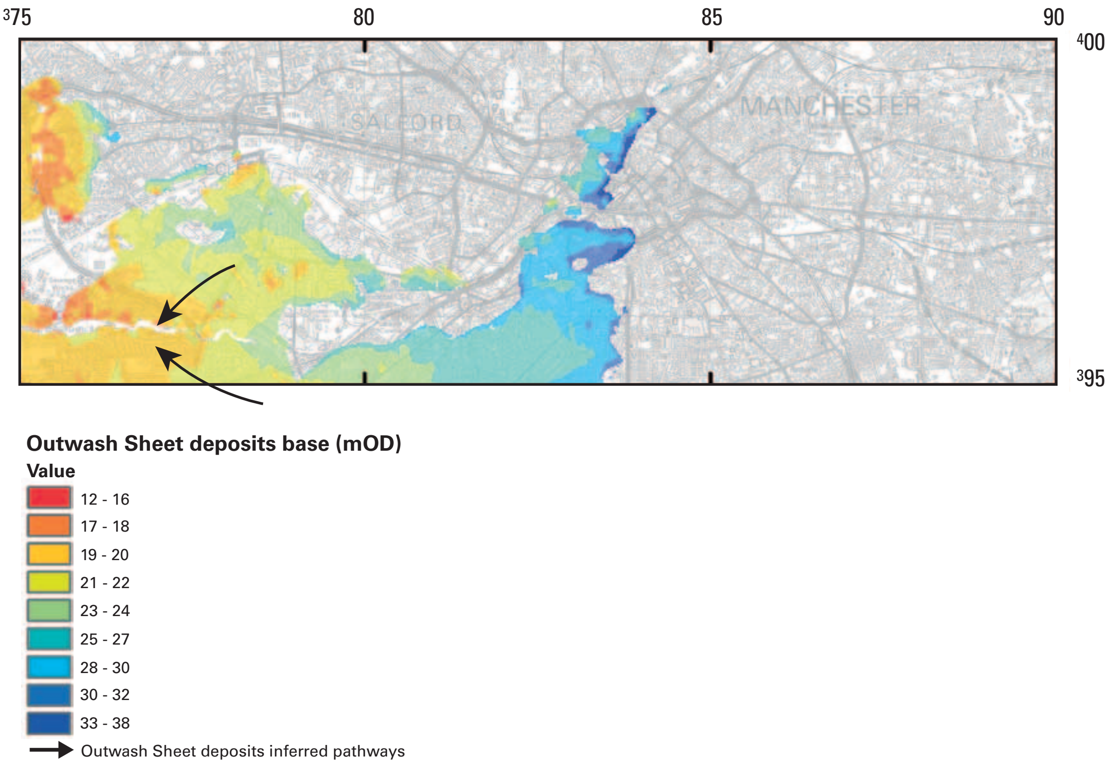


Figure 28 Conceptual hydrogeological pathways in outwash sheet sands [lgfg].

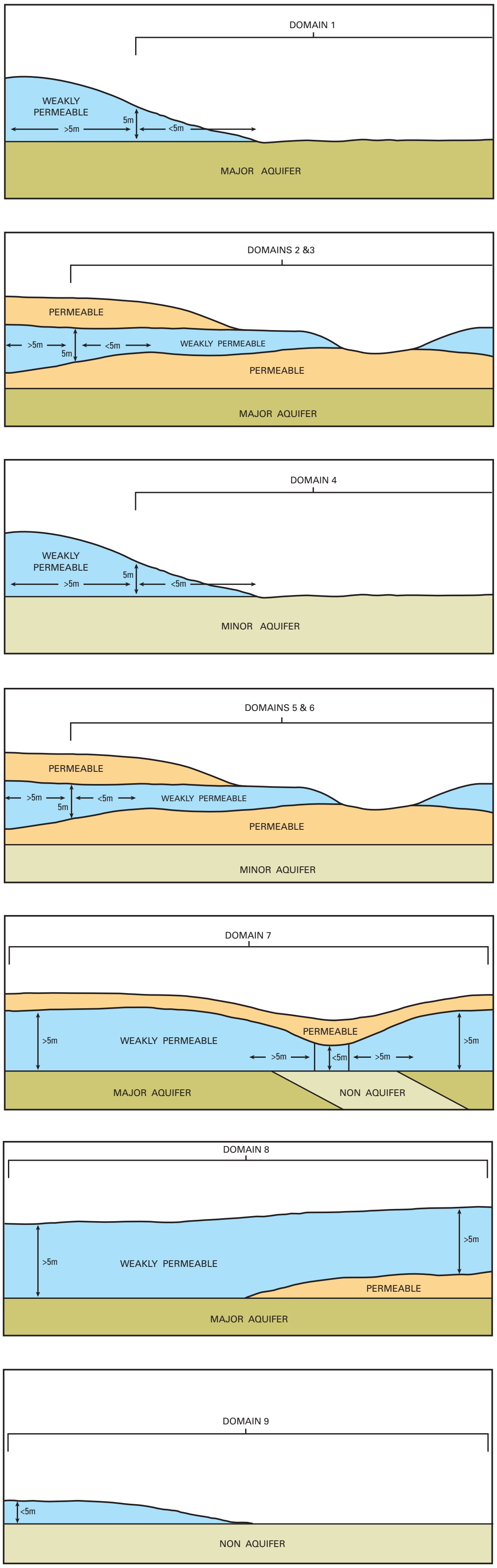


Figure 29 Domains defined schematically.

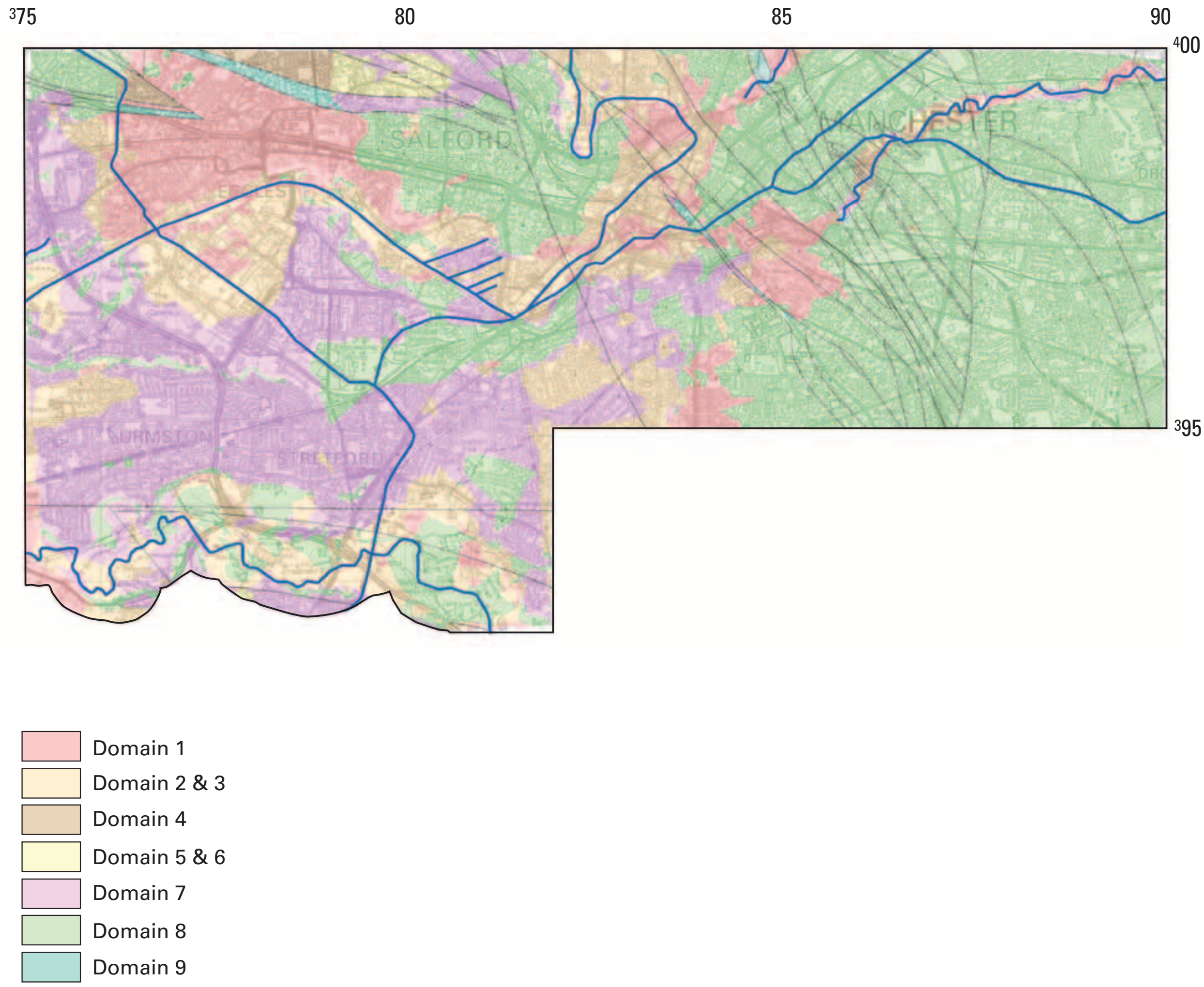


Figure 30 Hydrogeological domains.

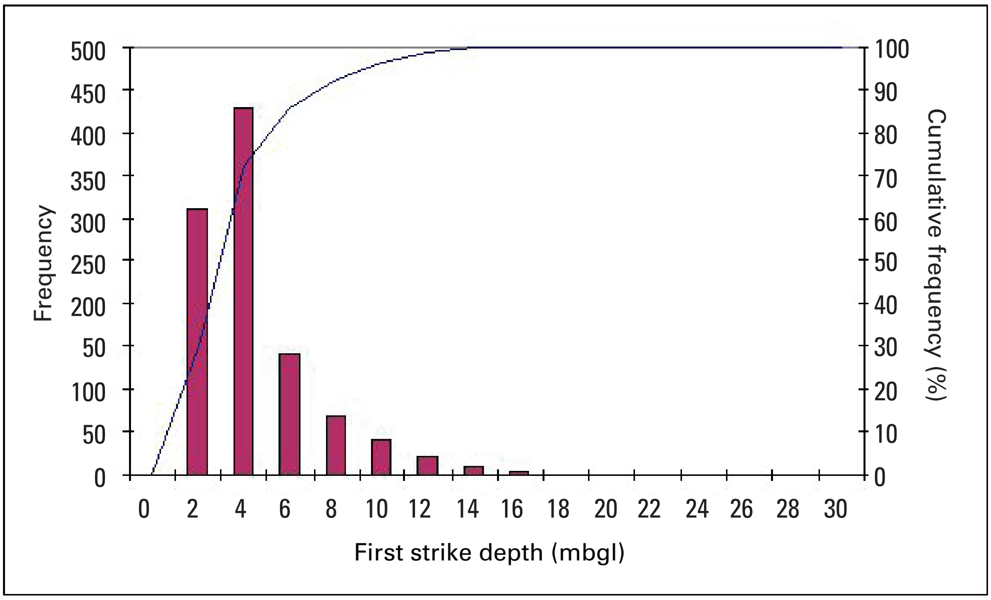


Figure 31 Histogram showing frequency and depth to first strike.

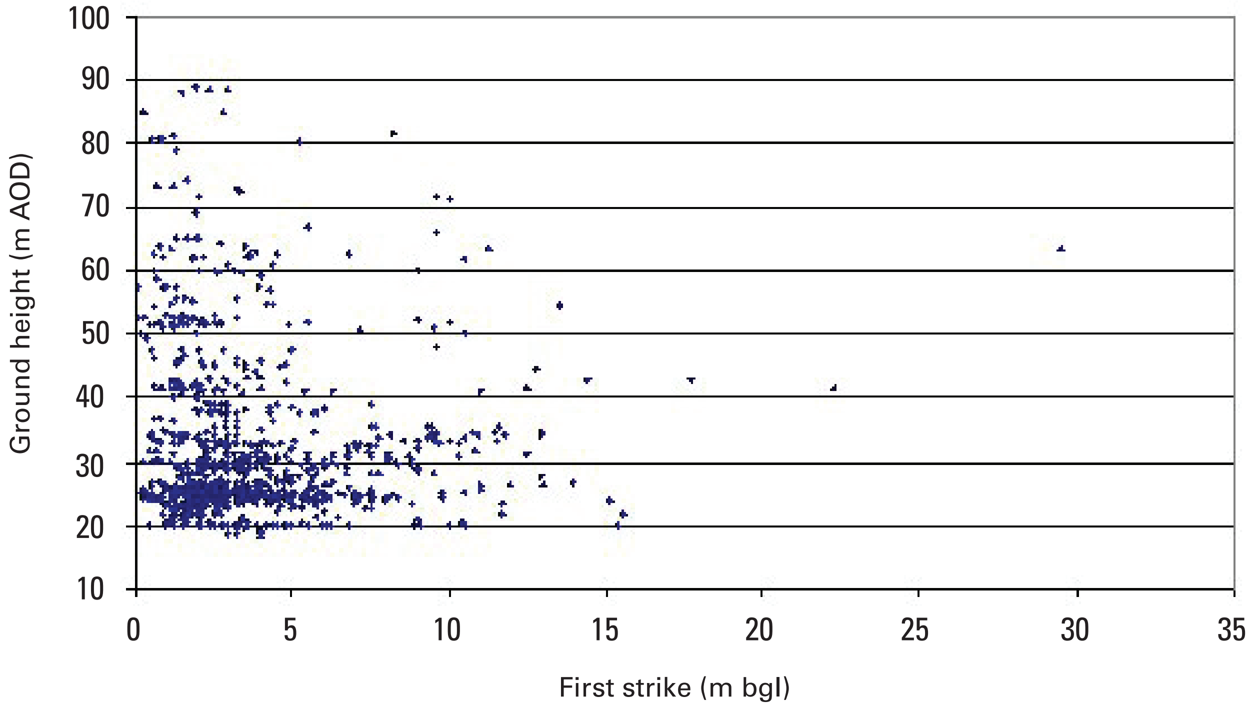


Figure 32 Relationship between topography and first strike.

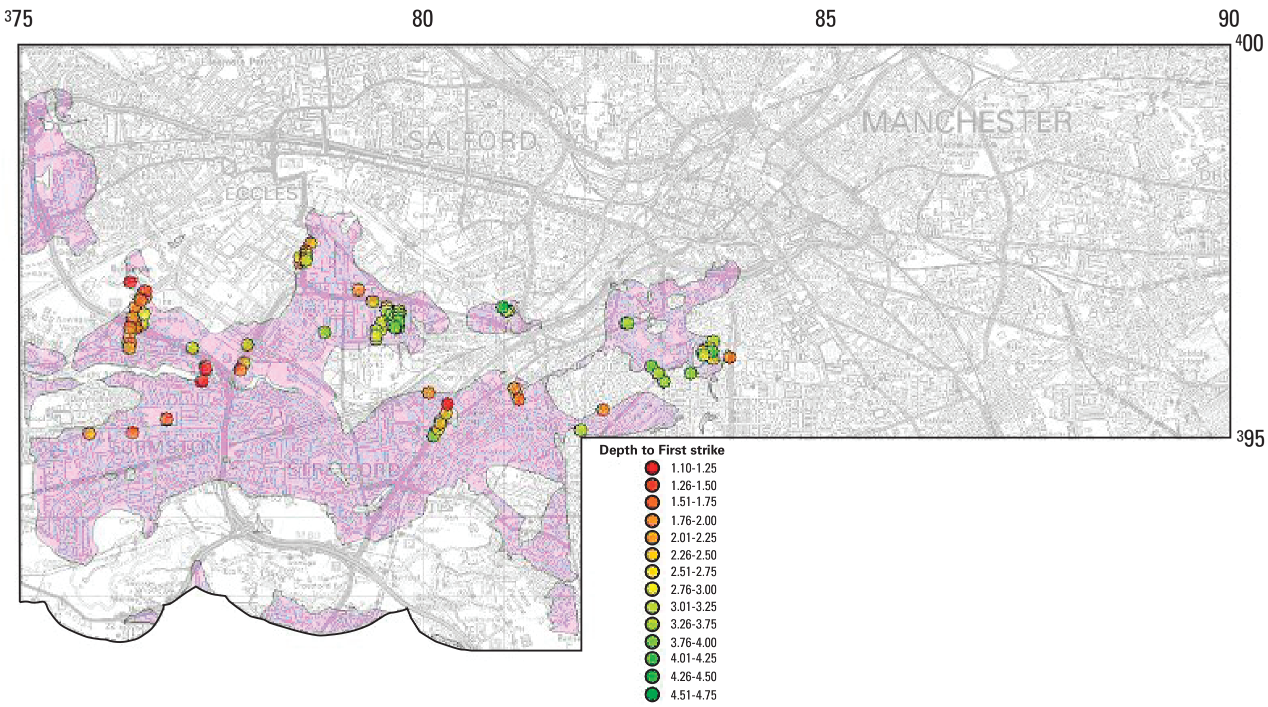
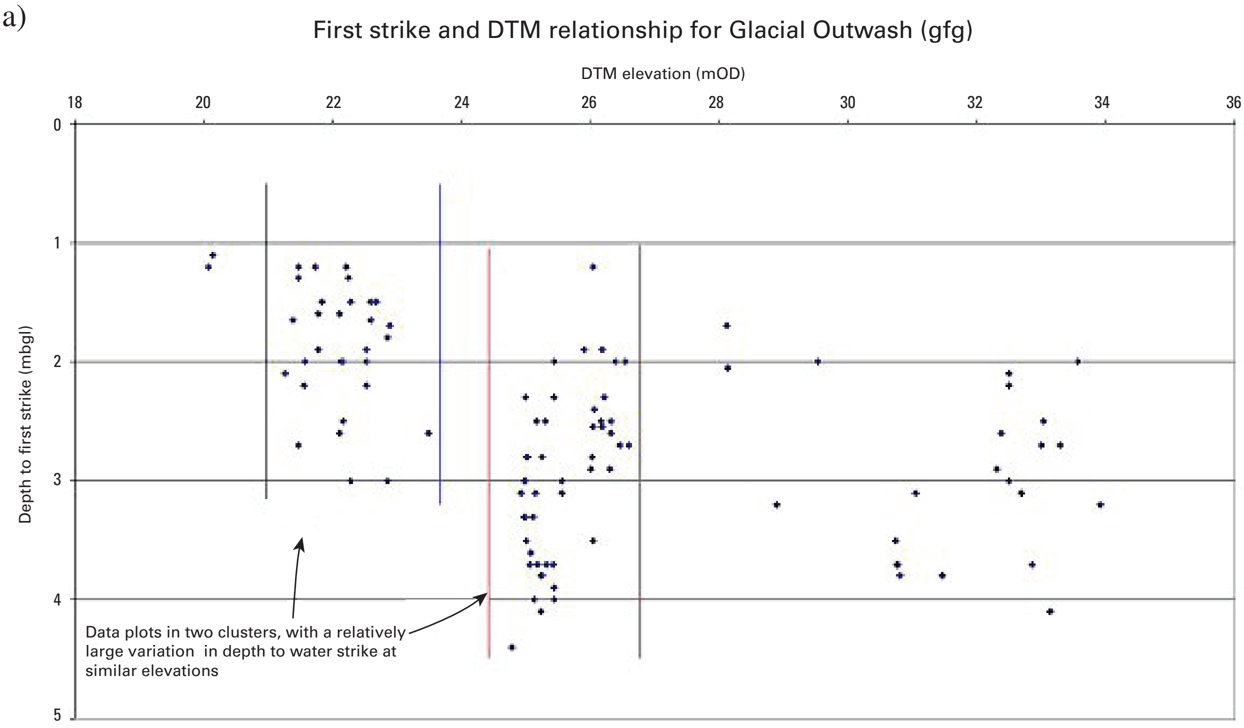


Figure 33 Depth to first strike in Domain 7.

a)



b)

Figure 34 First strike and DTM relationship for glacial outwash (lgfg).

a First strike clusters

b Spatial distribution

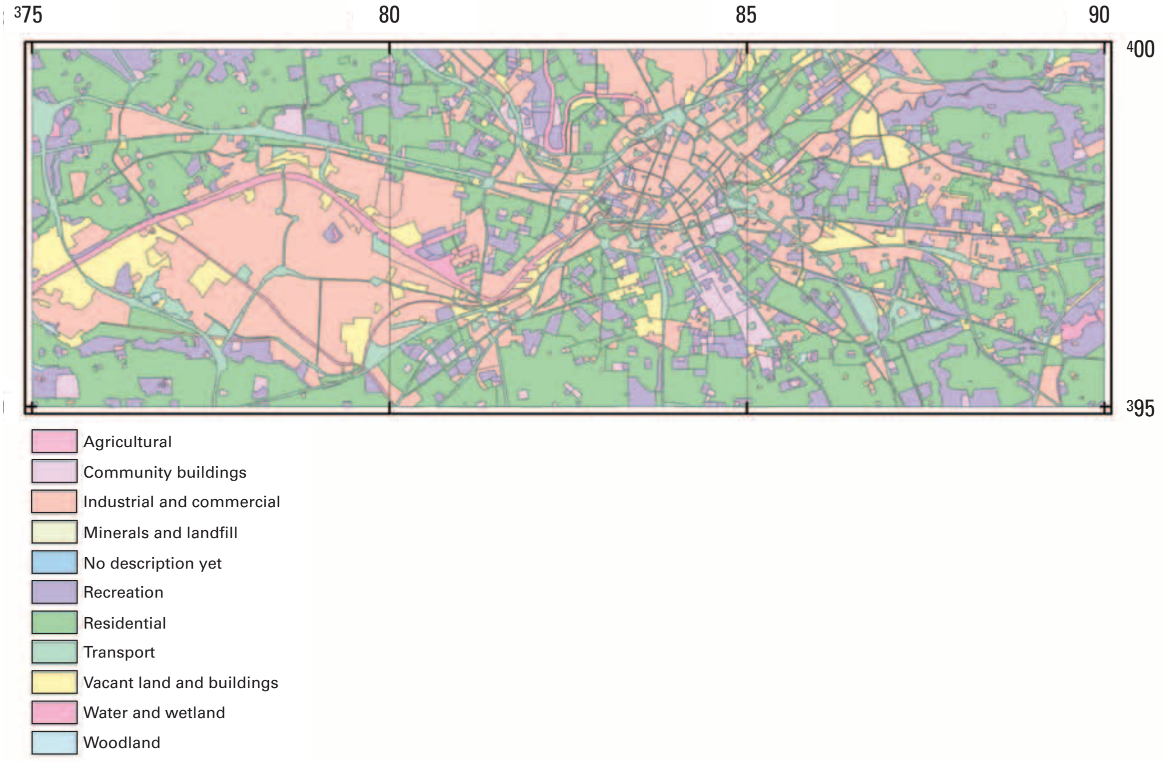


Figure 35 Present-day land use.

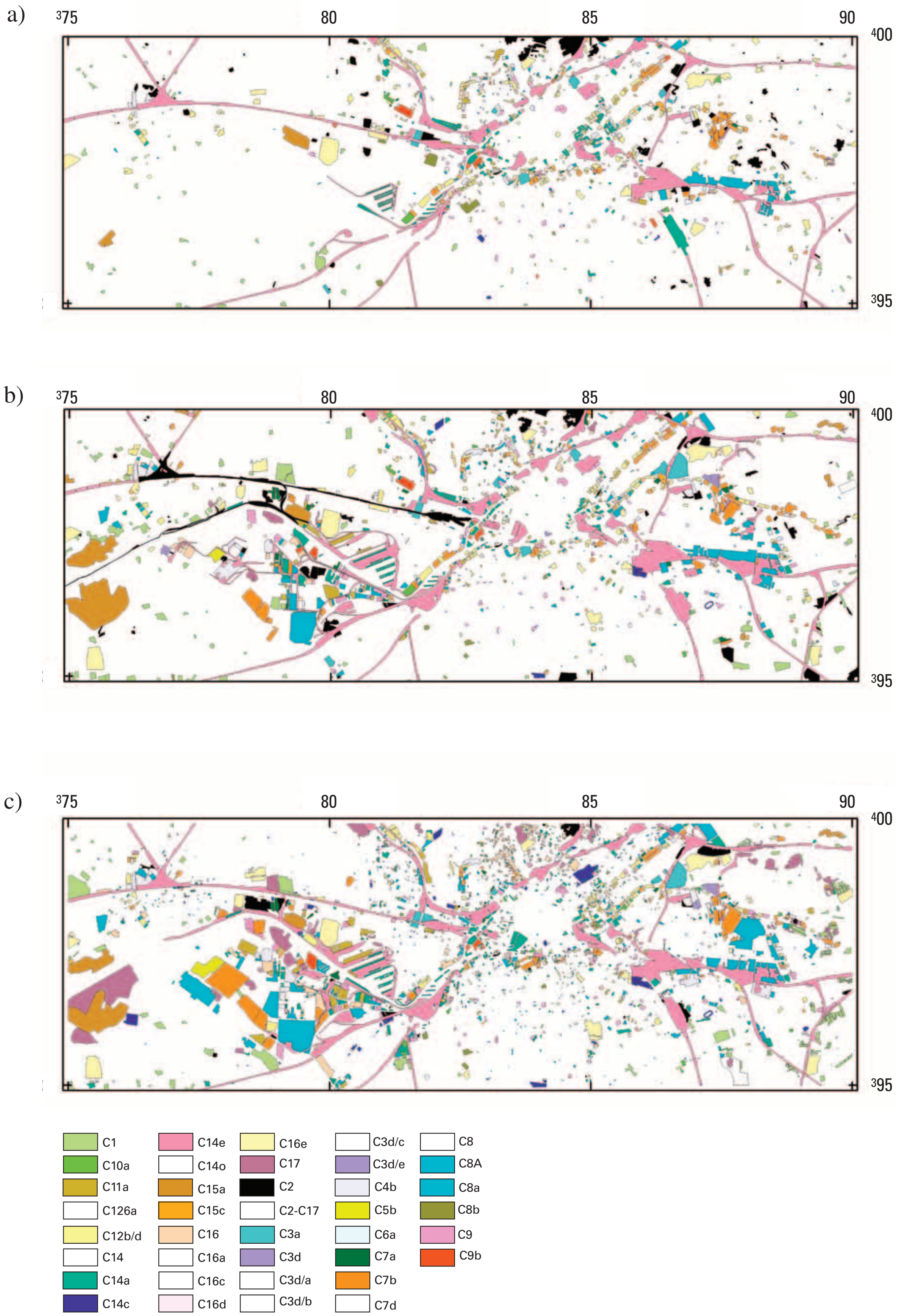
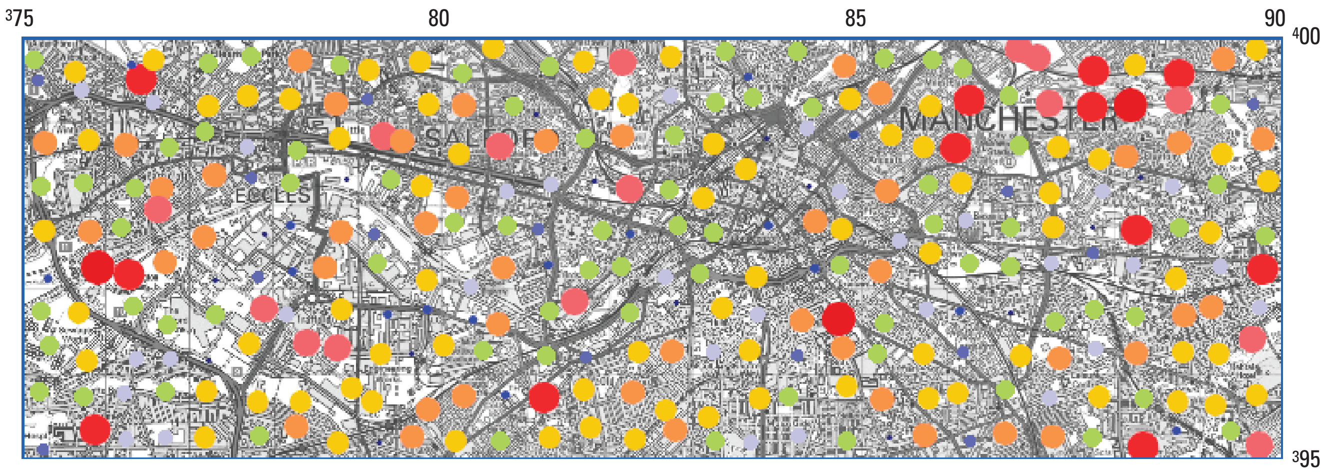


Figure 36 Land use.

a 1890
b 1920
c 1950

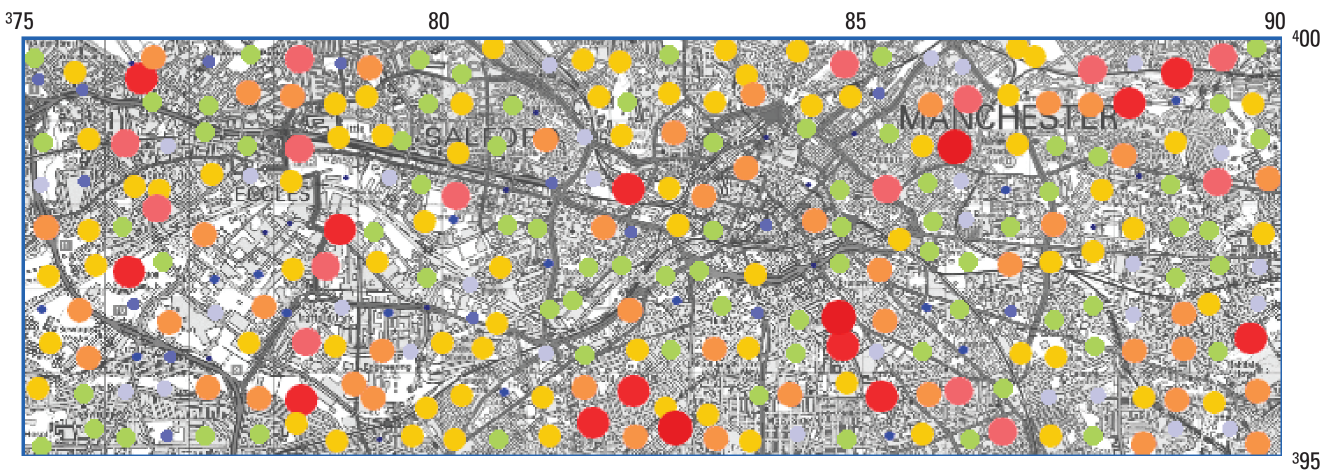
a)



As (ppm)

- 111 - 1001
- 50 - 110
- 40 - 49
- 29 - 39
- 21 - 28
- 17 - 20
- 15 - 16
- 14
- 13
- 3 - 12

b)



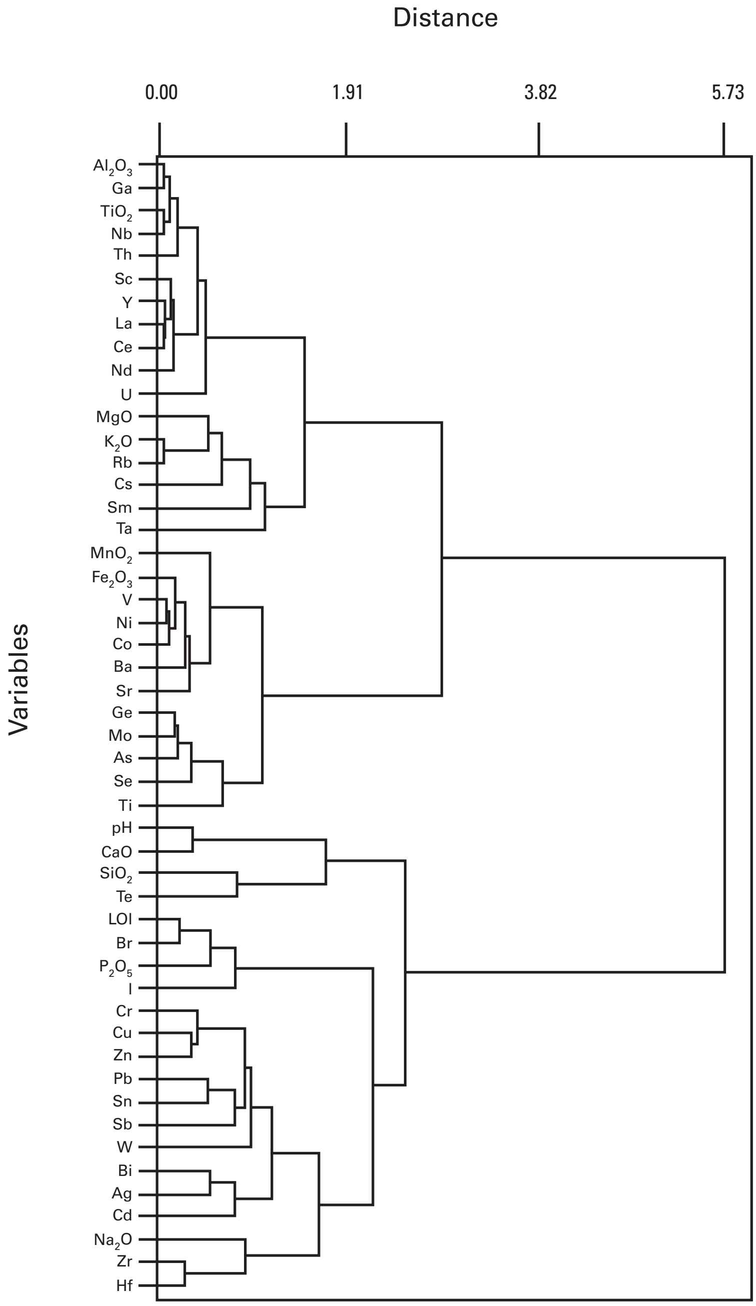
Pb (ppm)

- 1463 - 12758
- 581 - 1462
- 449 - 580
- 319 - 448
- 219 - 318
- 149 - 218
- 120 - 148
- 101 - 119
- 72 - 100
- 20 - 71

Figure 37 Maps showing distribution of lead and arsenic in surface soils, indicated by graduated symbols.

a Lead (Pb)
b Arsenic (As)

Figure 38 Dendogram produced using cluster analysis showing the spatial relationship of elements, pH and LOI (loss of ignition) for data collected from the Manchester/Salford keys geochemical survey. Elements clustered at short distances are more strongly related and the relationship weakens between clusters as distance increases.



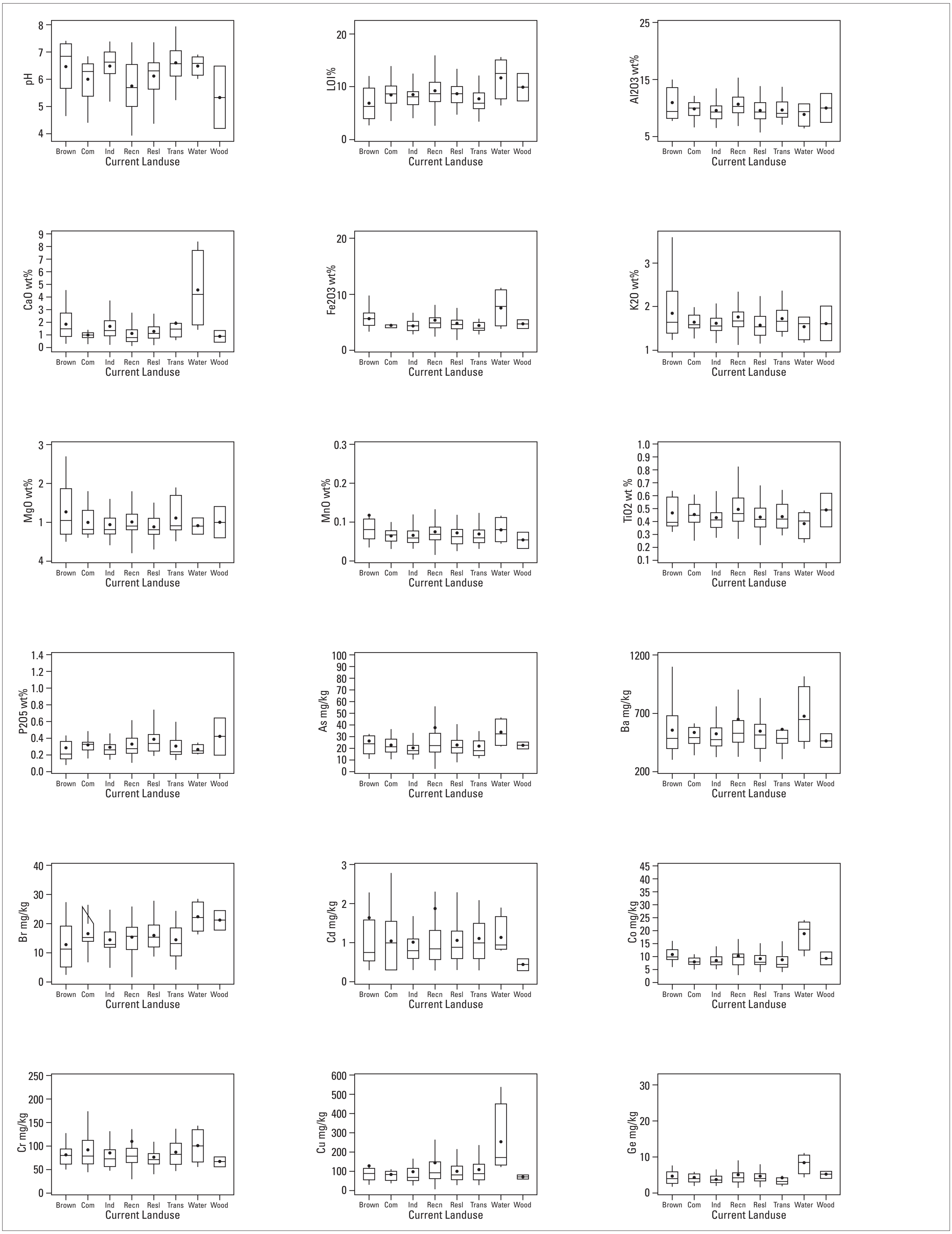


Figure 39 Element distribution in surface soils plotted against current land use. Plots show the mean concentration (•) and the 5th, 25th, 50th, 75th and 95th percentiles. LOI (loss on ignition) and pH is also shown.

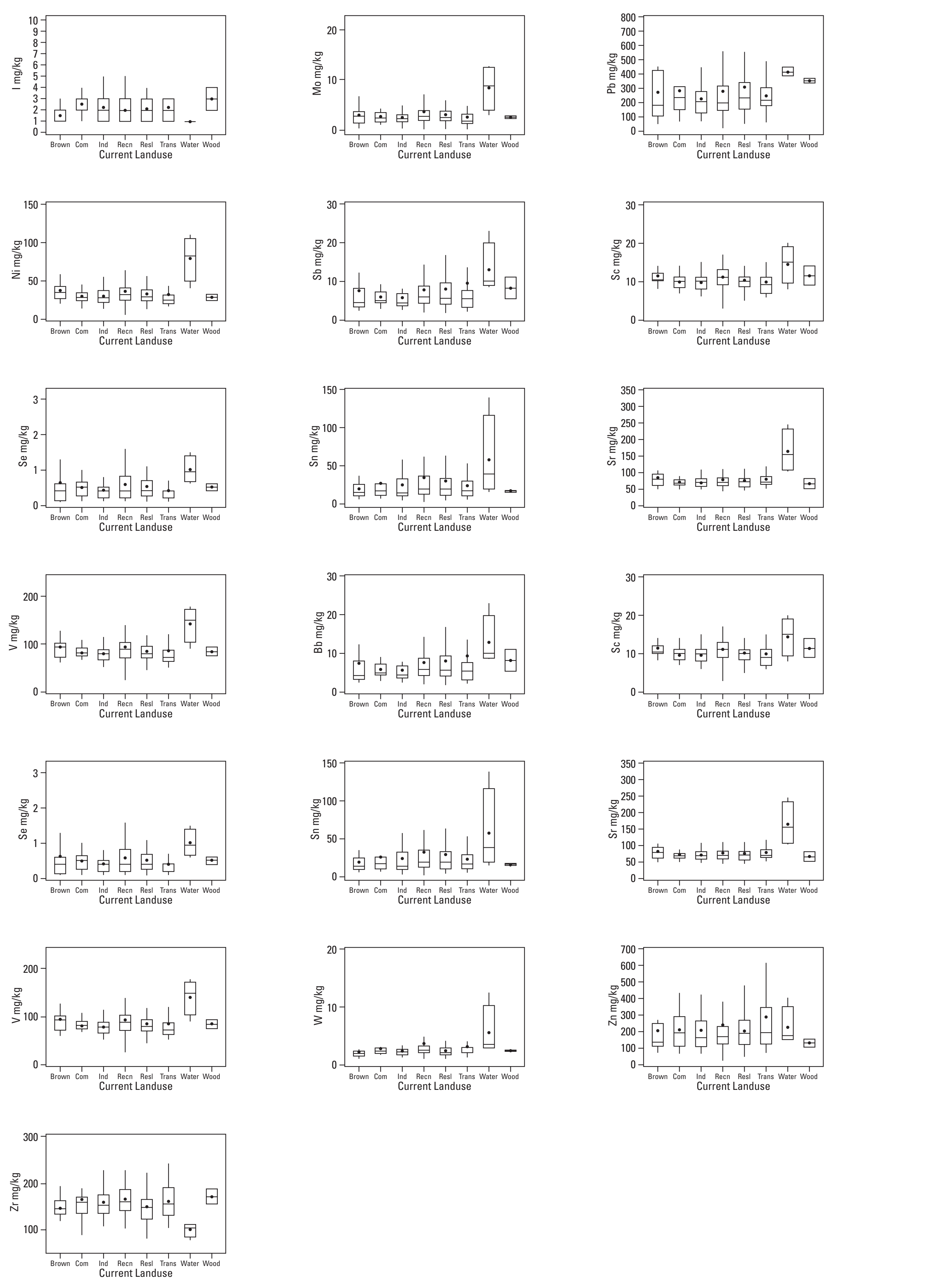


Figure 39 *Continued.*

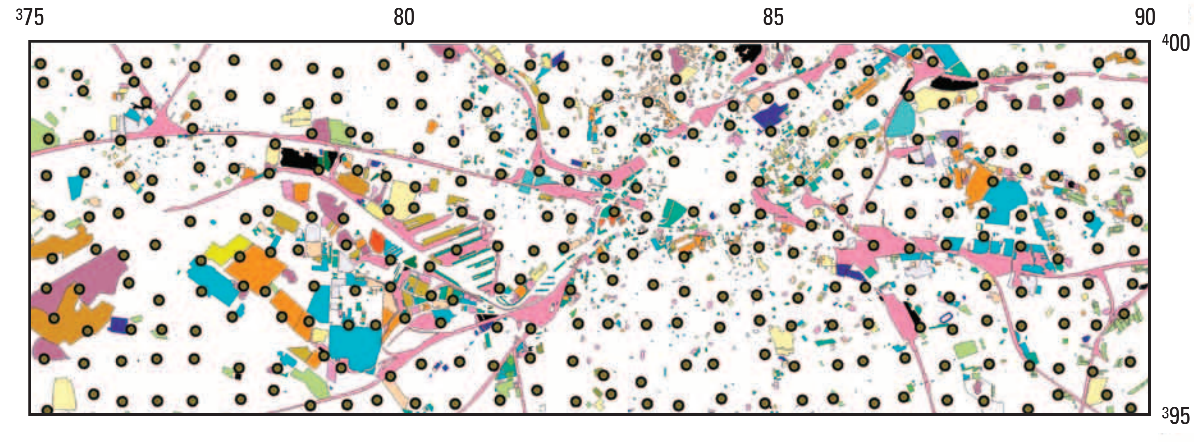


Figure 40 Land use (1950s) and soil sample locations.

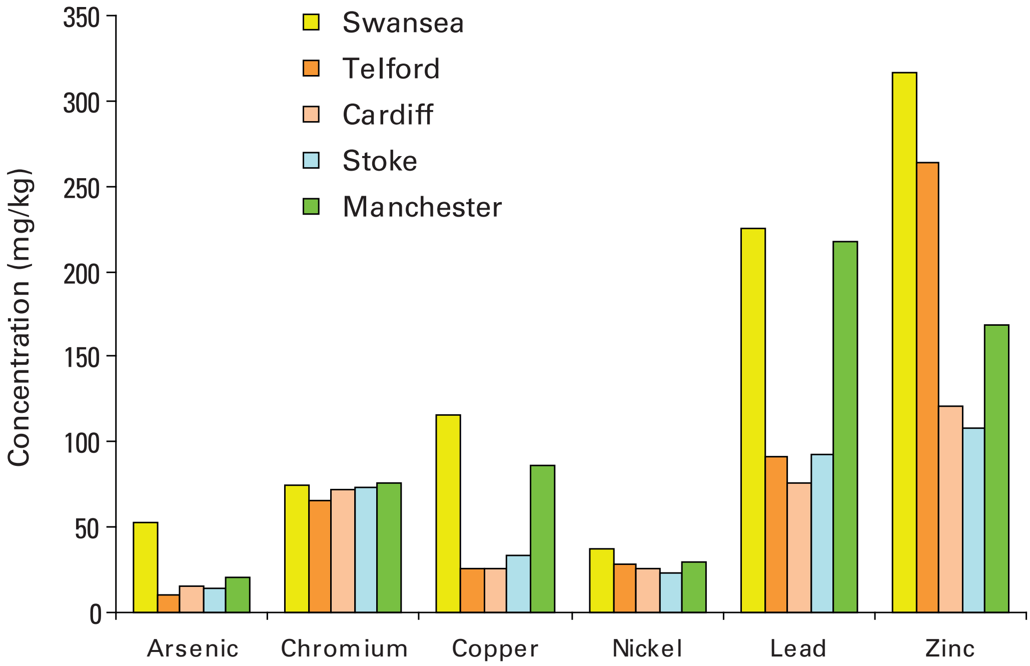


Figure 41 Concentration of selected metals (median values) across five urban areas that have an historical association with metallurgical industries.

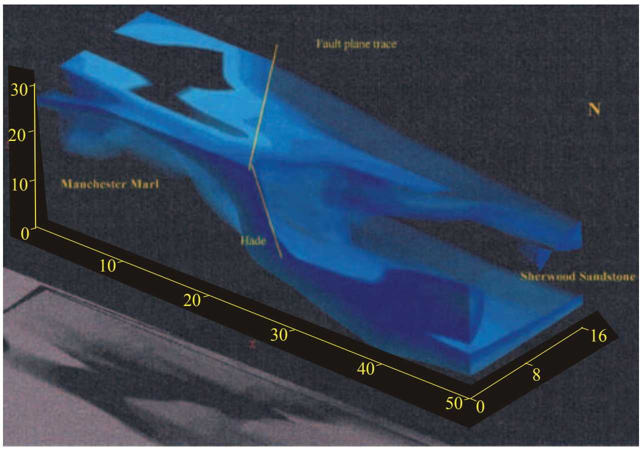
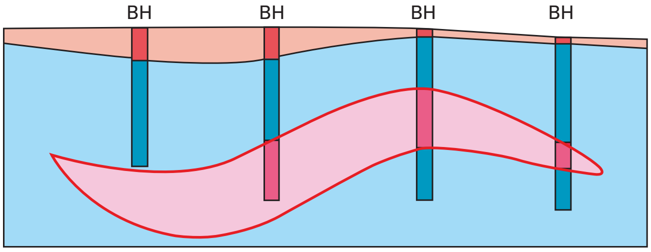
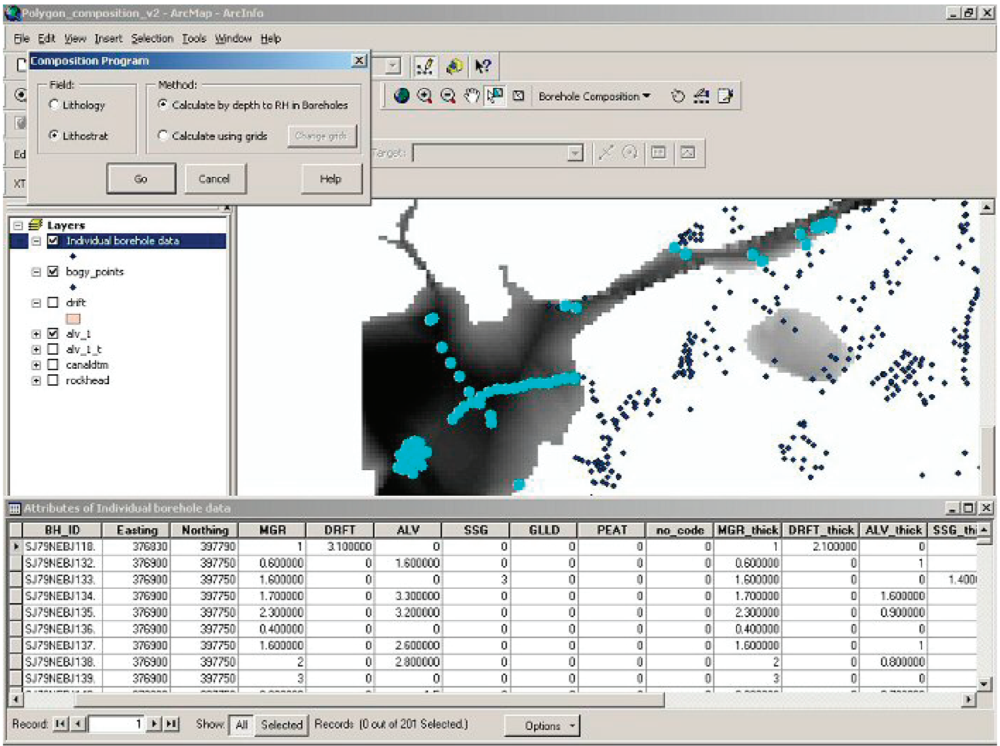


Figure 42 Electrical tomographic response across a splay of the West Manchester Fault, central Manchester [837 979] showing the high response of the Manchester Marls on the upthrow side of the fault (top left of image) and low response of the Chester Pebble Beds on the downthrow side (bottom right of image). Scale in metres. Image courtesey of REL and Sub Terra Surveys (S. Shedlock).

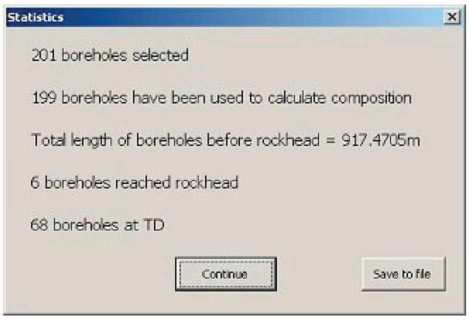
a)



b)



c)



d)

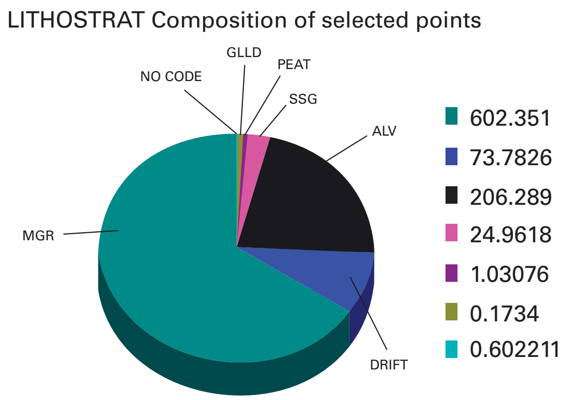


Figure 43 Borehole composition tool.

a Schematic cross-section showing how the tool selects borehole records that occur between two specified surfaces, enclosing a lens (purple)

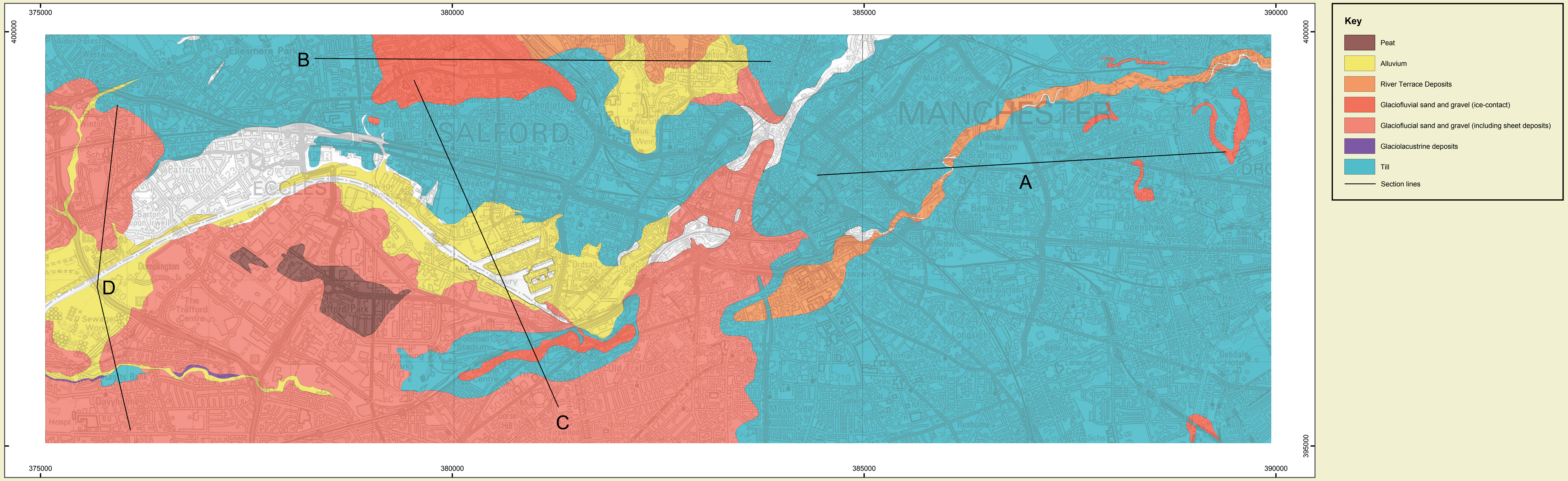
b Screen shot of the borehole composition tool in ArcGIS. Highlighted points are selected boreholes under analysis. The opened shapefile table details lithological depth and thickness of deposits in the selected interval

c Summary statistics

d Pie chart

Superficial Deposits

Scale 1:30 000



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NATURAL ENVIRONMENT RESEARCH COUNCIL

GROUND CONDITIONS IN CENTRAL MANCHESTER AND SALFORD: THE USE OF THE 3D GEOSCIENTIFIC MODEL AS A BASIS FOR DECISION SUPPORT IN THE BUILT ENVIRONMENT

MAP 1: SUPERFICIAL AND BEDROCK GEOLOGY

Geological linework based on BGS 1:10 000 scale mapping:

Original geological survey on the 10:10 560 scale by E Hull, published 1862-4.
Resurveyed on the 1:10 560 scale by R C B Jones, W Lloyd, L H Tonks and R L Sherlock, 1924-7.
Bedrock geology revised by J I Chisholm in 1973.
Reconstituted on the 1:10 000 scale by E Hough and R A Ellison, with minor amendments in 2001.

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British Geological Survey, Keyworth, Nottingham NG12 5GG. Tel. 0115 9363100**

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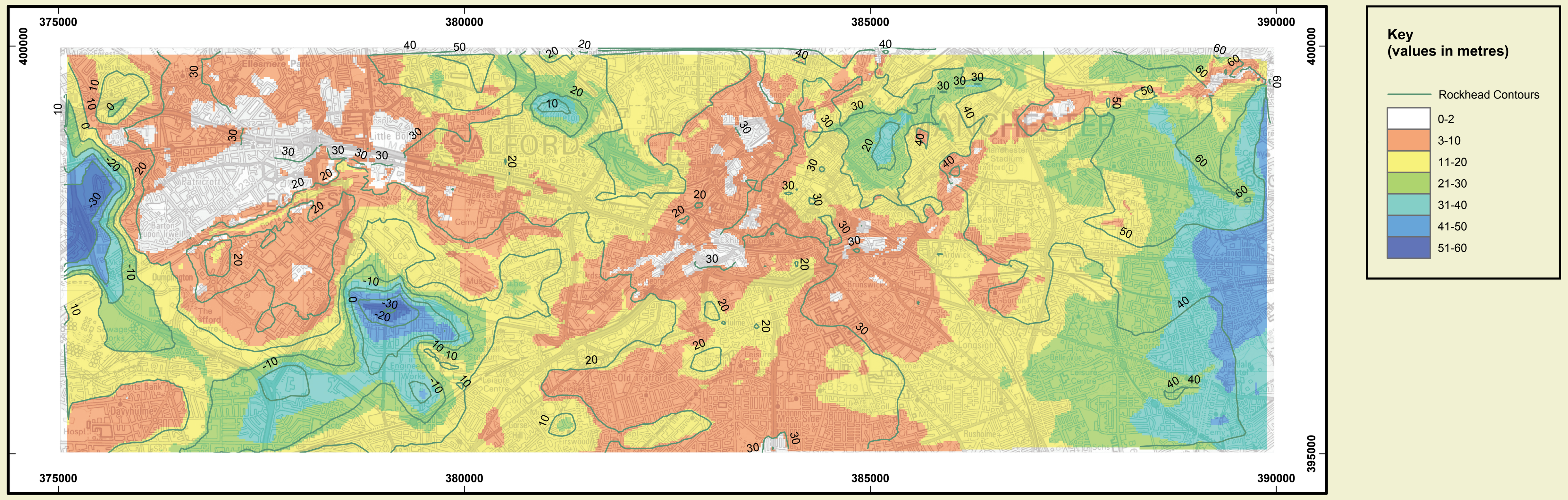
Compiled by C. Simpson, BGS, Keyworth.

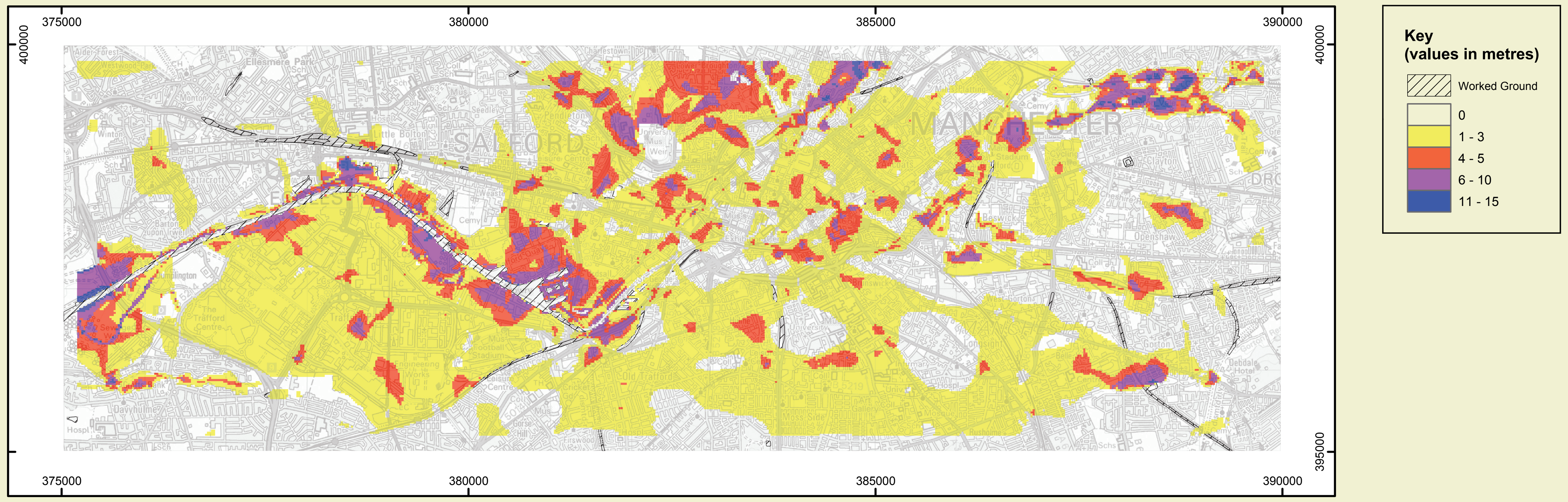
Thickness of Superficial Deposits (including Artificial Ground)

Scale 1:50 000



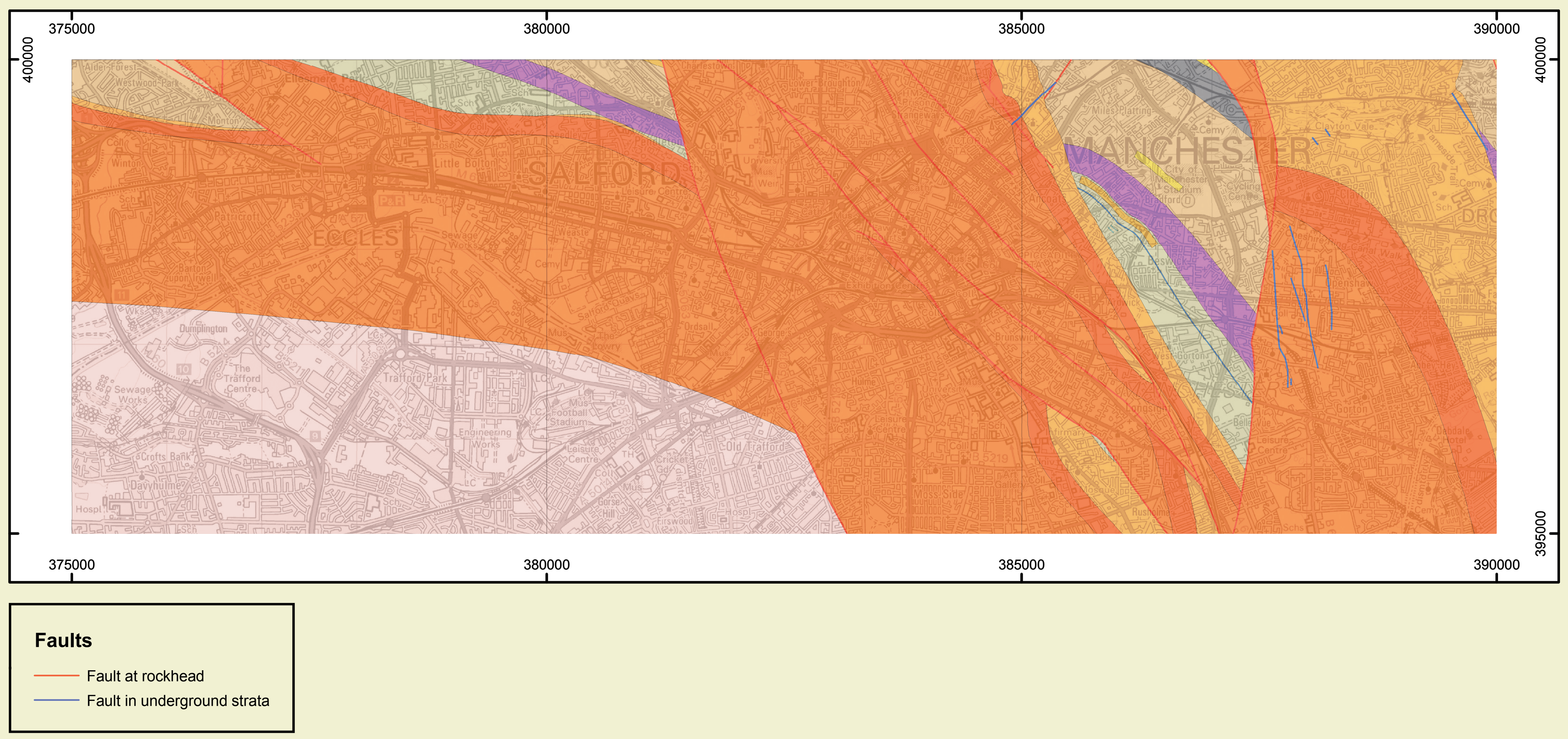
Thickness of Artificial Deposits

Scale 1:50 000

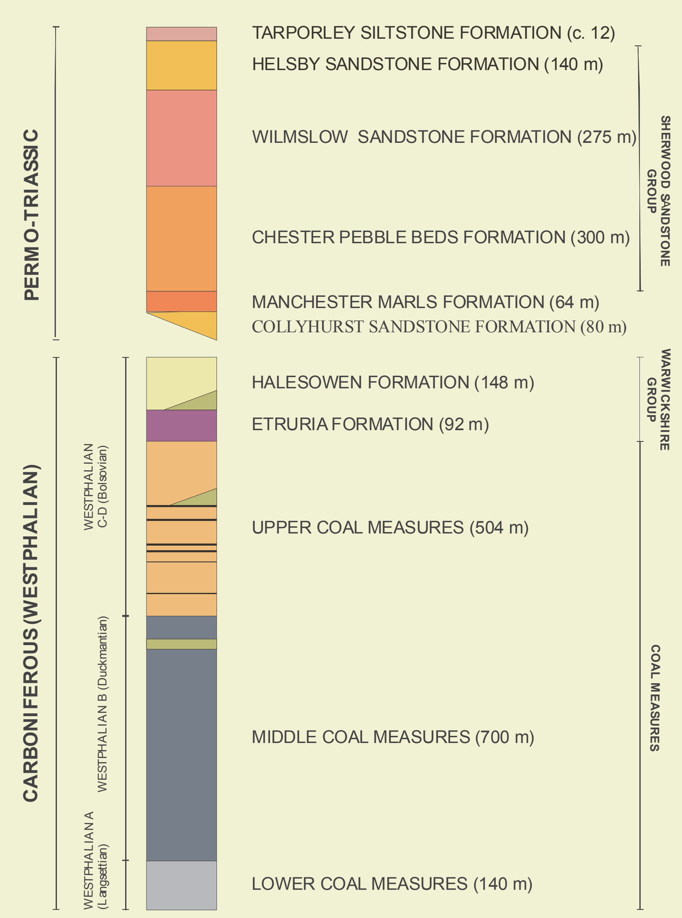


Bedrock Geology (key as per GVS)

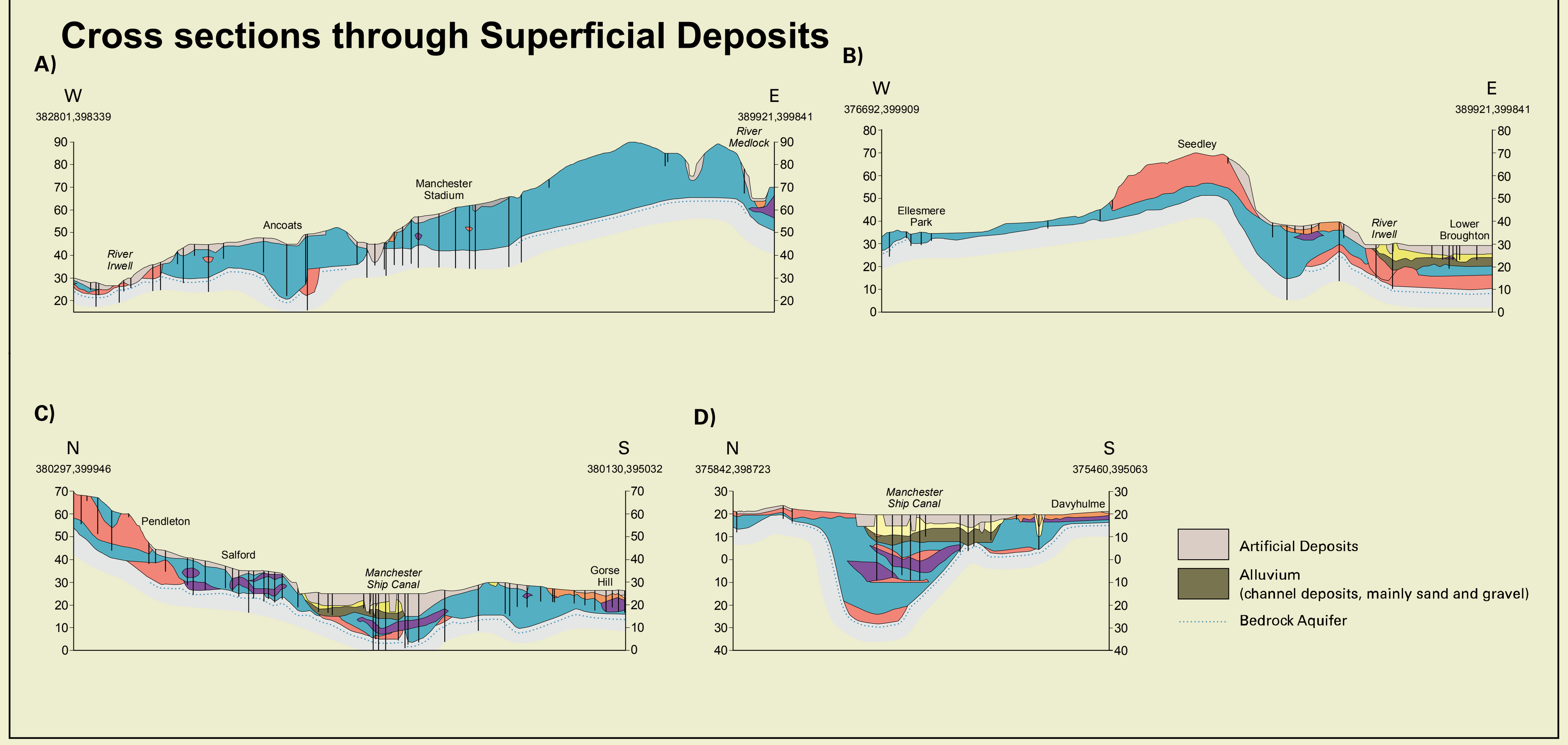
Scale 1:50 000



Generalized Vertical Section Bedrock Units

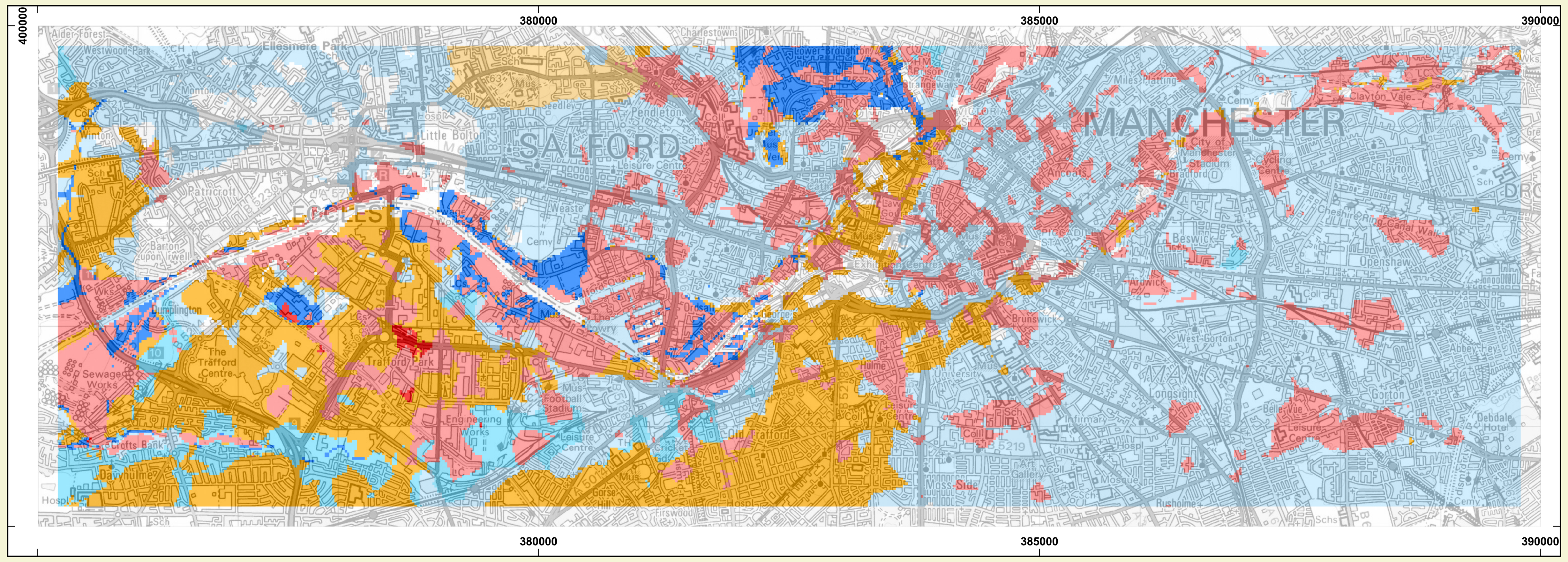


Cross sections through Superficial Deposits



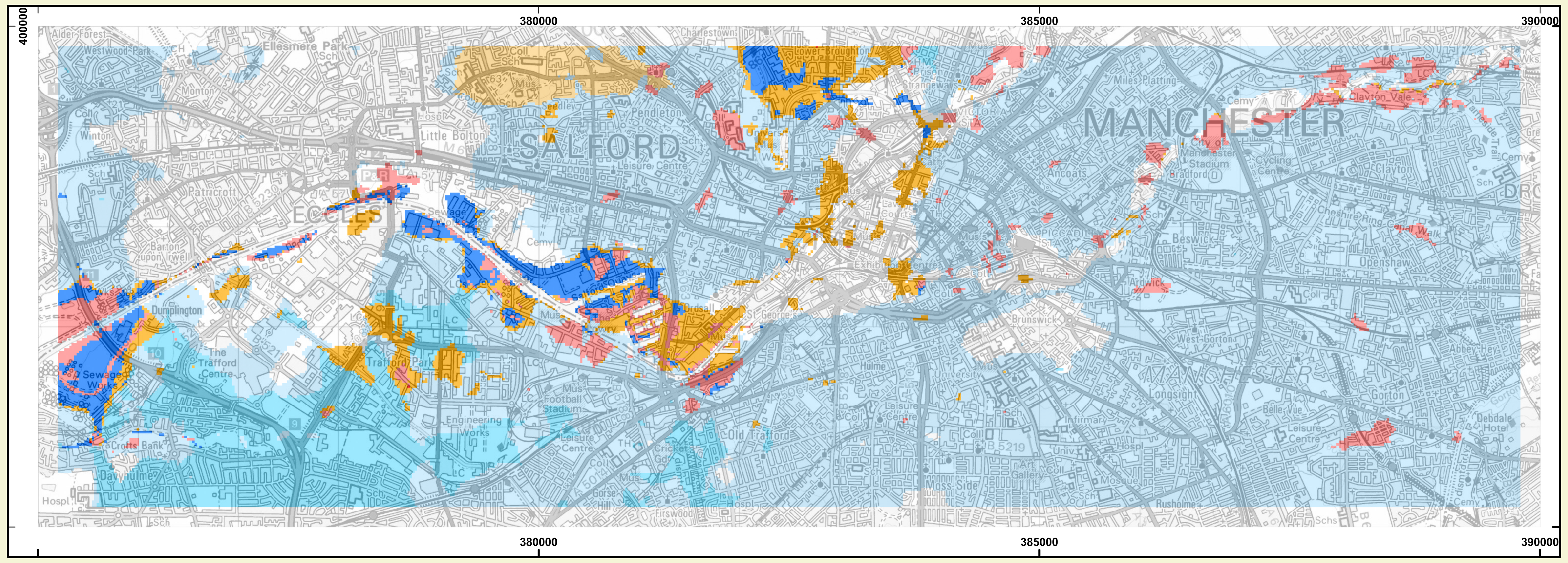
Engineering Geology units: 2m below ground surface

Scale 1:40 000



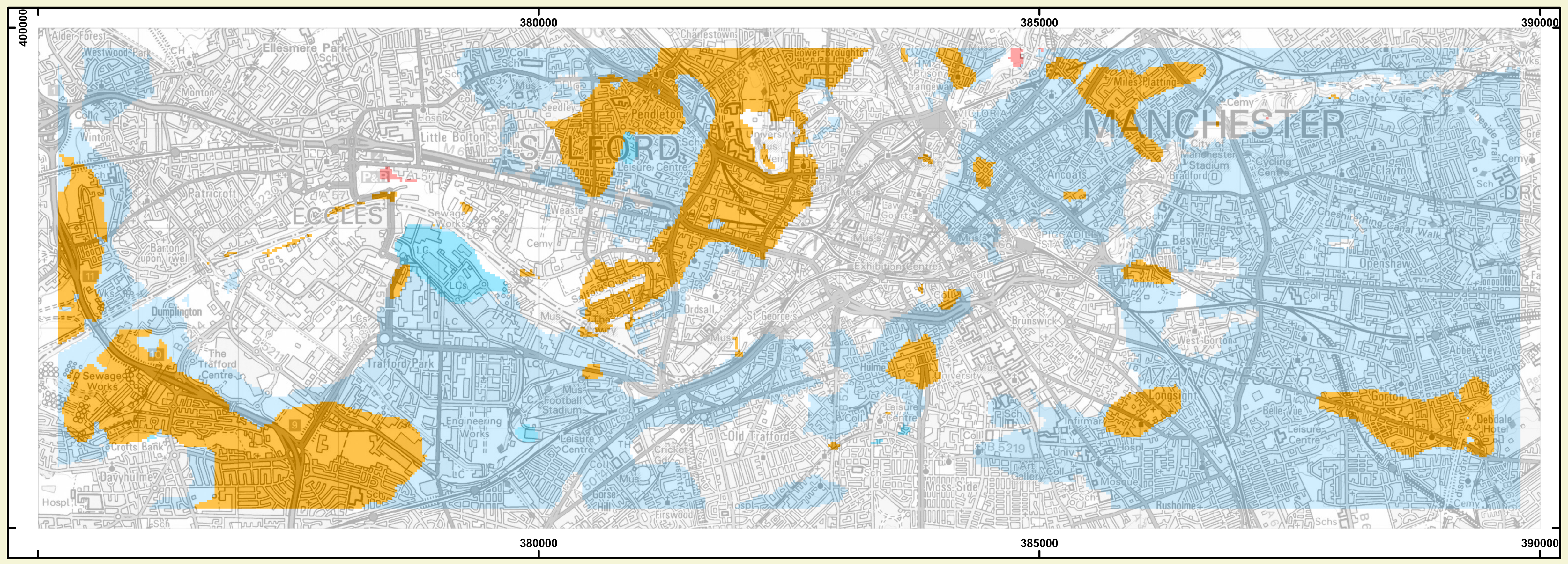
5 m below ground surface

Scale 1:40 000



10 m below ground surface

Scale 1:40 000



Maps (above) represent slices through the 3D attributed engineering geological model at depths of 2, 5 and 10 m below ground surface. Used in conjunction with the engineering classification and properties tables, they provide an indication of changing ground conditions across the district, and at depth.

Bedrock

Summary Statistics of the principal "Engineering Geological Soils" of the district

			PLASTICITY			STRENGTH	TRIAXIAL			SPT	CHEMICAL			DENSITY	
		m	LL	PL	PI	c_u	π_u	c'	π'	N Value	SO_3	pH	ORG.	Bulk	Dry
		(%)	(%)	(%)	(%)	(kPa)	(degr)	(kPa)	(degr)		%		%	(Mg/m^3)	(Mg/m^3)
Peat	min	13.0				9					0.03	5.4		0.99	
	max	453.4				32					0.53	6		1.36	
	median	123.0	193.0	94.0	99.0	15					0.28	5.7		1.17	
	mean	170.6				18					0.28	5.7		1.14	
	count	18	1	1	1	8					2	4		8	
Alluvium (overbank deposits) [alv_1]	min	13.0	22.0	11.0	4.0	10		0	30	2.0	0.00	5.1		1.31	0.99
	max	61.0	125.0	38.0	88.0	62		8	33	18.0	0.31	8.0		2.25	1.64
	median	29.0	36.0	21.0	15.0	31		4	32	5.0	0.04	7.0		1.90	1.32
	mean	31.4	41.4	21.8	19.6	34		4	32	6.4	0.08	5.0		1.89	1.32
	count	139	43	43	43	49		2	2	34	32	18		143	2
Alluvium [alv_2] * Results only from fines in sample	min	2.8*	31*	15*	10*	10				6.0	0.01	7.9		2.04	1.72
	max	18*	73*	42*	32*	91				134.0	0.09	8.4		2.25	1.91
	median	9.5*	42*	25*	20.5*	30				26.0	0.01	8.1	4.70	2.09	1.87
	mean	8.9*	47.5*	26.4*	21.1*	39				32.6	0.04	8.1		2.12	1.85
	count	22*	10*	10*	10*	18				92	9	7	1	12	6
River Terrace Deposits [rtdu]	min									8.0	0.06			1.86	
	max									63.0	0.29			2.02	
	median									14.5	0.17			1.94	
	mean									19.3	0.17			1.94	
	count									18	2			2	
Glaciofluvial Sand & Gravel – sheet deposits (lgfg)	min									2.0	0.00	3.6		1.86	
	max									80.0	0.07	9.1		2.30	
	median									14.0	0.03	7.2		1.99	
	mean									16.9	0.03	7.0		2.02	
	count									373	23	86		2	
Glaciofluvial Sand & Gravel - [gfdu_b]	min									21.0	0.01	6.4			
	max									49.0	0.15	7.8			
	median									37.0	0.09	6.6			
	mean									36.0	0.08	6.8			
Buile Hill Sands [glld_s]	count									9	15	7	6.40	2.05	
	max									53.0	0.42	7.7	6.40	2.26	
	median									11.0	0.09	6.9	6.40	2.16	
	mean									12.7	0.14	7.1	6.40	2.16	
	count									67	10	3	1.00	14	
Glaciolacustrine Deposits [glld_1]	min	9.0	22.0	10.0	8.0	20				4.0	0.01	7.0		1.93	
	max	35.0	71.0	37.0	50.0	444				98.0	0.07	8.9		2.33	
	median	21.0	44.0	18.0	26.0	154		50	25	18.0	0.02	7.5		2.11	
	mean	21.3	44.3	18.7	25.6	178				22.5	0.03	7.6		2.11	
	count	605	187	187	187	60		1	1	81	12	20		72	
Till [till_1]	min	2.8	20.0	9.0	6.0	7		0	21	1.0	0.00	4.2	1.18	1.03	1.45
	max	38.0	67.0	34.0	49.0	775		57	40	152.0	0.49	9.2	7.30	2.55	2.13
	median	17.0	36.0	17.0	19.0	142		10	26	21.0	0.05	7.5	2.99	2.14	1.81
	mean	17.3	36.3	16.9	19.4	158		13	27	25.8	0.07	7.6	3.51	2.12	1.81
	count	3218	715	715	715	1114		27	27	1456	252	330	11	1903	100

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NATURAL ENVIRONMENT RESEARCH COUNCIL

GROUND CONDITIONS IN CENTRAL MANCHESTER AND SALFORD: THE USE OF THE 3D GEOSCIENTIFIC MODEL AS A BASIS FOR DECISION SUPPORT IN THE BUILT ENVIRONMENT

MAP 2: ENGINEERING GEOLOGICAL CLASSIFICATION OF SOILS

USERS RESPONSIBILITY

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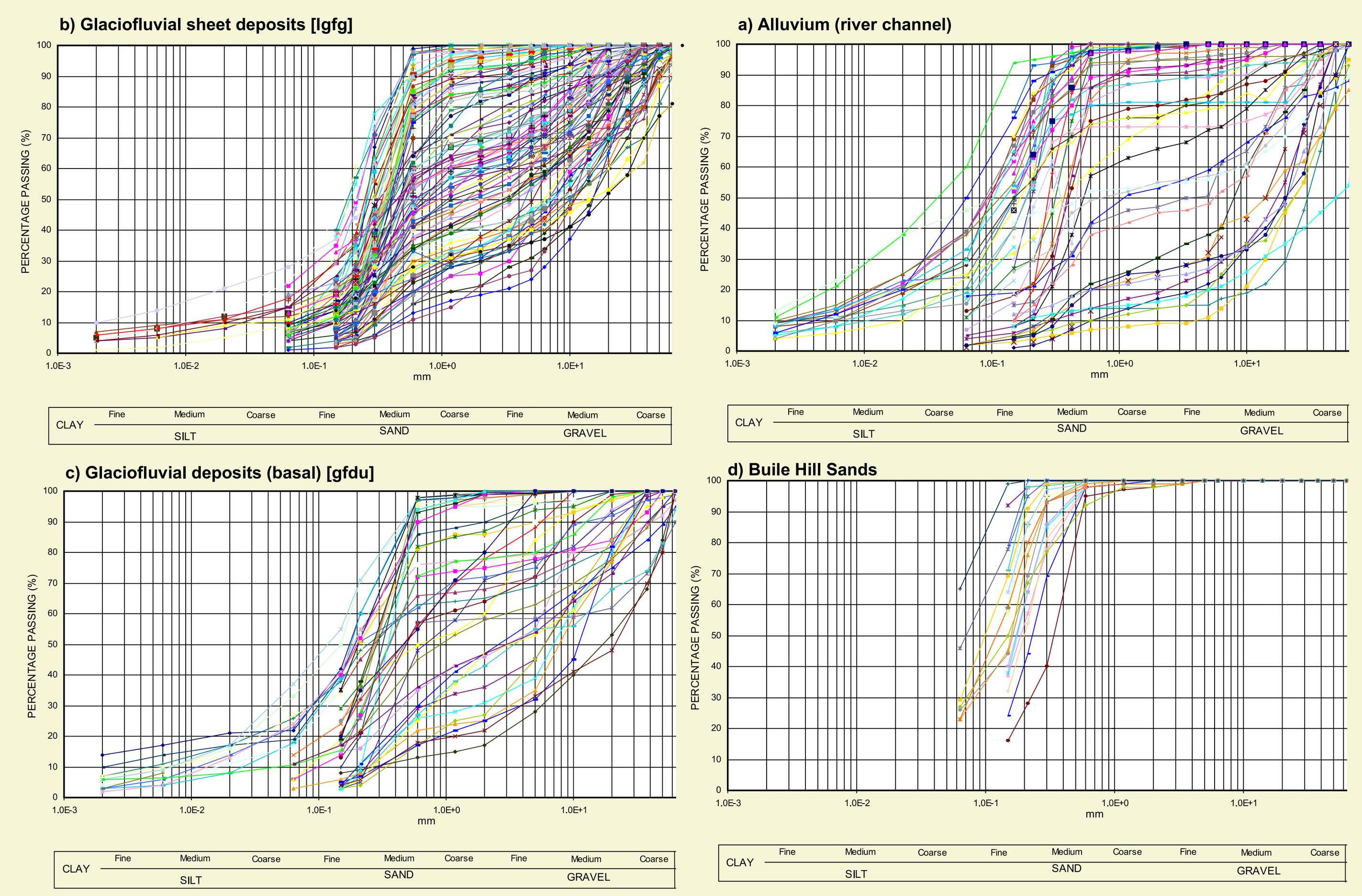
Compiled by C. Simpson, BGS, Keyworth.

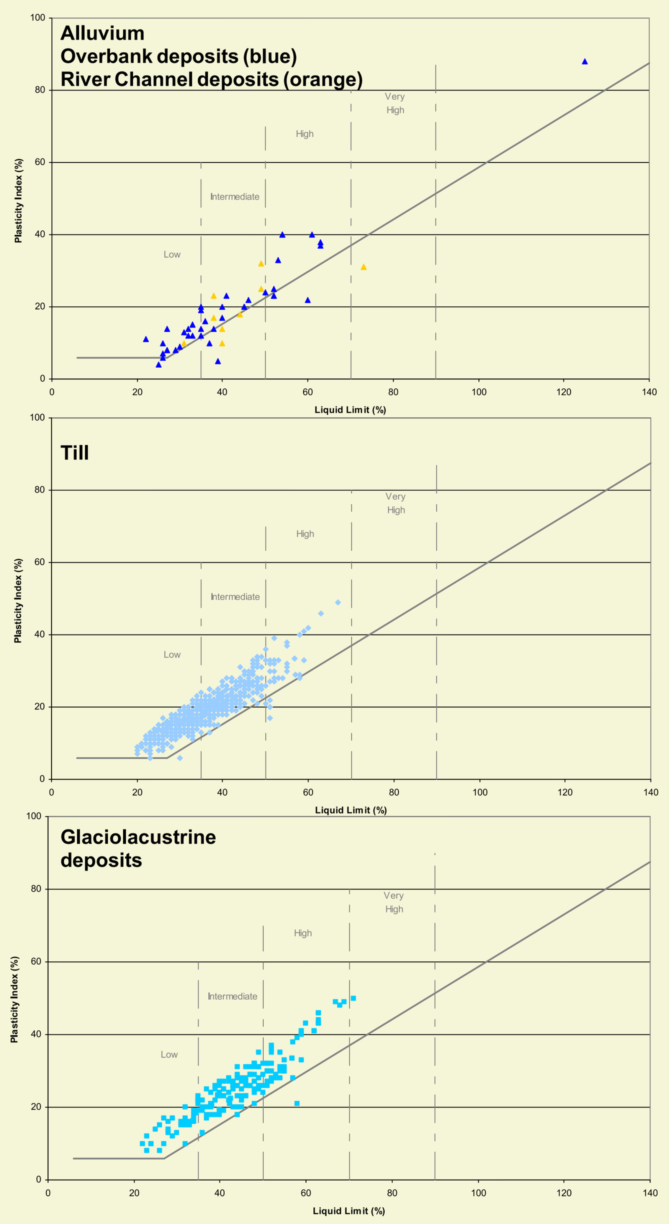
Principal "Engineering Geological Soils" of the district (Descriptions based on BS5930 and excavatability based on Pettifer and Fookes 1994)

ENGINEERING GEOLOGICAL UNITS		GEOLOGICAL UNITS	DESCRIPTION/ CHARACTERISTICS	ENGINEERING CONSIDERATIONS: FOUNDATIONS	EXCAVATION	ENGINEERING FILL	SITE INVESTIGATION
ENGINEERING SOILS							
HIGHLY VARIABLE ARTIFICAL DEPOSITS		Made Ground (mgr) Infilled Ground (wmgr)	Highly variable composition, thickness and geotechnical properties.	Highly variable. May be unevenly and highly compressible. Hazardous waste may be present causing leachate and methane production.	Usually diggable. Hazardous waste may be present at some sites.	Highly variable. Some material may be suitable.	Essential to determine depth, extent, condition and type of fill. Care needs to be taken as presence of pollution and contaminated ground likely. Essential to follow published guidelines for current best practice.
COARSE SOILS		Alluvium - River Channel deposits (Alv_2) River Terrace Deposits (rtdu) Glaciofluvial sand & gravel (lgfg, gfdu & gfdu_b)	Medium dense to dense SAND & GRAVEL with some buried channels and lenses of clay, silt & peat.	Generally good. Variable thickness of deposit. Thick deposits in buried channels may be significant in foundation design due to differential settlement.	Diggable. Support may be required. May be water bearing.	Suitable as granular fill.	Important to identify the presence and dimension of buried channels and characteristic of infilling deposits. Geophysical methods may be appliciable.
		Buile Hill Sands (glld_s)	Loose to medium dense fine to medium SAND.	Poor foundation.	Easily diggable. Generally poor stability. Running sand conditions possible below the water table and in pockets at perched water tables.	Unsuitable as granular fill .	Determine the presence, depth and extent of deposit and depth to sound strata.
FINE SOILS	FIRM	Till (Till_1)	Firm to very stiff sandy, gravelly CLAY with some channels and lenses of medium dense to dense sand and gravel	Generally good foundation, although sand lenses may cause differential settlement. Possibility of pre-existing slips can also cause a strength reduction.	Diggable. Support may be required if sand lenses or pre-existing slips encountered. Ponding of water may cause problems when working.	Generally suitable if care taken in selection and extraction. Moisture content must be suitable.	Determine the depth and extent of deposit, especially the frequency and extent of lenses and channels. Investigate whether any pre-existing slips and shear planes are present.
	SOFT	Alluvium (Alv_1)	Soft to firm CLAY occasional sand, gravel and peat lenses.	Poor foundation. Soft highly compressible zones may be present; risk of differential settlement.	Easily diggable. Moderate stability, decreasing with increasing moisture content. Running sand conditions possible below the water table and in pockets with perched water tables. Risk of flooding.	Generally unsuitable.	Determine the presence, depth and extent of soft compressible zones and depth to sound strata.
		Glaciolacustrine Deposits (glld_1, glld_lenses & glld_ic)	Soft to stiff laminated CLAY with occasional lenses of sand.	Generally poor foundation as long term consolidation and differential settlement possible.	Easily diggable. Support may be required if sand lenses encountered in deep excavations. Ponding of water or exposure to rain may cause softening of formation.	Generally suitable if care taken in selection and extraction. Moisture content must be suitable.	Determine the depth and extent of deposit, especially the frequency and extent of lenses.
ORGANIC SOILS		Peat	Very Soft to soft brown fiberous or amorphous PEAT.	Very poor; very weak; highly compressible foundation. Acidic groundwater.	Diggable. Poor stability. Generally wet ground conditions.	Generally unsuitable.	Determine the depth and extent of deposit and groundwater's acidity.

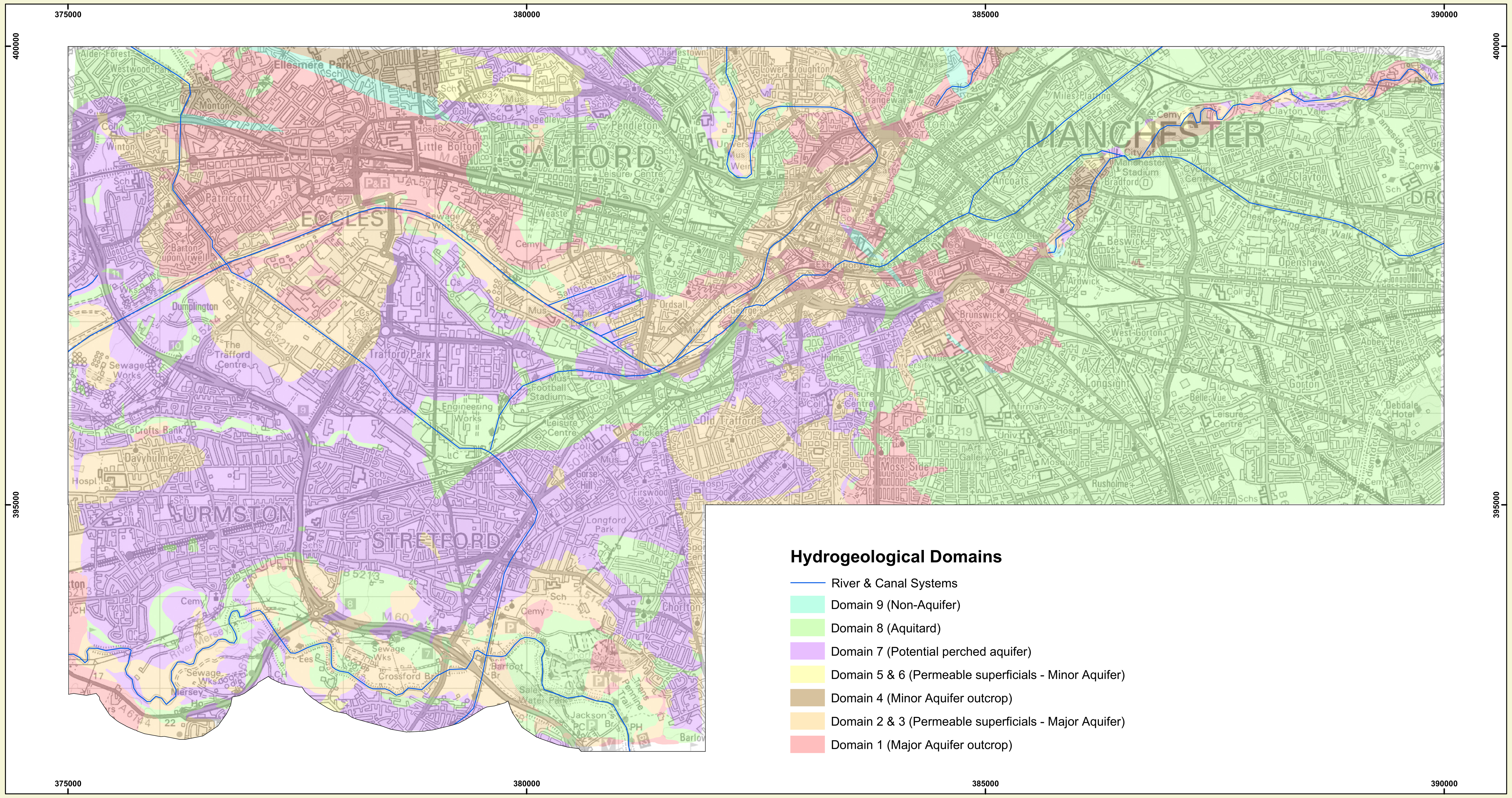
A selection of particle (gradings) data from the coarse "Engineering Geological Soils" of the district



A selection of plasticity charts from the fine"Engineering Geological Soils" of the district



Scale 1:30 000



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NATURAL ENVIRONMENT RESEARCH COUNCIL

GROUND CONDITIONS IN CENTRAL MANCHESTER AND SALFORD: THE USE OF THE 3D GEOSCIENTIFIC MODEL AS A BASIS FOR DECISION SUPPORT IN THE BUILT ENVIRONMENT

MAP 3: HYDROGEOLOGICAL PATHWAYS

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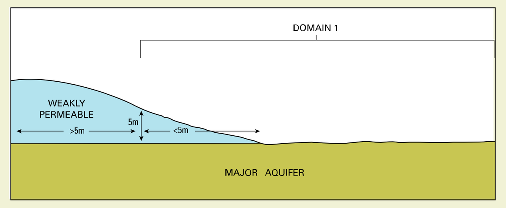
Compiled by C. Simpson, BGS, Keyworth.

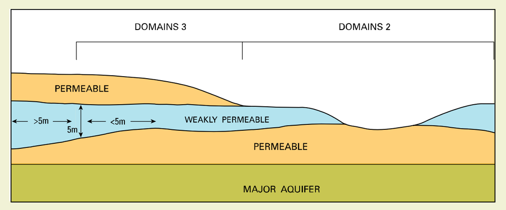
Manchester Aquifer vulnerability and recharge

- Manchester is underlain by a major Permo-Triassic aquifer, from which groundwater is abstracted primarily for industrial usage. Coal Measures and Upper Carboniferous strata in the northern part of the district constitute a minor aquifer, and the Permian Manchester Marls, a non-aquifer.
- Intensive industrial practice during the early 1900s dramatically reduced groundwater levels in the major aquifer, however, these have now recovered to a quasi-equilibrium status, with a significant cone of depression centred on Trafford Park (cross section 2). In the coalfield, mine abandonment has led to groundwater recovery and outflow of mine water.
- Key groundwater management issues are the vulnerability of the aquifer to pollution and the impact of the superficial deposits on groundwater recharge. These issues have been addressed through development of an attributed 3D model of the superficial deposits.
- Hydrogeological pathways have been assessed based on the inferred permeability of the superficial deposits in vertical profile. Permeability has been estimated from published literature (Todd, 1980, Brassington, 1999), and validated using an empirical formula (Hazen method) based on grain size analysis. The deposits are accordingly classified as permeable or weakly permeable.
- Cross sections, derived from the model, show the changing character of the superficial deposits along key features (i.e. rivers) and in areas of concern (i.e. Trafford Park). The sections are annotated to show where potential pathways from ground surface to the aquifer are likely to occur. Pathways are either direct (i.e. aquifer at outcrop), or via permeable deposits. Where weakly permeable deposits (>5m thick) intervene, they are considered to impede or restrict the vertical movement of water.
- Seven schematic sections depict the criteria used to define vulnerability and recharge potential. The scenarios take account of the thickness of the modelled units (greater or less than 5 m), their inferred permeability, and the nature of the underlying aquifer system (major, minor or non aquifer). By extrapolating theses scenarios into 3D and mapping out their occurrence as domains, the hydrogeological performance of the superficial deposits across the district can be estimated.
- The domain map shows the distribution of domains ranked 1 to 9. Domain 1 has the greatest recharge potential but is also the most vulnerable to pollution. Domains lower down the order include weakly permeable units above less sensitive aquifers and are accordingly less vulnerable.
- Limitations on the use of this map are discussed in the accompanying report.

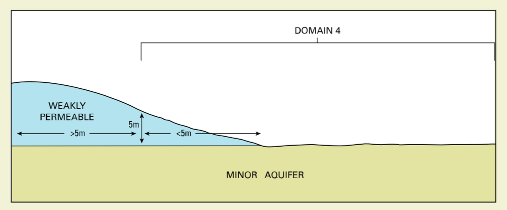
Schematic Domain Classification



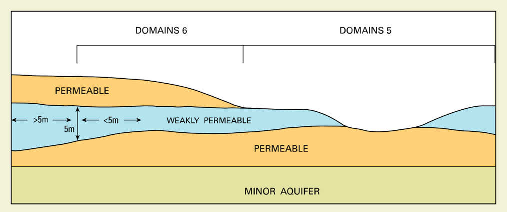
Domain 1: Major aquifer at or < 5m below, ground surface



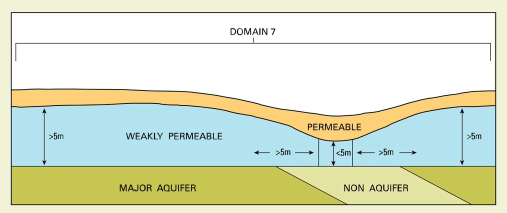
Domain 2 & 3: Single and multiple permeable superficial deposit(s) overlying Major aquifer



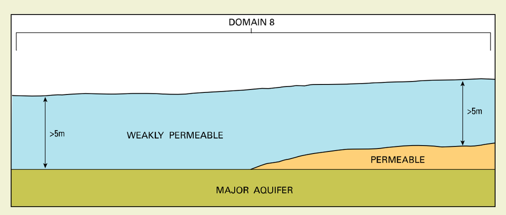
Domain 4: Minor aquifer at or < 5m below, ground surface



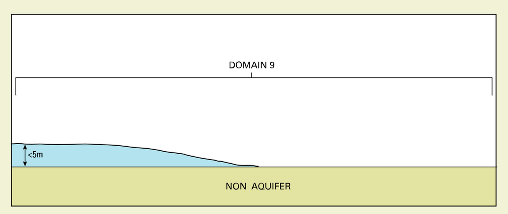
Domain 5 & 6: Single and multiple permeable superficial deposit(s) overlying Minor aquifer



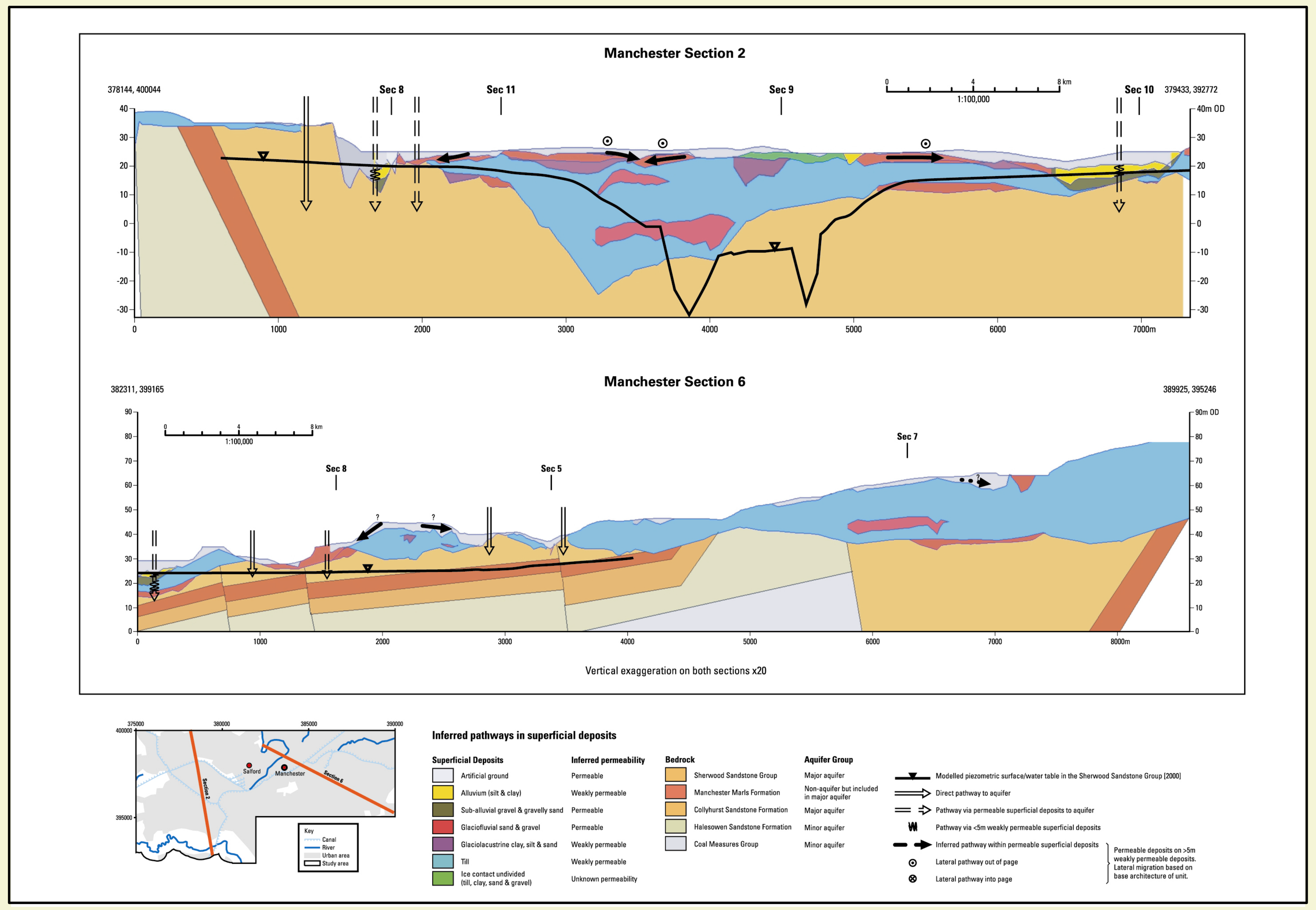
Domain 7: Permeable superficial deposit(s) overlying > 5m weakly permeable deposits



Domain 8: > 5m weakly permeable deposits at ground surface



Domain 9: Non aquifer bedrock at, or < 5m below ground surface



Hydrogeological domains and sub-domains

Decreasing aquifer vulnerability

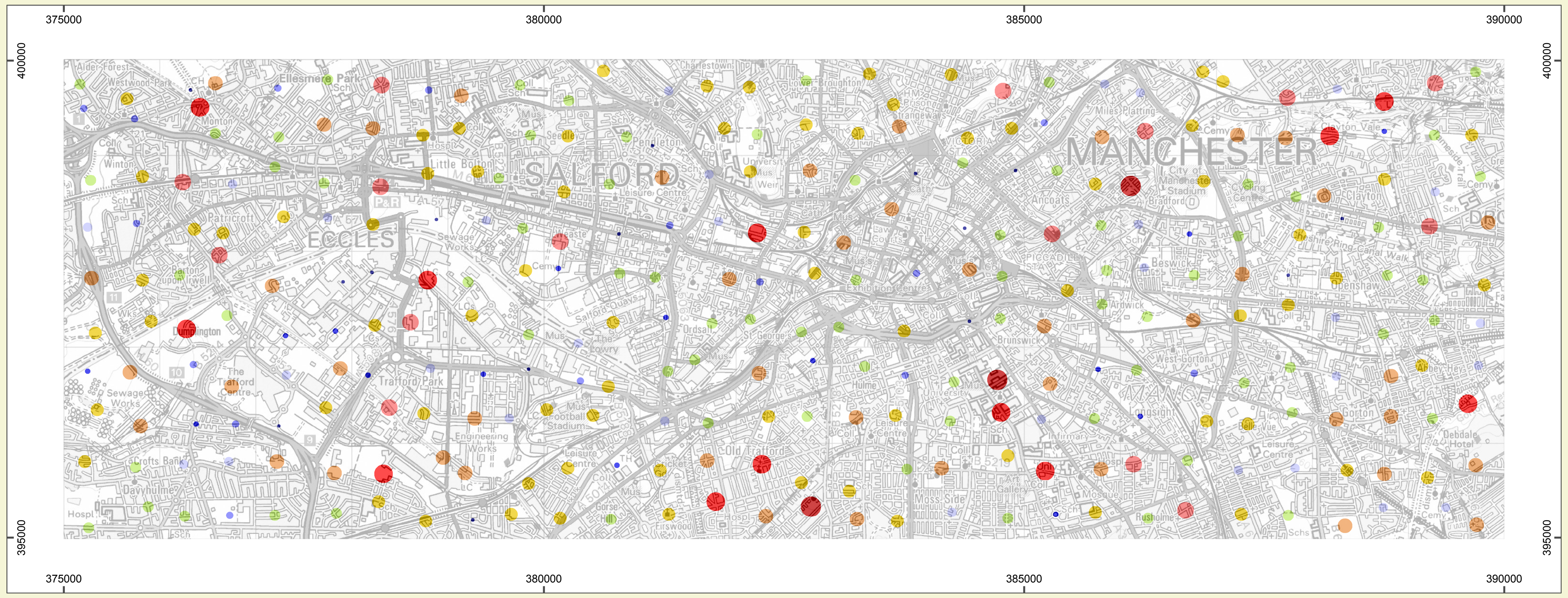
Group	Domain		Sub-Domain	
Major Aquifer	1	Outcrop	1a	Bedrock at outcrop
			1b	Bedrock overlain by <5m weakly permeable strata
	2	Permeable superficial deposit	2a	River Channel deposits
			2b	River Terrace deposits
			2c	Outwash Sheet deposits
			2d	Basal Gravel deposits
			2e	Glaciolacustrine Sand deposits
	3	Multiple permeable superficial deposits	3a	River Channel deposits & Basal Gravel deposits
			3b	River Terrace deposits & Basal Gravel deposits
			3c	Outwash Sheet deposits & Basal Gravel deposits
			3d	Glaciolacustrine Sand deposits & Basal Gravel deposits
Minor Aquifer	4	Outcrop	4a	Bedrock at outcrop
			4b	Bedrock overlain by <5m weakly permeable strata
	5	Permeable superficial deposit	5a	River Terrace deposits
			5b	Outwash Sheet deposits
			5c	Basal Gravel deposits
			5d	Glaciolacustrine Sand deposits
	6	Multiple permeable superficial deposits	6a	Glaciolacustrine Sand deposits & Basal Gravel deposits
Perched aquifer	7	Perched permeable superficial strata	7a	River Channel deposits
			7b	River Terrace deposits
			7c	Outwash Sheet deposits
			7d	Glaciolacustrine Sand deposits
Aquitard	8	Low permeability superficial strata	8a	Overbank deposits
			8b	Till
			8c	Glaciolacustrine lake clay deposits
Non Aquifer	9	Non-aquifer bedrock strata	9a	Manchester Marls Formation

Inferred permeability of Superficial deposits

Model unit/notation	Lithology	Inferred permeability	Estimated hydraulic conductivity range md^{-1})
Alluvium overbank floodplain deposits) (alv_1)	Silt, clay, peat	Weakly permeable	$10^{-5} – 10^{-2}$
Alluvium (river channel) (alv_2)	Sand, gravel, peat	Permeable	$10^{-3} – 10^{4}$
River terraces (rtdu)	Sand, gravel, possibly with a clay rich upper surface	Permeable	$10^{-3} – 10^{4}$
Outwash sheet deposits (lgfg)	Silty sand, on clayey sand & gravel	Permeable	$10^{-4} – 10^{3}$
Glaciolacustrine deposits (glld_1)	Laminated silts and clay	Weakly permeable	$10^{-6} – 10^{-4}$
Glaciolacustrine sands (ice-contact) (glld_s)	Loose, fine sands overlying laminated silts	Permeable	$10^{-2} – 10^{1}$
Till (till_1)	Till, interbedded sands, impersistent laminated clays	Generally weakly permeable but some permeable lenses	$10^{-4} – 10^{1}$
Basal sand & gravel (gfdu_b)	Clayey sand & gravel	Permeable	$10^{-5} – 10^{3}$

Lead in surface soils

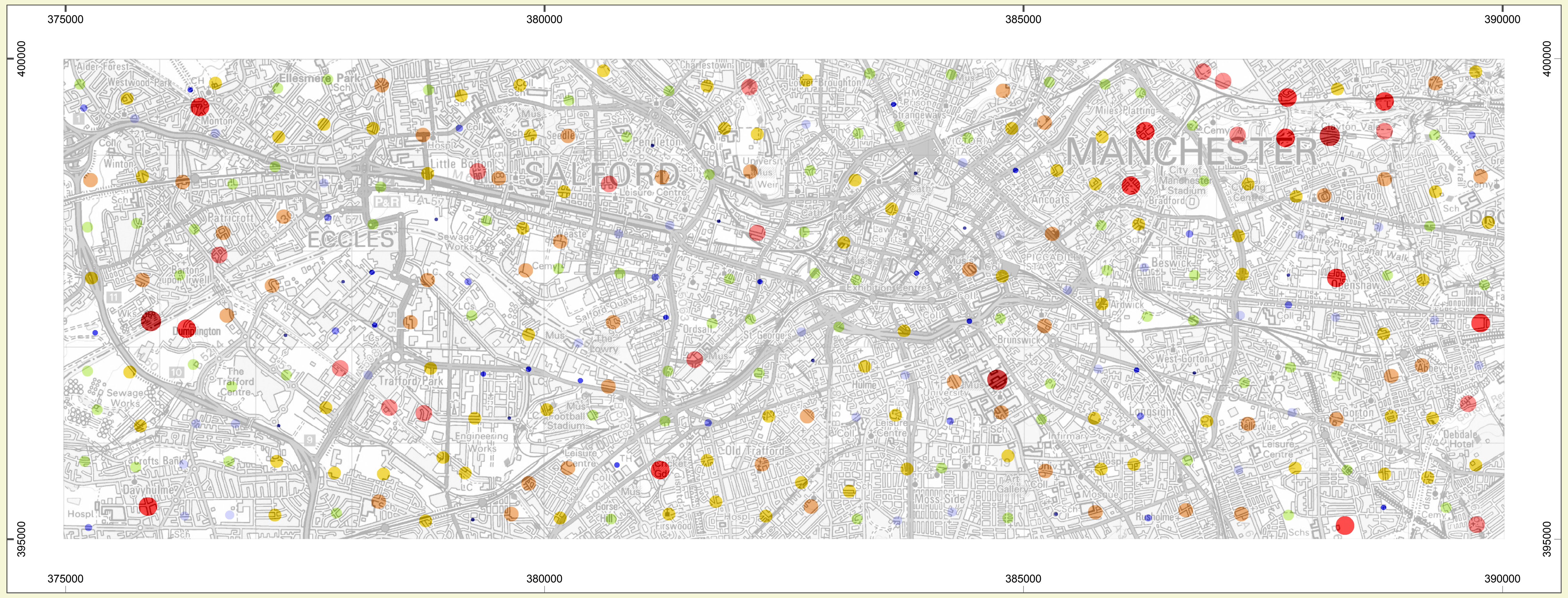
Scale 1:40 000



100	99	95	90	75	50	25	15	5	0	Percentage
1553 - 2758	594 - 1462	449 - 580	322 - 448	219 - 318	148 - 218	119 - 148	100 - 119	71 - 100	20 - 71	Concentration (ppm) mg / kg

Arsenic in surface soils

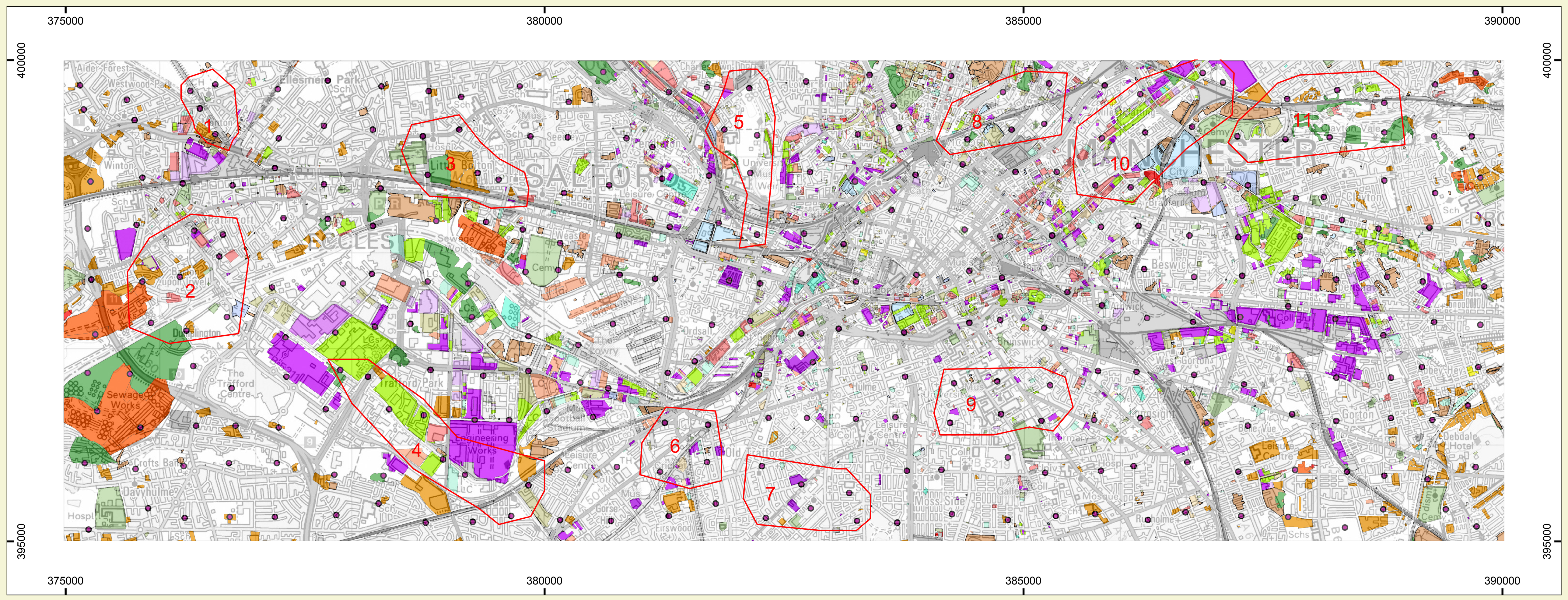
Scale 1:40 000



100	99	95	90	75	50	25	15	5	0	Percentage
111-1001	50-110	40-49	29-39	21-38	17-20	15-16	14	13	3 -12	Concentration (ppm) mg / kg

Land use 1890 and 1950

Scale 1:40 000



Sample clusters with elevated metal concentrations (see accompanying report for details)

Surface soil sample point

Percentile at which DEFRA Soil Guideline Values are exceeded for Manchester surface soils

Metal	Standard Land Use		
	Residential with plant uptake	Residential without plant uptake	Commercial / industrial
Arsenic	48	48	No soils exceed SGV
Cadmium	pH6=58 pH7=91 pH8=No soils exceed SGV	No soils exceed SGV	No soils exceed SGV
Chromium	97.2	No soils exceed SGV	No soils exceed SGV
Lead	86.4	86.4	No soils exceed SGV
Nickel	90.5	97.2	No soils exceed SGV
Selenium	No soils exceed SGV	No soils exceed SGV	No soils exceed SGV

Comparison between Rural and Urban Surface Soils

Element	Manchester		NW England & N Wales	
	Mean (mg/kg $^{-1}$)	Median (mg/kg $^{-1}$)	Mean (mg/kg $^{-1}$)	Median (mg/kg $^{-1}$)
Cadmium	1.4	0.9	0.7	<0.6
Copper	120	86	43	21
Lead	276	218	117	43
Nickel	34	29	35	32
Tin	30	18	8.4	2
Zinc	222	168	147	105

Land Use

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

British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

GROUND CONDITIONS IN CENTRAL MANCHESTER AND SALFORD: THE USE OF THE 3D GEOSCIENTIFIC MODEL AS A BASIS FOR DECISION SUPPORT IN THE BUILT ENVIRONMENT

MAP 4: GEOCHEMISTRY OF URBAN SOILS AND LAND USE

USERS RESPONSIBILITY

This map provides only a general indication of ground conditions and must not be used as a source of detailed information about specific areas, or as a substitute for site investigations or ground surveys. Users must satisfy themselves that ground conditions are suitable for any particular land use or development, by seeking appropriate professional advice and carrying out ground surveys and site investigations if necessary.

This map should be used in conjunction with the report:

Bridge, D McC et al. 2010. Ground conditions in central Manchester and Salford: the use of the 3D model as a basis for decision support in the built environment. British Geological Survey Research Report RR/10/06.

Any enquiries concerning this map should be directed to:
British Geological Survey, Keyworth, Nottingham NG12 5GG. Tel. 0115 9363100

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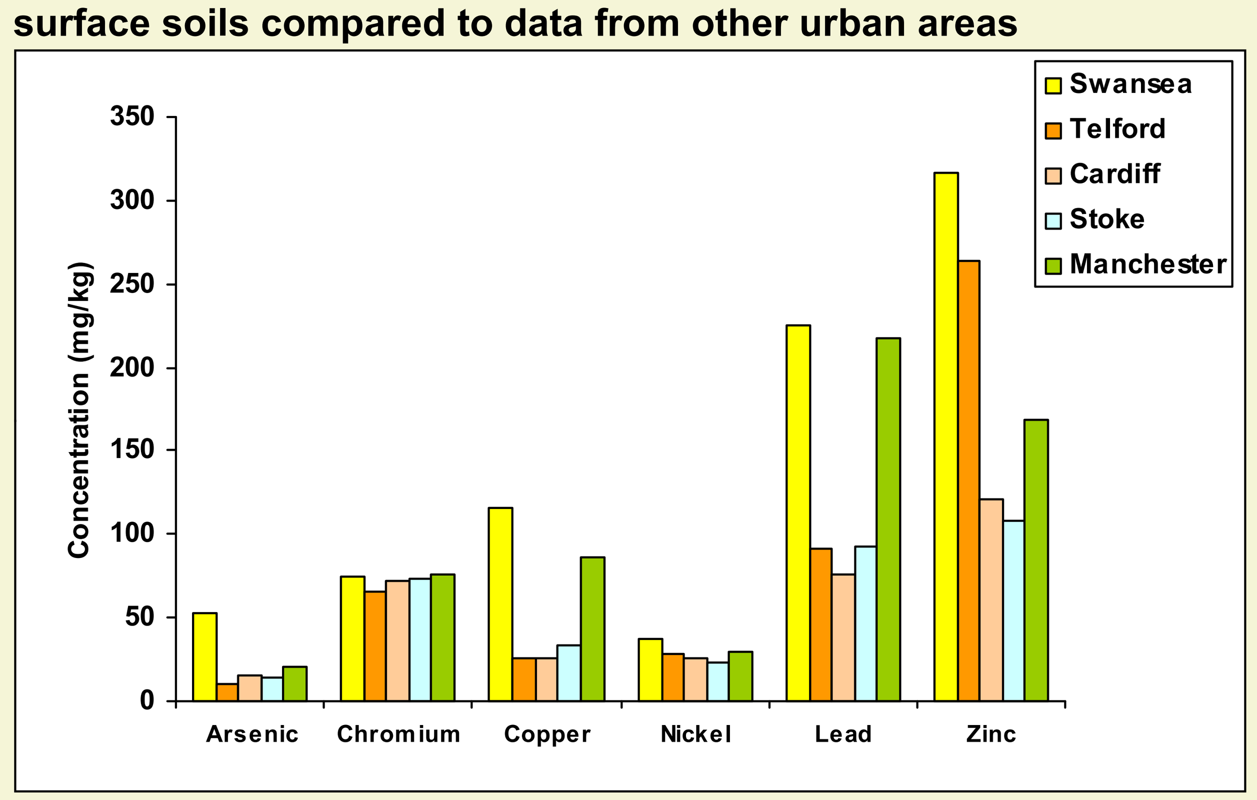
Compiled by C. Simpson, BGS, Keyworth.

Median concentrations of selected elements in Manchester surface soils compared to data from other urban areas



Summary

Topsoils in Manchester and Salford contain elevated concentrations of metals compared to baseline levels found in rural NW England and N Wales

Elevated metal concentrations are very localised and generally Confined to specific areas. Many of the elements show little variance in median values across the different made ground types.

Potentially a large number of residential soils could exceed the Soil Guideline Values in the 'residential with plant uptake' category for both As and Cd (pH=6)

Median values of metals in topsoil are comparable to other urban Areas investigated under the BGS G-SUE program