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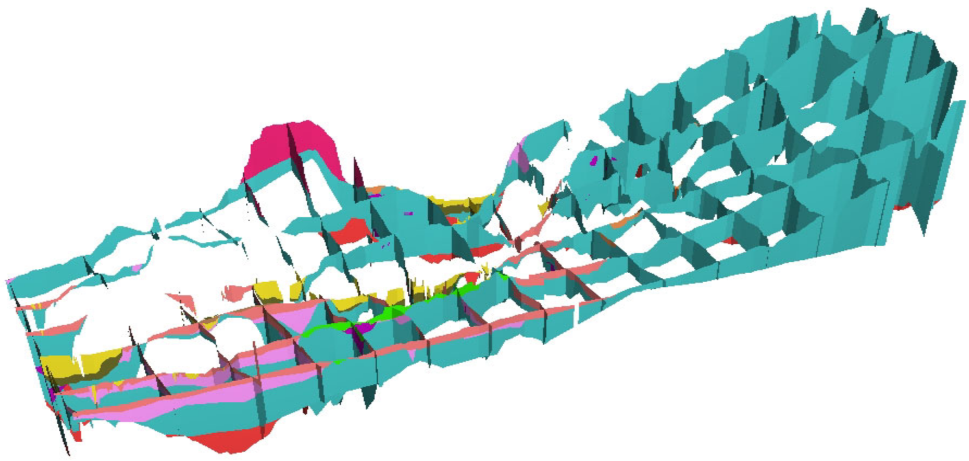
Urban Manchester – Hydrogeological Pathway Project

Urban Geosciences and Geological Hazards Programme

Commercial Report CR/04/044N



BRITISH GEOLOGICAL SURVEY

COMMERCIAL REPORT CR/04/044N

Urban Manchester - Hydrogeological Pathway Project

H. Kessler, D. Bridge, H.F. Burke, A. Butcher, S.K. Doran, E. Hough, M. Lelliott, R.T. Mogdrige, S.J. Price, A.E. Richardson, N. Robins and Keith Seymour.

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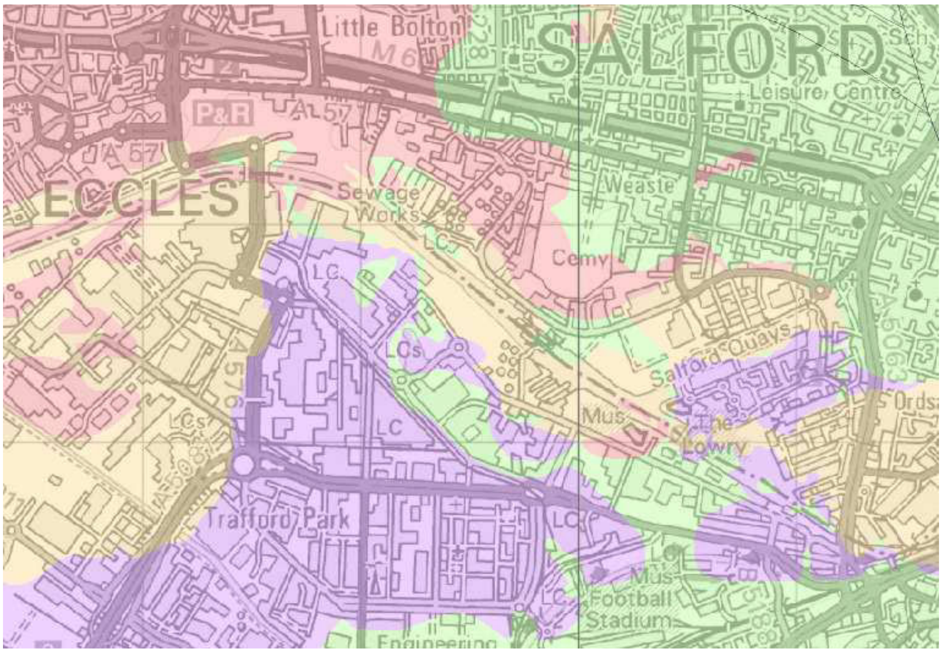

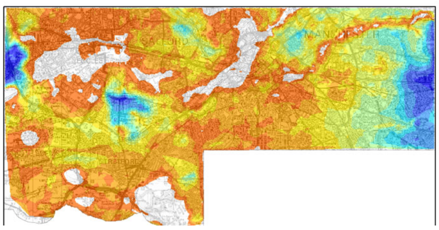

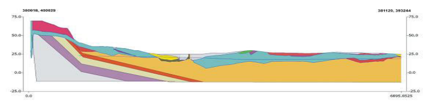

Keyworth, Nottingham British Geological Survey 2004

Key words

Manchester; Cheshire; Quaternary geology; 3D modelling; Rockhead GSi3D; Hydrogeology; superficial aquifers; pathways, watertable; shipcanal, faults; boreholes.

Front cover

Automatically generated cross-sections in Manchester using GSI3D

Bibliographical reference

KESSLER, H.. ET AL 2004 Urban Manchester - Hydrogeological Pathway Project. *British Geological Survey Internal Report*, CR/04/044N; 65 pp.

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) for the North West Region of the Environment Agency (the Agency).

Staff Involved in Study

Many BGS staff were involved in the coding of boreholes, construction and correlation of cross-sections, GIS compilation and derivation of thematic maps in this commissioned project. Their work is gratefully acknowledged and individual members of staff and their contributions are outlined below.

Dave Bridge	Modelling, geological interpretation, report compilation
Helen Burke	Borehole coding cross-section construction and correlation
Andy Butcher	Hydrogeological interpretation and reporting
Sarah Doran	Borehole coding, cross-section construction and correlation
Holger Kessler	Project management
Mike Lelliot	Hydrogeological interpretation and method development
Roy Mogdridge	Land use data gathering
Amina Morton	Administrative support and databasing
Simon Price	Supervision of modelling; Artificial Ground research
Amanda Richardson	Borehole coding, cross-section construction and correlation
Nick Robins	Hydrogeological interpretation and reporting

The study also draws on work and results of the 4-year strategic Urban Geoscience programme, in particular the Manchester Urban study. Apart from most staff above it is these people

Marieta Garcia-Bajo	GIS development, modelling
Richard Ellison	Geological mapping and reporting, borehole coding
Dave Entwisle	Geotechnical interpretation
Emilia Fiorini	GIS and remote sensing support
Vincent Hulland	GIS development
Ed Hough	Geological mapping and reporting, borehole coding
Paul Lappage	Cartographic design
Tony Myers	GIS and database development
Bruce Napier	GIS development
Levinia Nelder	Hydrogeological databasing
Katie Rowlands	Land use data gathering
Margaret Slater	Database entry
Geraldine Wildman	GIS development and troubleshooting

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1 Executive Summary

This report summarises the results of a collaborative study jointly funded by the North-west Region of the Environment Agency (the Agency) and the British Geological Survey (BGS).

BGS was commissioned to carry out a geological and hydrogeological characterisation of the superficial deposits of the Central Manchester and Salford district as a contribution to a regional groundwater study of the Manchester and Cheshire aquifer being undertaken by the Agency.

The overall objective of the study was to use a three-dimensional (3D) model of the superficial deposits to examine potential groundwater-surface water interactions. By integrating the modern 1:10,000 geological map with sub-surface (site investigation) information, the relationships within the quaternary deposits have been characterised and potential hydrogeological pathways between the surface water bodies and the deeper sandstone aquifer were identified.

The work has shown that the Permo-Triassic aquifer is largely protected by glacial clay and silt deposits. However, the distribution and thickness of these deposits varies greatly across the area and hydraulic windows have been identified in the lowland areas where recharge may occur. Extensive sandy outwash sheet deposits, which are locally in contact with the underlying Permo-Triassic aquifer, offer the potential for lateral migration of groundwater in perched aquifers. Large areas and thicknesses of man-made material have been described and modelled and these could form potential sources of pollution, especially where they are in direct contact with the major aquifer or perched aquifers.

The work involved four main tasks:

- Determining the geometry, composition and spatial distribution of the principal superficial (drift) deposits;
- Identifying potential pathways for groundwater movement through the drift;
- Constructing a suite of land-use maps to help assess the locations of potentially contaminative activities;
- Constructing a domain-based aquifer vulnerability model.

Outputs of the study include:

An **attributed model** of the superficial geology that can be interrogated at any x,y,z location

An indication of **potential flowpaths** along bespoke sections through the 3D model and in plan view along the major superficial aquifers

A novel **hydrogeological domains map**, based on established domain principals, but derived by computation from the 3D model

A detailed dataset on **past contaminative land use** and the distribution, thickness and variation of the main areas of **artificial ground**

All **data** delivered digitally (CD-ROM) and as a printed report with maps.

2 Introduction and Scope of Study

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. Historic over-abstraction in some parts of the aquifer has resulted in falling groundwater levels and the localised upflow of saline water. However, recent changes in patterns of abstraction in response to industrial policy, and the local policies of the Environment Agency (the 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 that 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 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 work is being undertaken principally by Environmental Simulations International (ESI). The third phase of this 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.

It was against this background that the Agency (North West Region) requested BGS to provide a 3-dimensional visualisation model of the superficial deposits of central Manchester, to investigate the potential hydrogeological impact of the highly variable superficial deposits on groundwater recharge to the Triassic sandstone aquifer.

The project described in this report follows on from a previous pilot study for the Agency, coding ca.100,000 boreholes over the footprint of the Manchester and East Cheshire sandstone aquifer (McKenzie and Hough, 2002), and a variety of hydrogeological domain mapping projects such as the Sellafield study (McMillan et al, 2000) and the Shrewsbury project (Bridge et al, 2001). The project has also been underpinned by a 3 year BGS core project in Manchester, and the report (Bridge and Kessler et al, 2004 in prep) will provide further detail on the 3D Geology, land use and in particular the geochemical and geotechnical properties of the model.

The key difference in this study is that the available 2-dimensional geological map was inadequate to represent the complex shallow geological relationships, and hence the potential hydrogeological pathways between the surface, water bodies and the deeper sandstone aquifer. Therefore, the most recent BGS methods and technology for 3D modelling and visualisation (Kessler et al, 2004) were employed to derive the final map and section outputs. The construction of the cross-sections was enabled by the interpretation, lithological coding and databasing of borehole data held within the National Geoscience Data Centre at BGS. It was agreed that the cross-section construction and geological correlation and 3D modelling would be performed digitally within GSI3D, a proprietary 3D modelling package developed by Dr Hans-Georg Sobisch (INSIGHT Ltd.) at the University of Cologne.

The results are presented as a printed report and as digital files for analysis in Geographic Information Systems (GIS). However it is anticipated that the entire 3D model will be delivered allowing flexible interrogation using the GSI3D analyst, which is to be released during 2004.

3 Geology

The following section provides an introduction to the geology of the area. A more detailed description and analysis of the superficial deposits is given in Section 4.

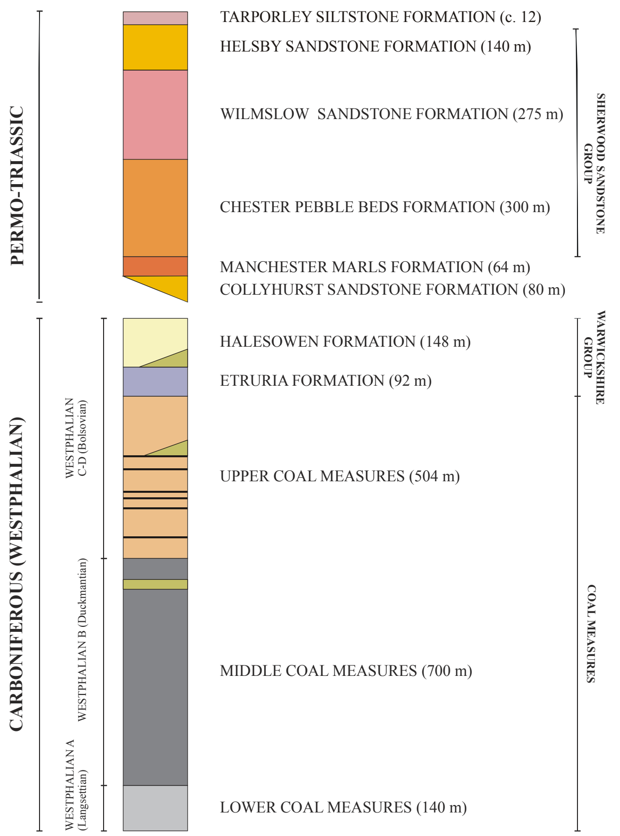
3.1 BEDROCK GEOLOGY

3.1.1 Stratigraphy

The Manchester and Salford district straddles 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 1 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 natural and man-made superficial deposits. However, mine plans and records, dating from the 19th and 20th centuries when the area supported a thriving coal-mining industry, provide information on 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 [376290; 399140], and from Agecroft [379990; 401550] until the late 1970s. An inlier of *Coal Measures* forms the small Bradford Coalfield. The Coal Measures pass up into redbeds of the Etruria Formation, which in turn are overlain by grey measures of the Halesowen Formation.

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 a major groundwater resource that is used for both water supply, and in the urban Manchester conurbation, for industrial purposes.



Key to Figure 1

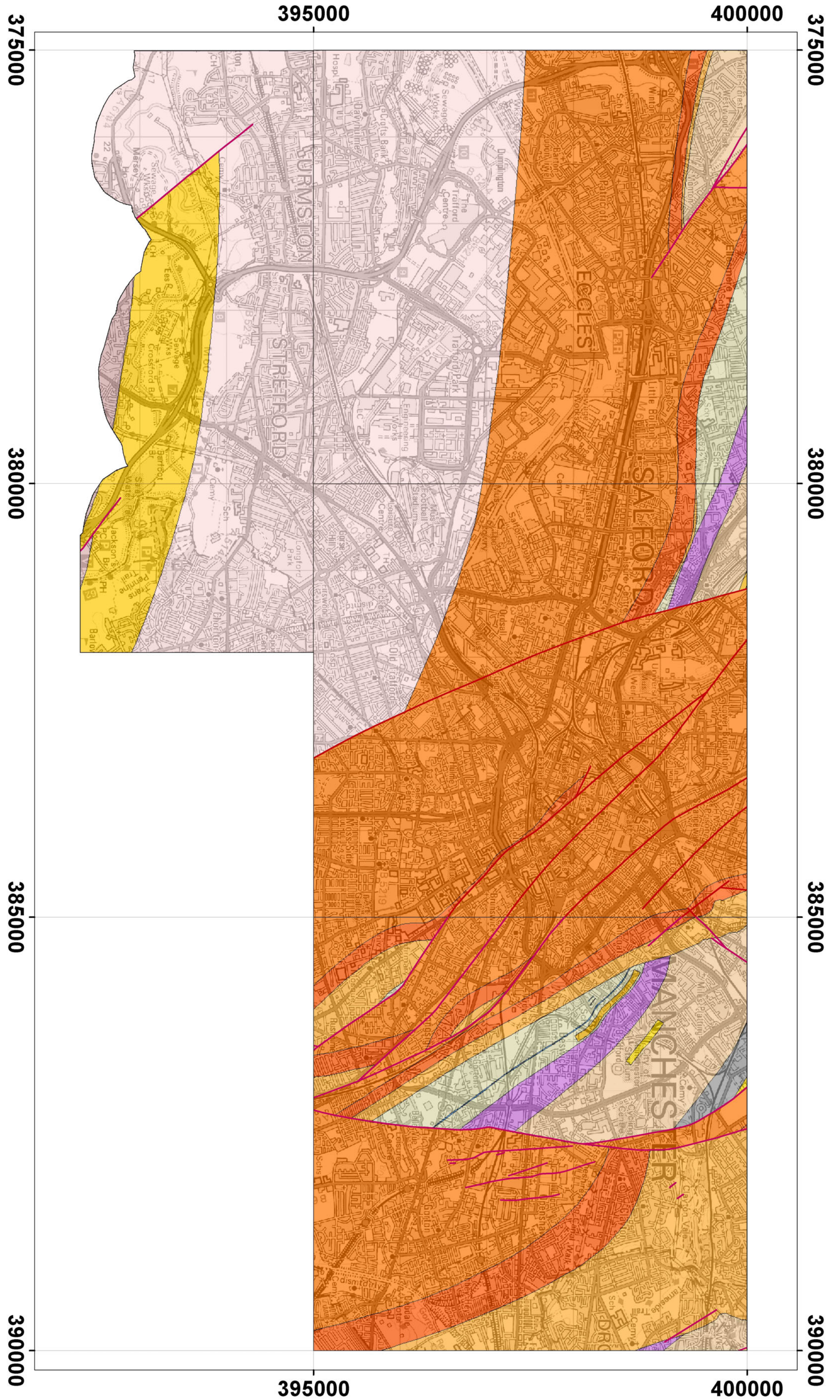


Figure 1 Bedrock geology (from DiGMapGB10)

The *Permo-Triassic* rocks are subdivided in upward sequence into the following divisions:

Collyhurst Sandstone Formation

The Collyhurst Sandstone rests unconformable 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 [389500; 398500], and in a series of faulted blocks to the west of the Bradford Coalfield. The sandstone is red and orange and fine- to medium-grained, and has been interpreted as being dominantly aeolian (Plant et al, 1999) or having a mixed aeolian and fluvial origin (Aitkenhead et al, 2002).

Manchester Marls Formation

The Manchester Marls are preserved as faulted slivers in the eastern, central and north-western parts of the district. The formation reaches a maximum thickness of 60 m in the eastern part of the area. It is conformable on the Collyhurst Sandstone, or locally oversteps the Collyhurst Sandstone to rest unconformably on the Halesowen Formation (e.g. in the Pendleton [381600; 398600] to Ellesmere Park [377000; 400000] areas). The base is lithologically well-defined, being taken at the incoming of 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.

Sherwood Sandstone Group

Plate 1 Chester Pebble Beds, Little Bolton Quarry

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: the *Chester Pebble Beds, the Wilmslow Sandstone and the Helsby Sandstone*. Sediment was supplied by broad fluvial systems that were sourced from the Varsican foldbelt to the south. The distal location of the north Cheshire region resulted in largely pebble-free sequences accumulating, and consequentially the junction between the Chester Pebble Beds and the overlying Wilmslow Sandstone is conjectural in this area. The Chester Pebble Beds attain an estimated maximum thickness of 300 m. There are numerous exposures in Manchester city centre, with particularly good sections preserved along the Irwell [383350; 398370] and at Castlefield [383210; 397550]. Exposure outside the city centre is restricted to Little Bolton Quarry [378800; 398500], east of Eccles. The western part of the quarry [378700; 398510] (Plate 2) exposes a thinly-laminated aeolian sandstone, overlain by a trough cross-bedded fluvial sandstone. Faces in the eastern part of the quarry [378870; 398420] show a lower sandstone unit overlain by a thin, weathered red-brown mudstone. Strata in the quarry dip 5–10 ºdegrees to the south-southeast.

The Wilmslow Sandstone Formation subcrops beneath drift in the southern part of the district but is not exposed. It is estimated to reach a maximum thickness of 275 m in Davyhulme [37500; 395000]. Elsewhere in the Cheshire Basin, the formation 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. The Helsby Sandstone Formation is present beneath drift in the Mersey Valley, between Barlow Moor [383000; 391000] and Ashton Upon Mersey [376500; 393500]. It is estimated to be approximately 120 m thick, and is typically comprised of red-brown pebbly sandstone and subordinate brown mudstone. The sandstone units are well-cemented in comparison to the underlying Wilmslow Sandstone Formation. The deposition of the Helsby Sandstone represents a return to fluvial sedimentation similar to that of the Chester Pebble Beds.

Mercia Mudstone Group

The Tarporley Siltstone Formation, which is the basal part of the Mercia Mudstone Group, subcrops beneath drift in the extreme southern part of the area, in the Barlow Moor area [381700; 392000]. The Tarporley Siltstones are estimated to be up to 10 m thick, and comprise a highly micaceous siltstone that may be interbedded with thin beds of sandstone, and is commonly ripple-laminated.

3.1.2 Structure

The Cheshire Basin is one of the largest British onshore post-Varsican rift basins. The Permo-Triassic rocks lie unconformably on Carboniferous strata, and in the north-eastern part of the basin, strata generally dip towards the south-west (Figure 2). Much of the eastern and north-eastern margin of the basin is defined by syn-depositional normal faults, on which the present day cumulative throw varies up to approximately one thousand metres.

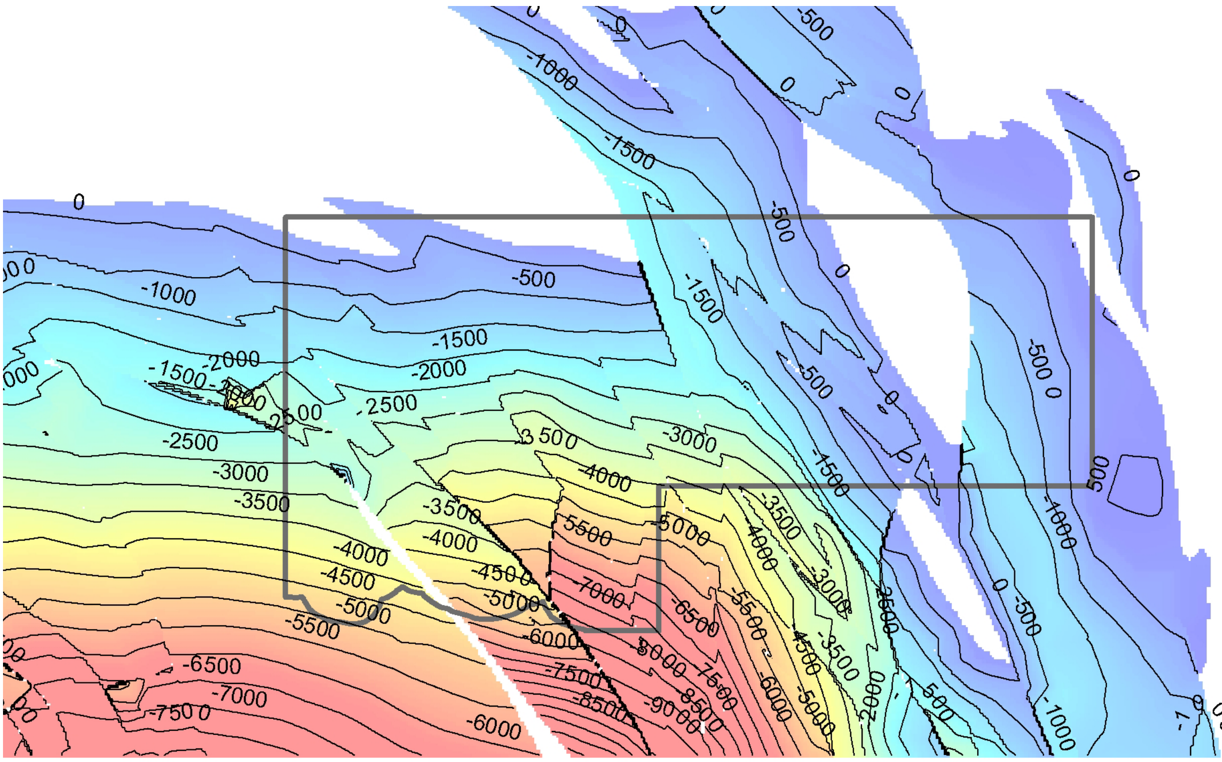


Figure 2 Structure contours on the base of the Permo-Trias

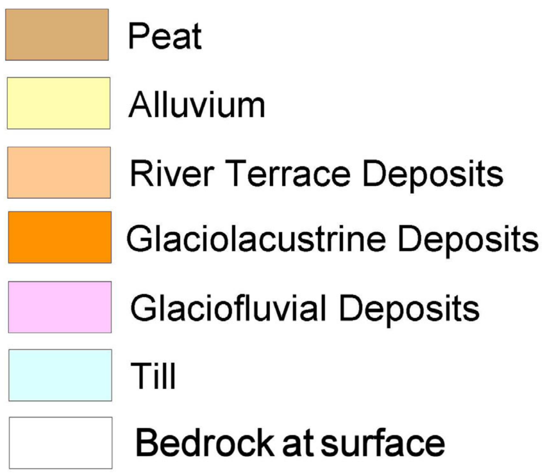
3.2 NATURAL SUPERFICIAL DEPOSITS

Much of the district is covered by extensive spreads of superficial deposits (Figure 3). These can be divided into three major categories: *glacial deposits*, presumed to be mainly of late-Devensian age, *post-glacial 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 adjoining Irish Sea Basin advanced across the district. The general pattern of movement, based on glacial striae and till fabrics (Worsley, 1968) supports movement into the area from a north-westerly direction, with subsidiary streams from a northerly direction 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 sediment 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 Pendleton Hill [381000; 399000] 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 were released sub-and supra-glacially, depositing 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 only recorded at one or two localities at outcrop. Towards the end of the glacial period, meltwaters carrying sand and gravel sourced in the upland areas deposited a spread of 'flood gravels' across much of the Manchester embayment.

Post-glacial (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.



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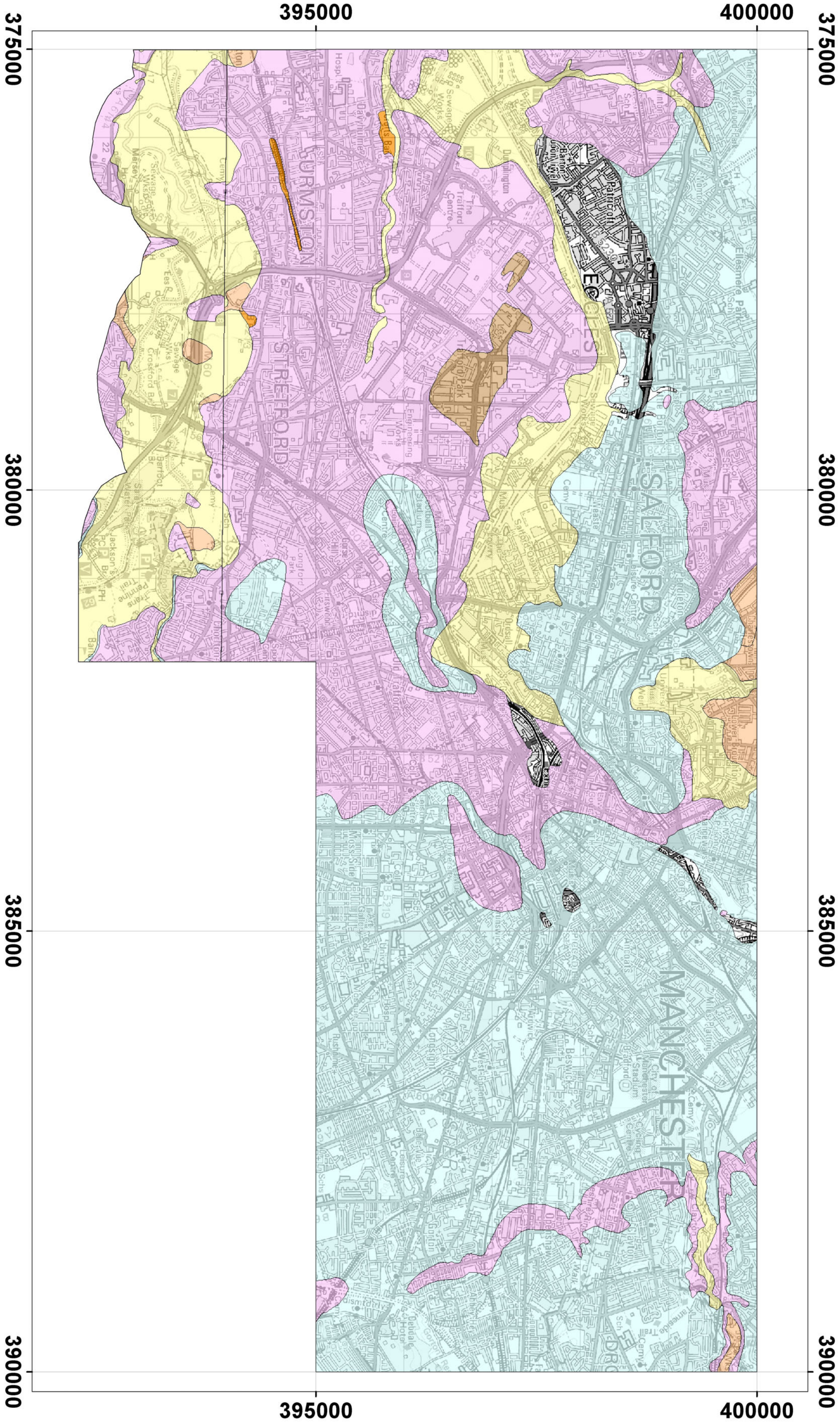


Figure 3 Superficial geology (from DiGMapGB 10)

3.3 ARTIFICIAL DEPOSITS

The legacy of Manchester and Salford's industrial past is a widespread cover of anthropogenic (artificial) deposits, proved in over 75 per cent of boreholes in the project database. In urban areas, the deposits often have 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 and provide some indication of their likely composition.

Three categories of deposit are recognised at the mapping level (Figure 4)

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 (Made Ground).

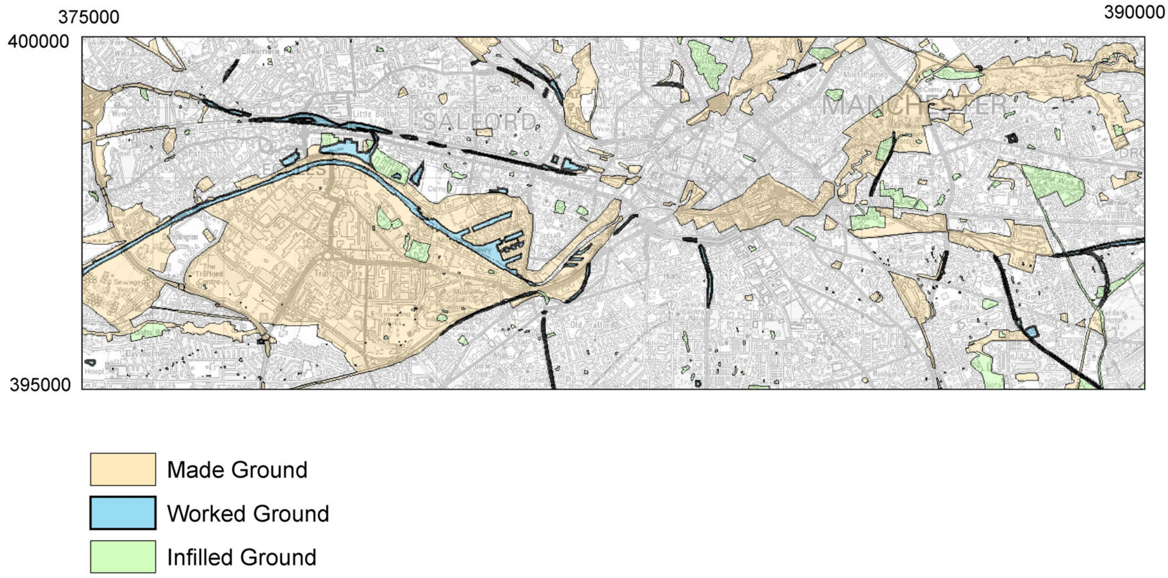


Figure 4 Distribution of artificial deposits (from DiGMapGB10)

As part of the modelling exercise 9 domains of artificial ground have been characterised in more detail (see section 5.1.2.11). Man made material or excavations were effectively treated as a continuum of the natural deposits and were therefore modelled using the same methods and principles described in Section 4 below.

4 Construction of the 3D model

4.1 DATA INPUTS TO THE MODEL

Datasets used to build the model are listed below:

Dataset	***Source***	***Comment***
Digital Terrain Model	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 o a grid using ESRI's Natural Neighbours Algorithm.
Digital geological maps	BGS: Digmap10K	1:10 000-scale bedrock, superficial and artificial layers
Borehole databases	BGS: borehole databases (SOBI and BOGI)	2000 records with lithological coding and partial geological interpretation.

4.2 BOREHOLE SELECTION

The 2000 boreholes used to build the model were selected from a larger subset of records held within the National Geoscience Data Centre. Records were selected to provide good geographical and stratigraphical coverage of the district. The final selection represents a compromise between logs of high reliability (usually from fairly shallow boreholes) and those that provide less detailed information but often prove the full Quaternary sequence (for example, water boreholes).

4.3 CODING METHODOLOGY

Boreholes were coded according to the lithological description recorded on the paper records. In some cases, this involved a degree of interpretation, particularly with older boreholes for which only rudimentary logs were available. Most deposits were also classified lithostratigraphically by reference to the published 1:10 000 scale geological maps and the emerging stratigraphical model. All digitisation was carried out using corporate dictionaries:

BGS Stratigraphic Lexicon (http://www.bgs.ac.uk/lexicon/lexicon.html)

BGS Superficial Deposits Coding Scheme (part of the BGS corporate Rock Classification Scheme (RCS).http://www.bgs.ac.uk/bgsrcs/searchRCS.html

The scheme for lithological coding uses six letters to denote the primary lithology of a deposit as shown below:

Lithological Units	Code
Peat	P
Sand	S
Silt	Z
Clay	C
Gravel	V
Cobbles	L
Boulders	B
Made Ground	FILLU

Where more than one lithological unit is present (for example a sandy clay) the letters can be combined to reflect the full lithology of the material. The coded lithological and lithostratigraphical information for each borehole was loaded to the BGS Borehole Geology database to be retrieved in the subsequent modelling process. For a full explanation of the classification scheme see Kessler; Cooper and Ford, 2004.

4.4 BOREHOLE ELEVATION

The start height (or collar height) of each borehole was recorded relative to Ordnance Datum. Where this information was not included on the written record, it was inferred from Ordnance Survey 5 m contours and spot heights.

4.5 CROSS SECTION CONSTRUCTION, CORRELATION AND MODELLING

The detailed Quaternary model of central Manchester and Salford was created under the Urban Geoscience and Hazards Program and extended to the River Mersey at the request of the Agency. Proprietary 2D and 3D modelling software (GSI3D) was used to build the model, which was constructed from a network of 209 cross-sections. The modelling process is described in detail by Kessler et al, (2004).

Coded boreholes are imported into GSI3D from the BGS Borehole Geology database. Each borehole selected for inclusion in a cross-section is displayed in its correct spatial position and builds a frame within GSI3D. In total, approximately 2000 fully coded and attributed boreholes were used in the final model.

Selected boreholes are displayed on screen and correlation lines drawn manually between boreholes to define "mappable" units. The correlation lines (and by default) the nodes that make up the lines are attributed with unique identifiers. Through computation of the bases of all geological units as triangulated irregular surfaces (TINs) all full geological objects can be calculated creating a seamless stack– the 3D geological map.

Existing 1:10 000 scale 2D digital geological map data and the surface topography (DigMapGB 10K) is used to aid correlation and define the limits and relationships of those geological units that come to crop. Essential in the modelling process however, is the detailed understanding of the geological history held as a conceptual model by the scientists involved in the project.

Solid geological boundaries were added manually to selected sections to aid hydrogeological interpretation in key areas of interest.

4.6 UNCERTAINTY

The cross-sections traverse data poor and data rich areas. The data poor areas tend to occur in some of the thicker Quaternary sequences where the number of boreholes penetrating to bedrock is low, and also in older residential areas where there has been little modern redevelopment. The borehole distribution map (Figure 5) gives a qualitative indication of where information is sparse and where model surfaces are likely to be less well constrained. Future work will focus on new ways to convey geological uncertainties in geological models (see Section 8)

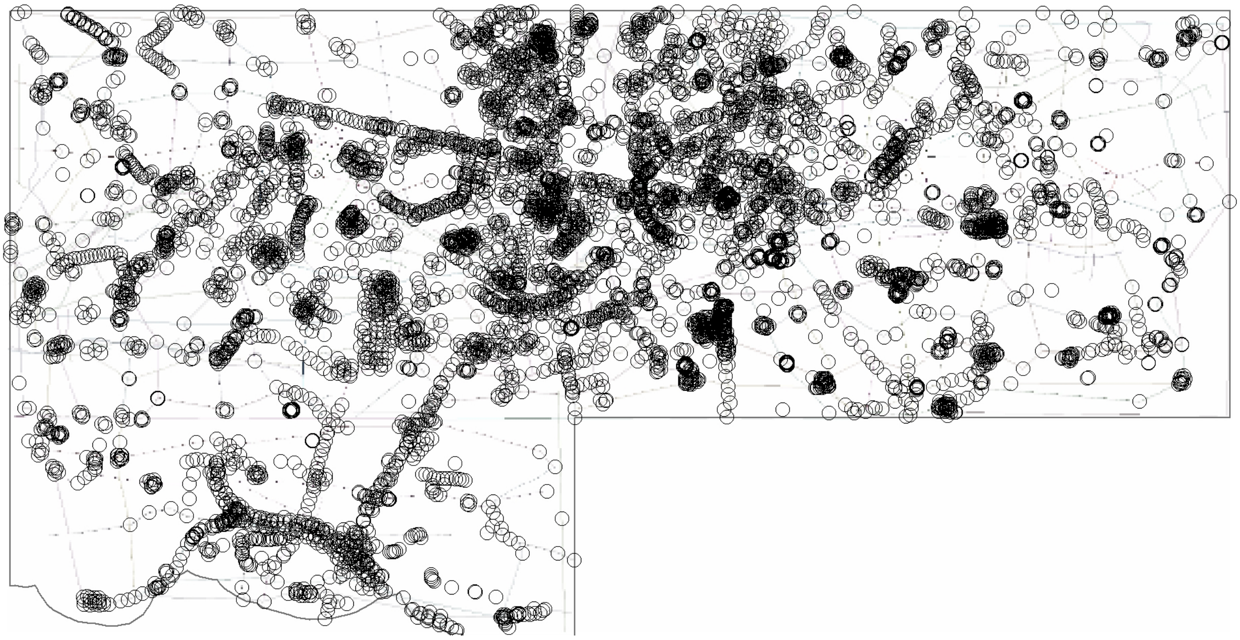


Figure 5 Distribution of boreholes and cross-section network

4.7 MODELLED UNITS DEFINED

The stratigrapical units included in the model are listed in Table 1 and their spatial relationships are illustrated schematically in Figure 6. Computer codes (e.g. glld) uniquely identify each of the modelled units and provide the link between the section correlations and the modelled surfaces. Units with good continuity form the framework for the model. Some are defined morphologically; others are inferred from sedimentary profiles. Impersistent lithologies are treated as lenses; they appear on sections but no attempt has been made to extend them beyond the immediate area in which they have been recorded.

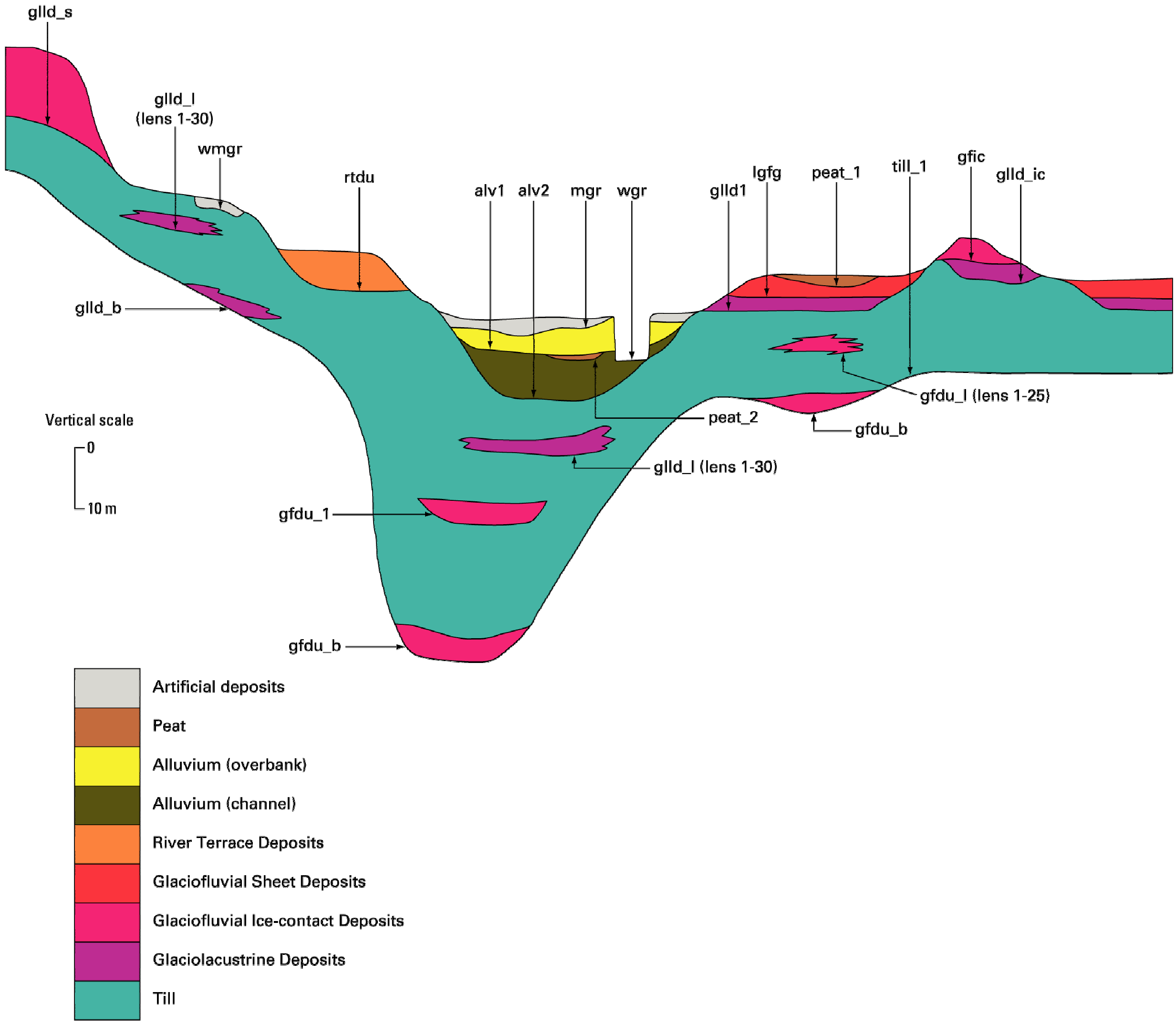


Figure 6 Schematic diagram showing relationships between modelled units

<table>
<tr><th></th><th>Map unit</th><th>Model unit</th><th>Lithology</th><th>Environment (inferred)</th><th>Model code of geological object</th></tr>
<tr><td rowspan="8">Holocene</td><td>Worked Ground</td><td>Worked Ground</td><td></td><td rowspan="3">Anthropogenic
(Artificial deposits)</td><td>wgr</td></tr>
<tr><td>Made Ground</td><td>Made Ground</td><td>Mixed
(see Table1)</td><td>mgr</td></tr>
<tr><td>Infilled Ground</td><td>Infilled Ground</td><td>Mixed
(see Table 2)</td><td>wmgr</td></tr>
<tr><td>Peat (lowland bog)</td><td>Peat</td><td>Peat</td><td>Organic</td><td>peat_1</td></tr>
<tr><td rowspan="2">Alluvium</td><td>Alluvium
Overbank floodplain deposits
Peat</td><td>Silt, clay,
Peat</td><td>Fluvial</td><td>alv_1
peat_2</td></tr>
<tr><td>River channel deposits</td><td>Sand, gravel</td><td>(may include glaciofluvial element)</td><td>alv_2,</td></tr>
<tr><td rowspan="2">River Terraces:
Undivided,
First
Second</td><td rowspan="2">River Terraces
Undivided
(River Irwell, River Medlock)</td><td rowspan="2">Sand, gravel</td><td rowspan="2">Fluvial/Ice marginal</td><td rowspan="2">rtdu,</td></tr>
<tr></tr>
<tr><td rowspan="6">Pleistocene (Devensian)</td><td>Glaciofluvial Sheet Deposits: Sheet deposits (formerly Late Glacial Flood Gravels)
Ice-contact Deposits</td><td>Glaciofluvial Deposits:
1. Outwash sheet deposits
2. Ice-contact feature-forming deposits
3. Supra-till channel deposits (major)
4. Intra-till lenses (minor)
5. Basal deposits</td><td>Sand, gravel
Fine sands
Sand, gravel
Fine sands
Sand and gravel
Sand and gravel</td><td>Sandur (?)
Ice-contact/?deltaic
Sub/supra glacial drainage</td><td>lgfg
glld_s, gfic
gfdu_1
gfdu_1_l_1-28
gfdu_b, gfdu_ch</td></tr>
<tr><td>Glaciolacustrine Deposits</td><td>Glaciolacustrine Deposits
1 Laterally extensive (km-scale deposits)
2. Intra till deposits (restricted distribution
3. Deformed glaciolacustrine deposits</td><td>Laminated silts</td><td>Ice-distal
Ice-proximal
Ice-contact Push moraine (?)</td><td>glld_l
glld_1_l_1-16
glld_ic</td></tr>
<tr><td>Glaciofluvial Ice-Contact Deposits</td><td>Glaciofluvial Ice-Contact Deposits
1. Sands forming south-facing topographic feature</td><td>Loose, fine sands, overlying laminated silts</td><td>Ice-contact, deltaic (?)</td><td>glld_s</td></tr>
<tr><td></td><td>Moraine complex
Till, sand and laminated clay, undivided</td><td>Till, sand, gravel, laminated silts (deformed)</td><td>Push moraine (?)</td><td>gfic</td></tr>
<tr><td>Till</td><td>Till</td><td>Till, interbedded sands, impersistent laminated clays</td><td>Lodgment and melt-out tills, undivided</td><td>till_1,</td></tr>
<tr></tr>
<tr><td>Bedrock</td><td></td><td></td><td></td><td></td><td>base_quat</td></tr>
</table>

Table 1 Map units and equivalent model units

5 Lithology and geometry of the Superficial Deposits

Four cross-sections reproduced from the model show the spatial relationships of the superficial deposits in different sectors of the district (Figure 7 a-d). The geometry and lithological characteristics of the individual units are discussed in the following sections in base-upwards sequence.

Furthermore, 11 bespoke synthetic sections derived from the model are published in the Appendix as individual fold out maps and as a compilation on Map 1.

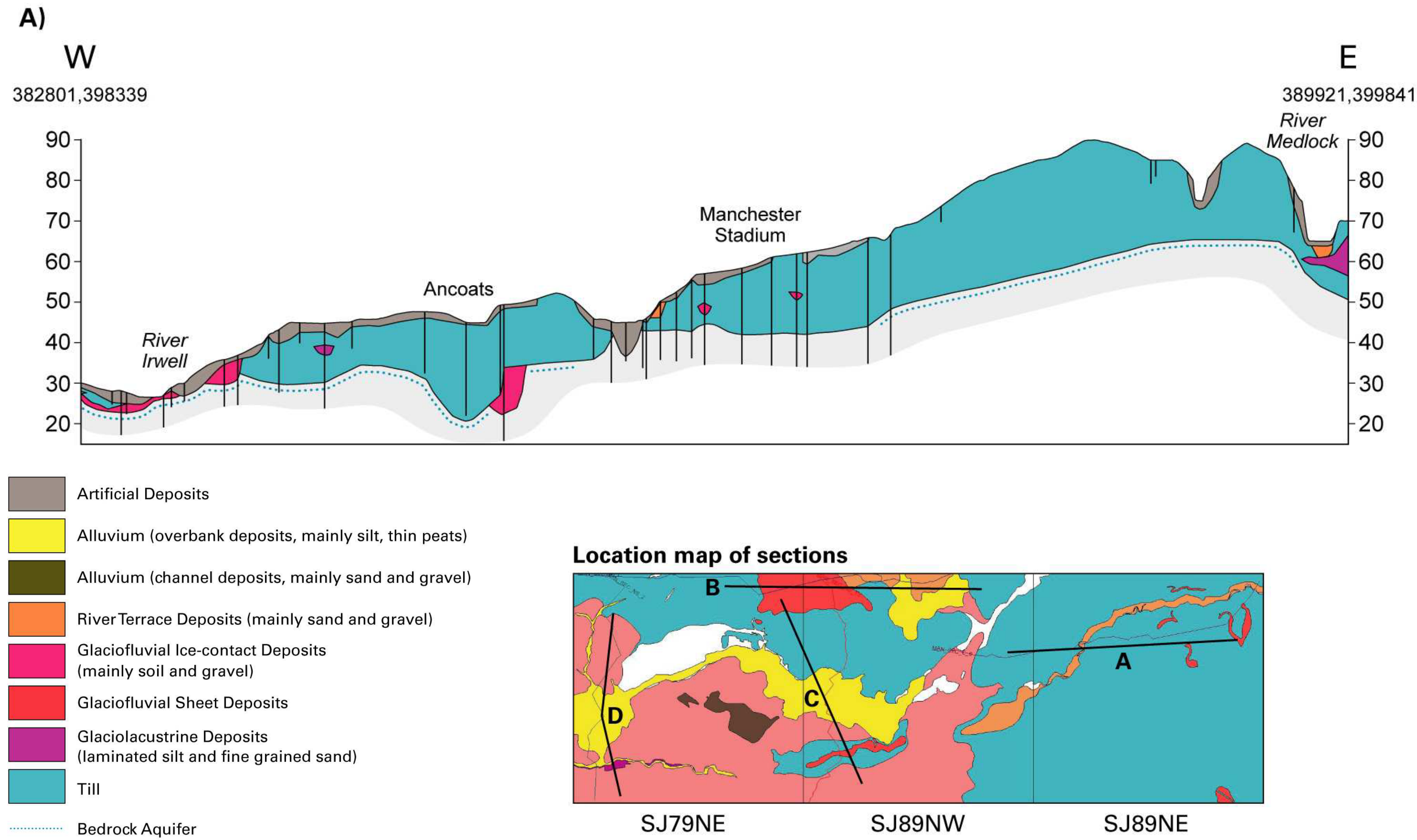


Figure 7a Selected cross-sections to illustrate the variability of the superficial deposits

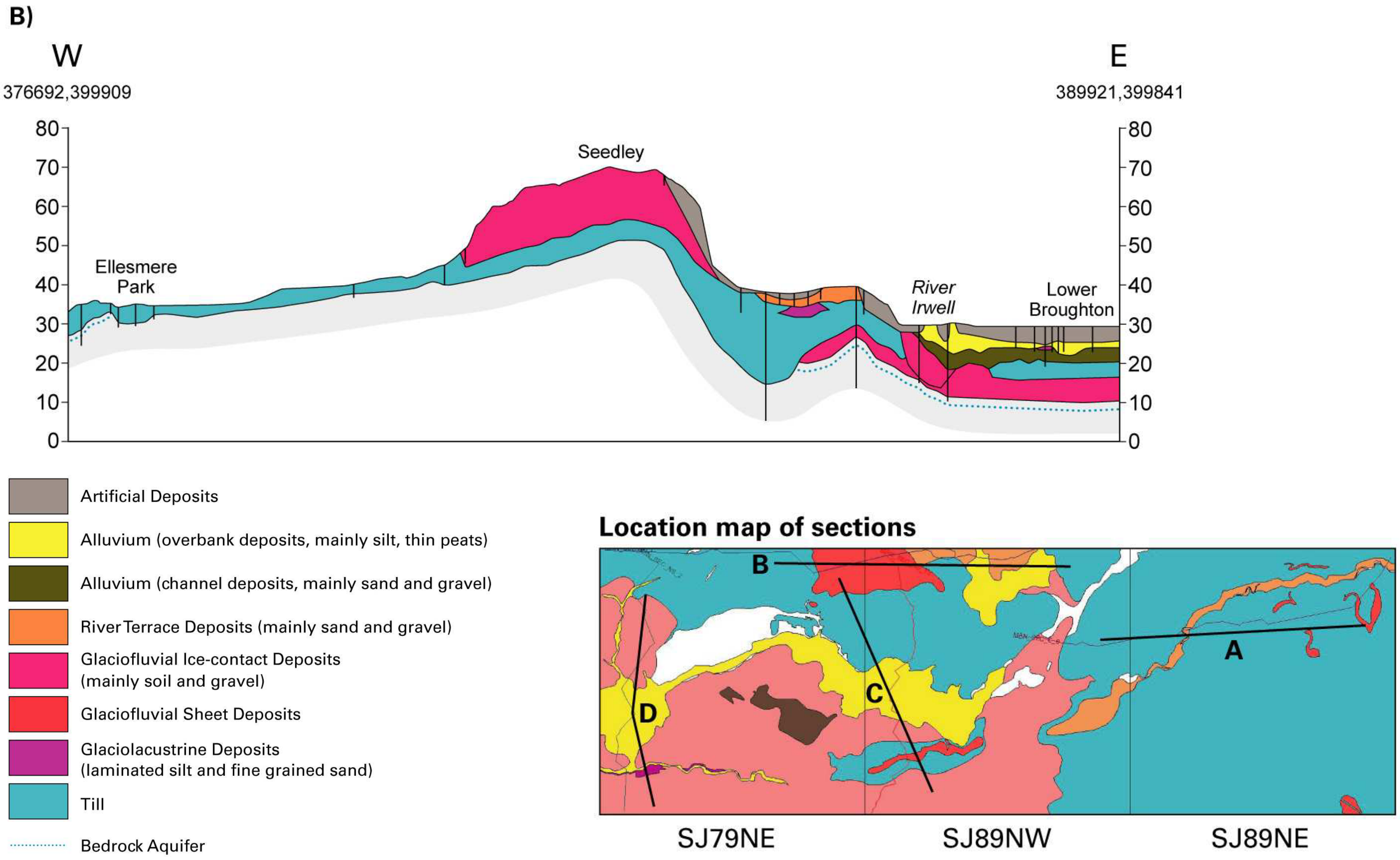


Figure 7b Selected cross-sections to illustrate the variability of the superficial deposits

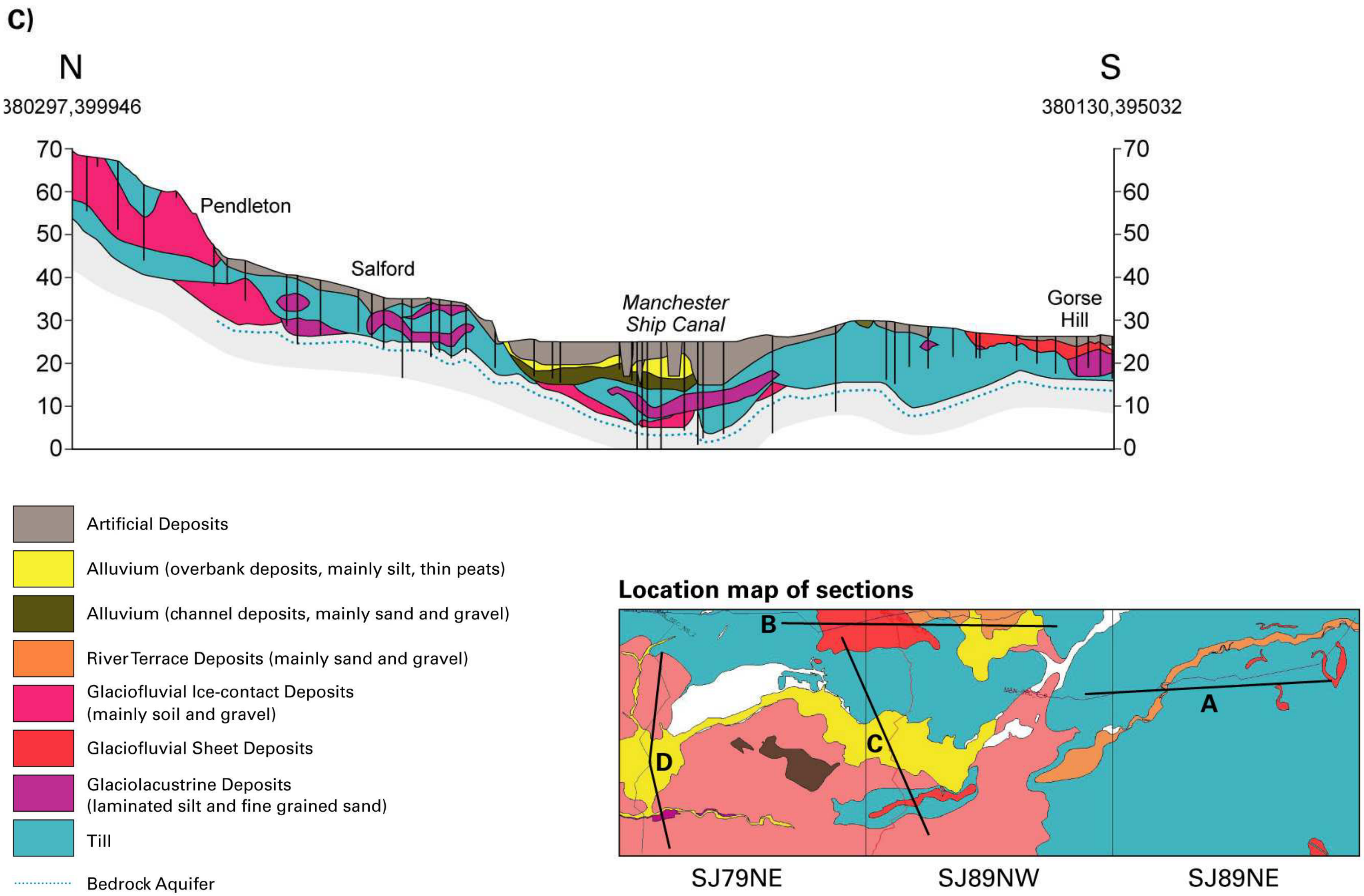


Figure 7c Selected cross-sections to illustrate the variability of the superficial deposits

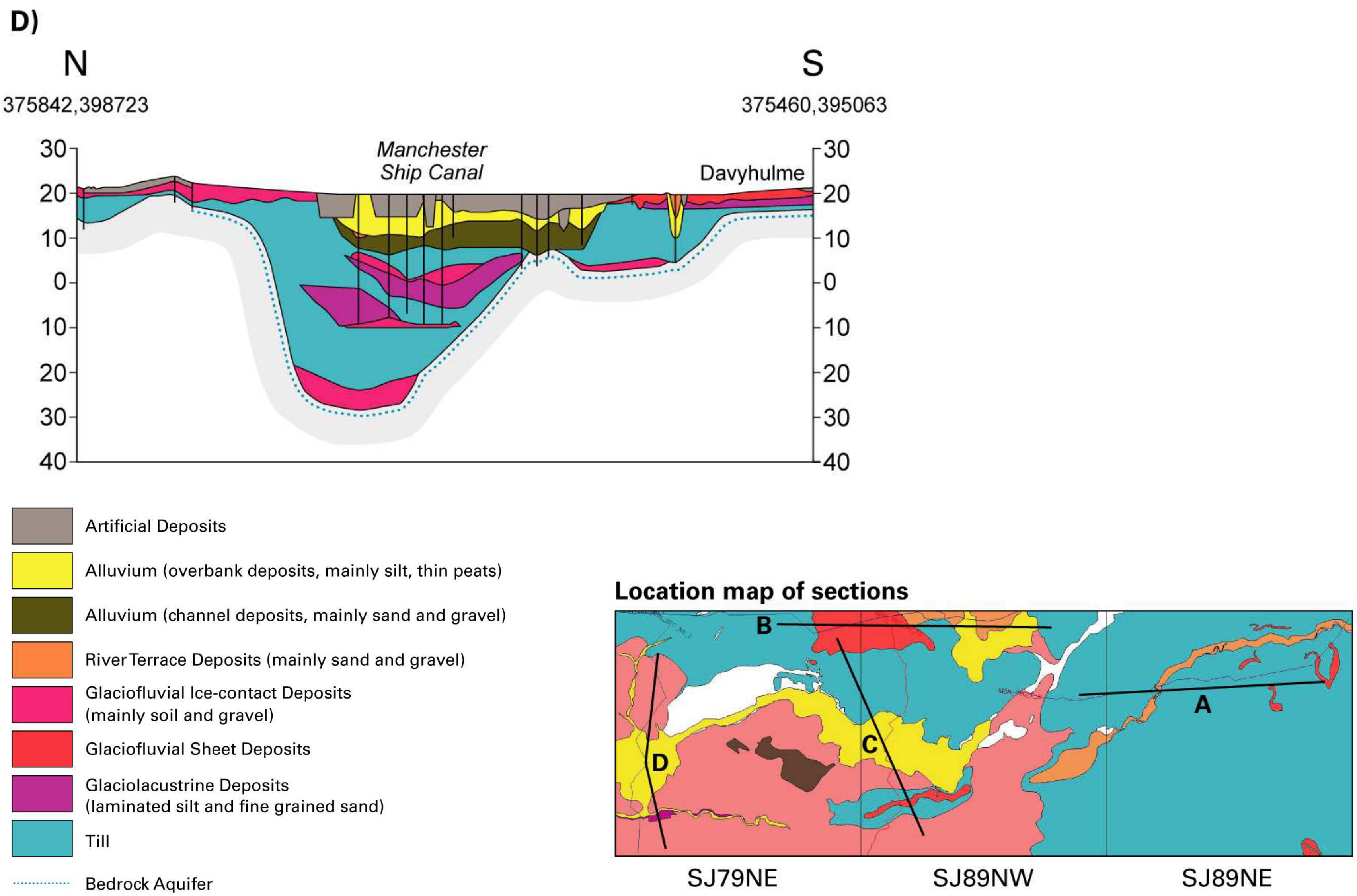


Figure 7d Selected cross-sections to illustrate the variability of the superficial deposits

5.1 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 or the geotechnical properties of the underlying bedrock. Thus, Permo-Triassic sandstones that have weathered to ‘rocksand’ at the bedrock -drift interface 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 8). 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 from part of a more extensive system of sub-parallel buried channels that cross the Greater Manchester and Merseyside area in a predominantly north-westerly direction (Howell, 1973, Grayson (1972). 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, that extends in places well below sea-level. The greatest depths (-38m below OD) are recorded to the west of Eccles. The depressions are believed to represent former drainage lines that were overdeepened during the Last Glacial Maximum by sub-glacial meltwaters flowing under hydrostatic pressure (e.g. Johnson, 1985, p. 253). The alignment of the troughs probably reflects a combination of structural control, and selective erosion of more easily weathered bedrock.

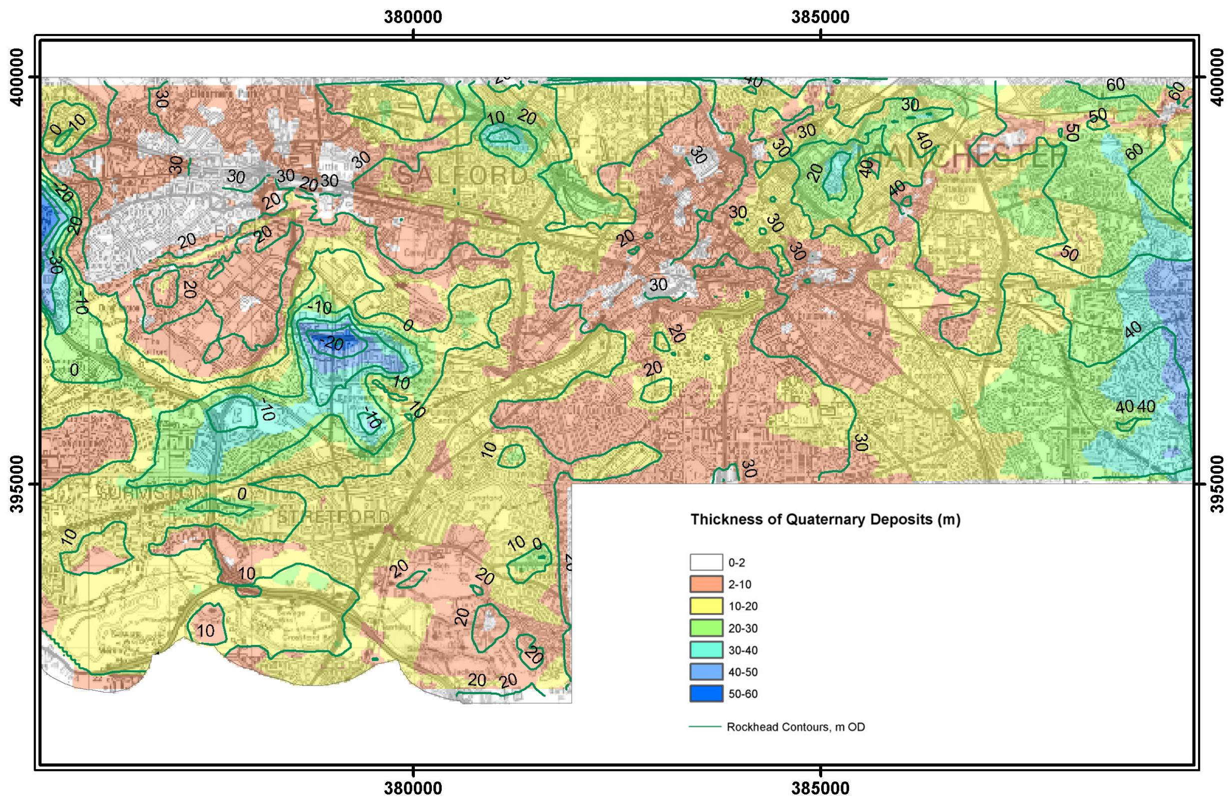


Figure 8 Rockhead elevation and thickness of superficial deposits

5.2 GLACIGENIC DEPOSITS

5.2.1 Basal outwash deposits [GFDU_B]

Sand and gravel deposits of variable thickness occur at the base of the glacigenic sequence. (Figure 9). 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 pro-glacial or sub-glacial setting is envisaged.

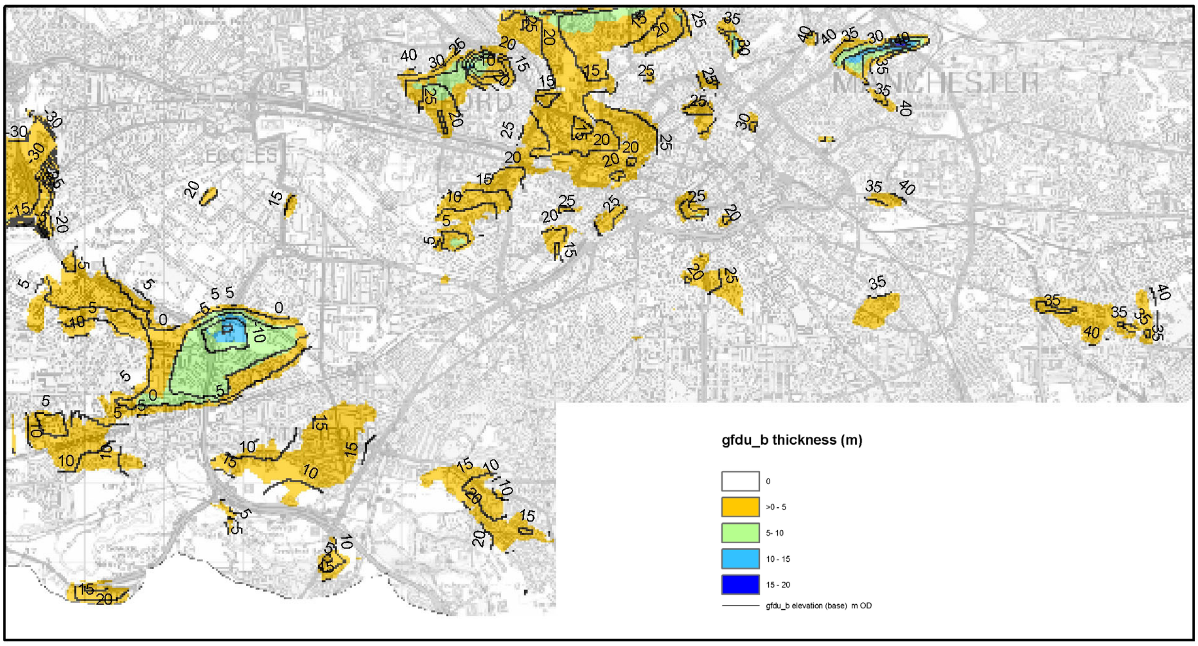


Figure 9 Thickness and base elevation of basal outwash deposits

5.2.2 Till [TILL_1]

Deposits of till mantle bedrock on the higher ground in the east and occurring 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 inter-stratified with, or capping, outwash. The basal till, at outcrop, is typically grey, and contains a predominance of clasts derived from the Coal Measures (Plate 2). In contrast, tills in the upper parts of the sequence tend to be brown, with a higher content of Triassic material.

Plate 2 Basal till, Whit Brook [388300, 407700]

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 the geotechnical evidence available, there is certainly evidence in the buried valley systems south of Trafford Park for multiple sequences of till sands and laminated clays (see Figure 7d) that could support this hypothesis.

The thickness of the till body including intra-till sands and clays is shown in Figure 10. The sheet thickens to over 30 m against rising ground in the east, and is the predominant deposit in the thick buried channel sequences of the Trafford Park area.

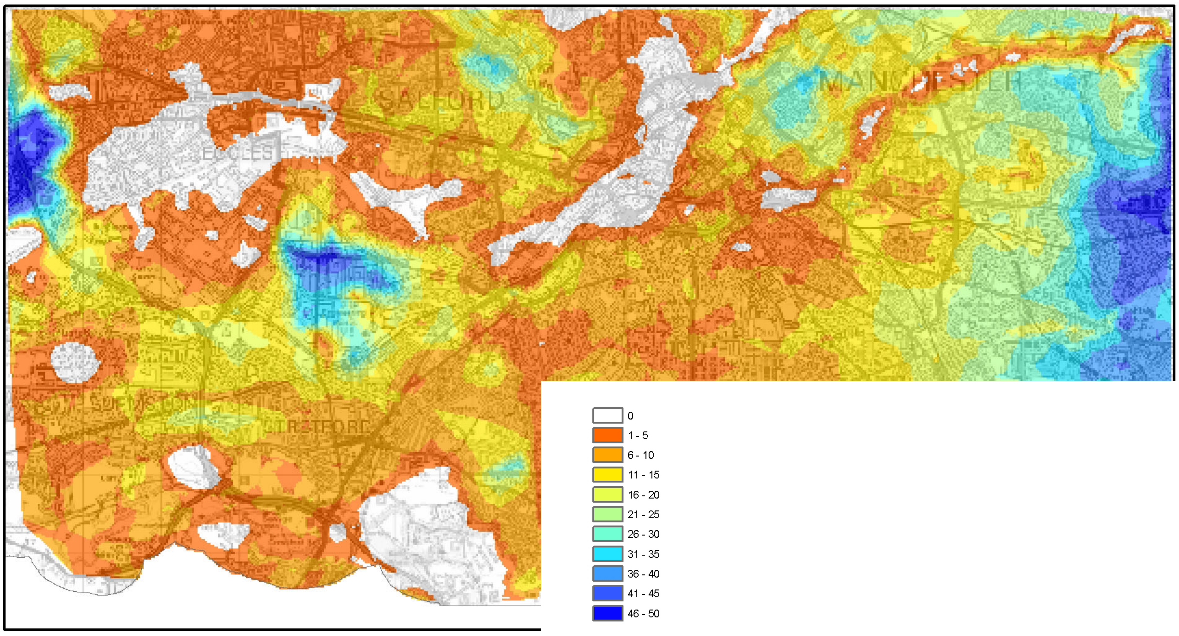


Figure 10 Till thickness (m)

5.2.3 Moraine complex [GFIC]

A low, elongate ridge rises above the outwash plain in the Old Trafford area [380000; 396000]. 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.

5.2.4 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:

5.2.4.1 INTRA- TILL DEPOSITS [glld_ic, glld_1_l1-16]

Glaciolacustrine lenses occur interbedded with other glacigenic deposits, notably in the north of the district and beneath the ice-contact sands at Brindle Heath [380400; 400100] (5.2.5). Similar deposits also occur in association with the moraine complex (5.2.3) where borehole records record laminated clay sequences inclined at 45° to the horizontal.

5.2.4.2 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 11). Although mainly concealed by outwash sands, the deposits were formerly exposed in a brick pit at Crofts Bank [375600; 395800]. The unit is of fairly constant thickness, around 5 m, and is underlain by till. It comprises brown silt and 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.

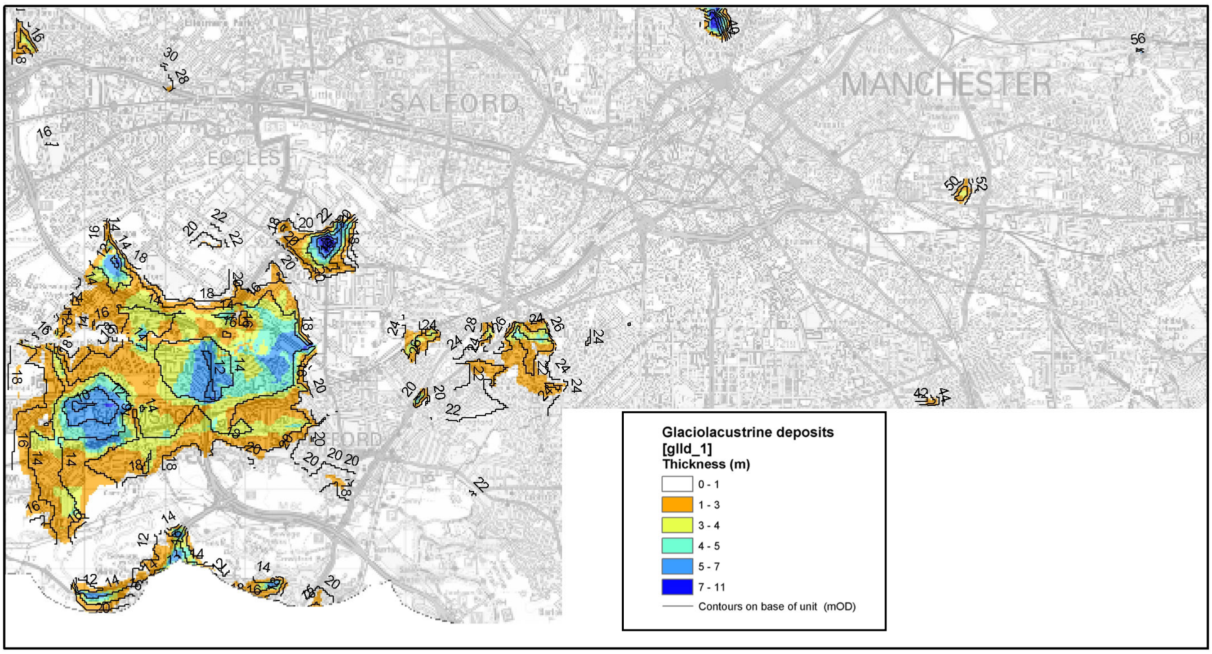


Figure 11 Thickness and base elevation of major glaciolacustrine deposits [glld_1]

5.2.5 Supra-till sand and gravel deposits (major) [gfdu_1], sheet deposits and lenses (minor) [GFDU_1_L_1-28]

Plate 3 The Cliff landslip [382700 401300]

Isolated small patches of glaciofluvial sands and gravel [gfdu_1] occur on top of the main till deposit. Intra-till channel sands [gfdu _1_1-28], up to 7 m thick, occur within the buried channel system. 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.

5.2.6 Glaciofluvial ice-contact deposits [GLLD_S]

Buile Hill [380000 399500] rises to 70 m above OD in the north-western part of the area. The steep south-facing slope suggests that the hill was 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 (SJ79NE1538) 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.

5.2.7 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. 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 an upper unit of brown, fine- to coarse-grained silty sand; the basal beds are of grey-brown, well graded sand and gravel with occasional cobbles. The junction with the underlying glacigenic deposits is sharp.

The deposits are interpreted as part of a fluvial or fluvioglacial outwash system fed by streams draining 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.

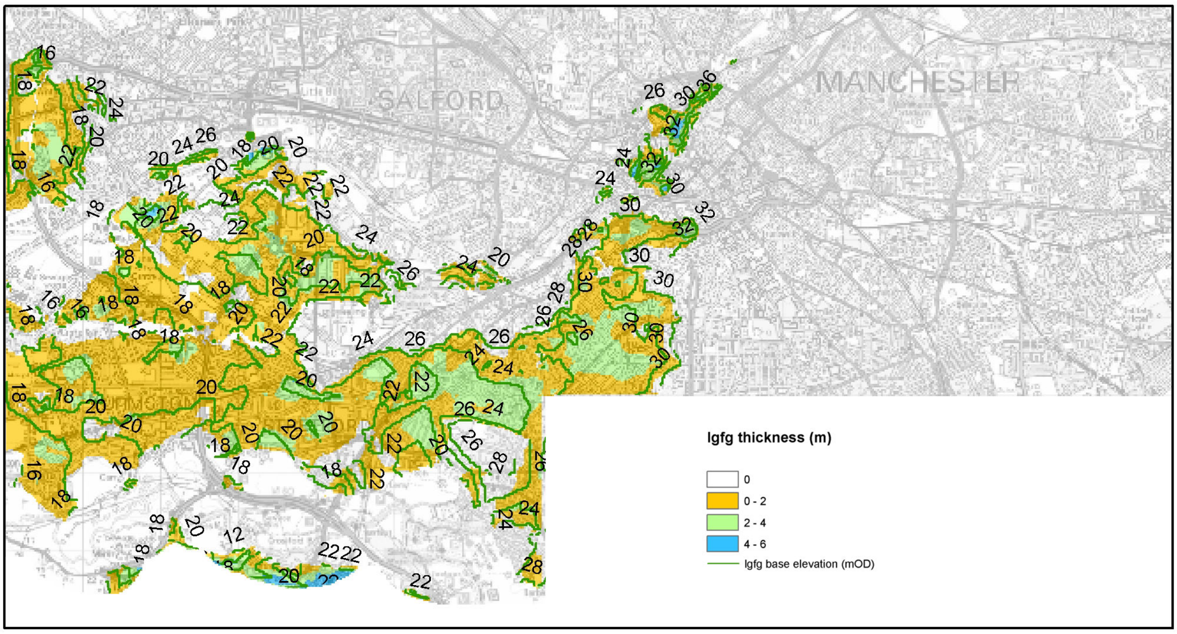


Figure 12 Thickness and base elevation of outwash sheet deposits [LGFG]

5.2.8 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, through which the modern river systems have become incised.

The terrace deposits in the Irwell valley are about 3 m thick and the base is at an elevation of 33 m AOD. The deposits consist of silty sand overlying sand and gravel, and are cut into till or laminated clay substrate. The terraces may represent the upstream equivalent of the outwash sheet deposits (5.2.6).

5.3 HOLOCENE DEPOSITS

5.3.1 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 Salford Quays [380600; 397100] and further downstream at Dumplington [376400; 397100]. 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 (Figure 15).

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.

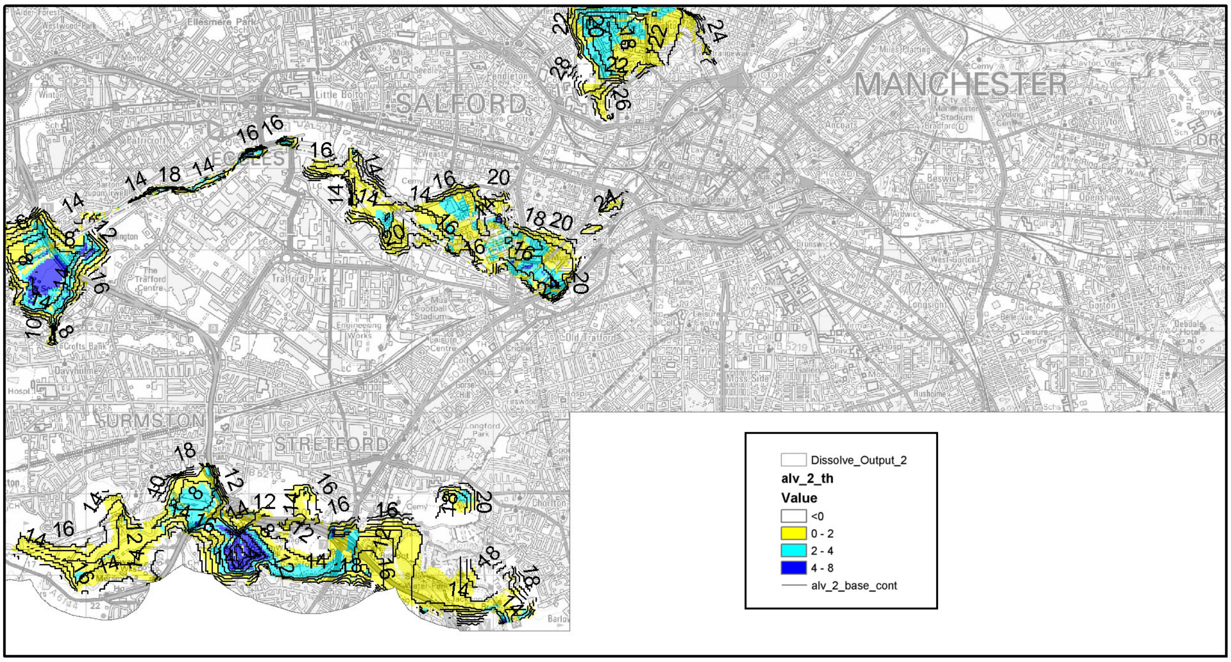


Figure 13 Thickness and base elevation of alluvial channel deposits [ALV_2].

5.3.2 Peat [PEAT_1, PEAT_2]

A formerly extensive area of lowland peat, known as Trafford Moss, lies beneath Trafford Park Industrial Estate [378400; 397000]. 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 original thickness of 3 m have been reported (Tonks, et al. 1931).

Thin layers of peat are also present locally within, and at the base of, the alluvial sequence as noted above.

5.3.3 Artificial (anthropogenic) deposits [MGR, WGR, WMGR]

Artificial Ground is extremely variable in terms of its composition, thickness and geometry (Figures 14, 15). Boreholes show that the composition of the material is highly variable, ranging from entirely anthropogenic material (bricks, rubble, plastic etc) to re-deposited natural material. One approach to dealing with this variability is to identify geographical areas characterised by similar historical land use processes or deposition of similar types of material. 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 city 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, a number of anthropogenic processes dominate in the district. Waste material associated with coal mining was deposited on the former natural ground surface either as spoil heaps or tipped into river valleys. Ash from domestic fireplaces was also disposed of into river valleys, raising the level of the former riverbed. Extensive tipping of colliery waste took place in the valley of the River Medlock in the Phillips Park area of Bradford. Other river valleys and stream courses affected by tipping include the River Irk, the River Irwell and Bent Lanes Brook.

In total, nine zones of significant artificial ground have been delineated and are shown in Figure 9. The characteristics of the deposits in each of the areas are summarised in Tables 2 and 3. Small-scale pits and quarries (generally less than 100 m^2) were not included the model but they are shown, together with road embankments, road cuttings, the Bridgewater Canal and small areas of made ground associated with individual sites, on Figure 4.

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. Using borehole records in these areas it is possible to identify areas of thick Made Ground (generally greater than 2 m) that form a persistent deposit and could be correlated, from areas of thin Made Ground (generally less than 2 m) that could not be correlated. This class is called Made Ground Undivided. Only the areas of thick Made Ground are included in the 3D model. It is important to note that the accuracy of these thickness calculations directly depend on the accuracy of the available Digital Terrain Model (DTM).

The modelled thickness of the artificial ground is illustrated in Figure 14.

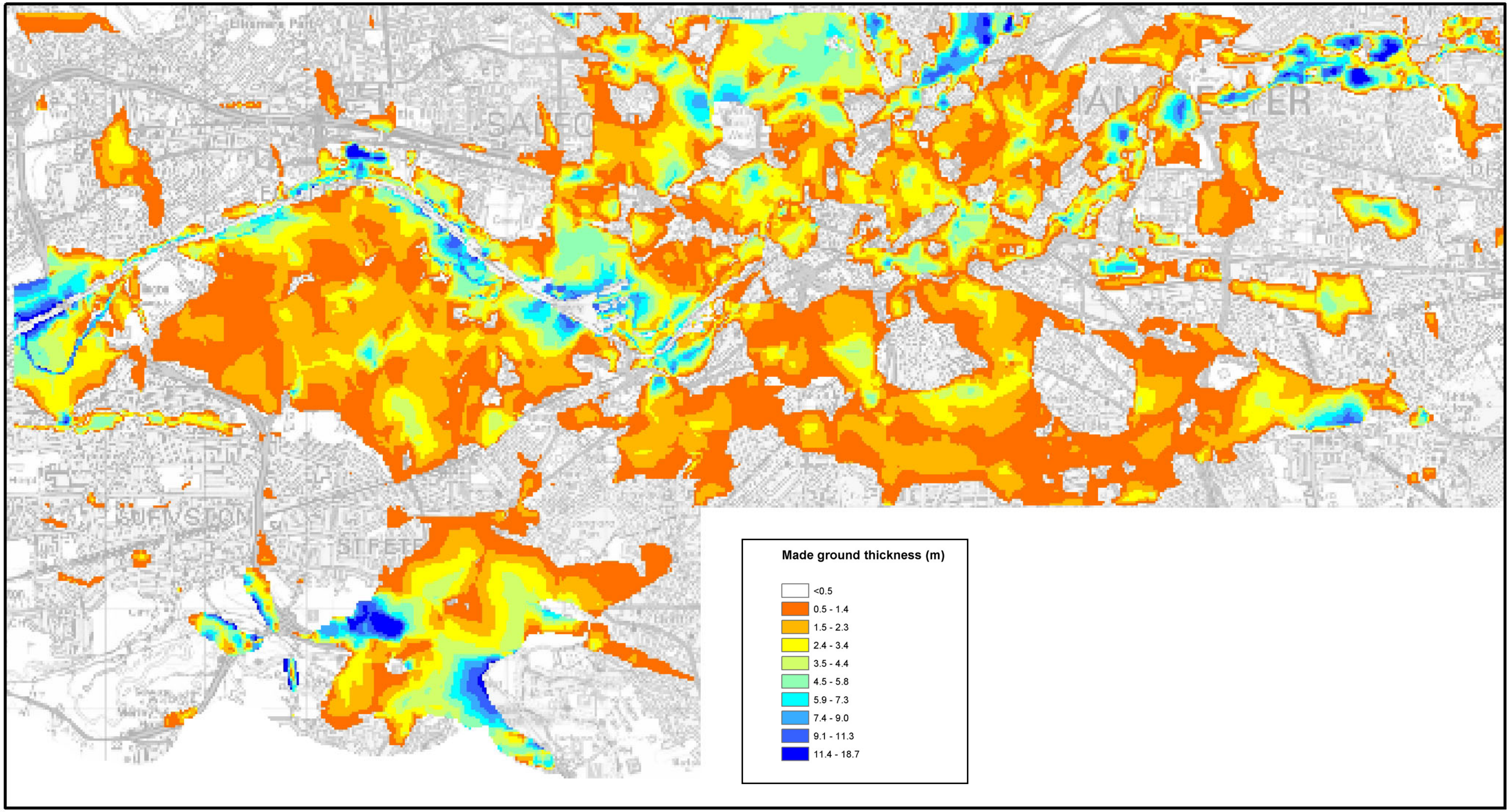
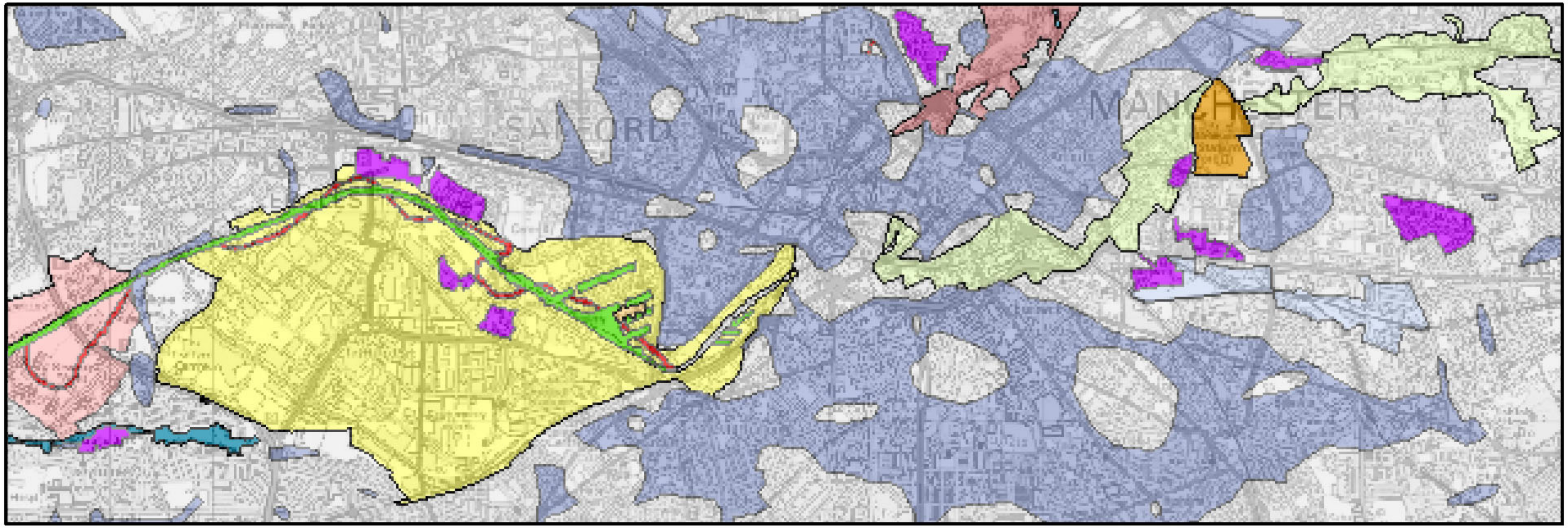


Figure 14 Thickness of artificial deposits (m)



Legend

- Made Ground Undivided generally thin or impersistent (Category 1)
- Made Ground Undivided generally thick or persistent (Category 1)
- Made Ground R.Irwell (Category 2)
- Made Ground Sewage Works & Refuse (Category 3)
- Made Ground Trafford Park Industrial Estate (Category 4)
- Made Ground Valley Infill R.Medlock (Category 5a)
- Made Ground Valley Infill Crofts Bank (Category 5b)
- Made Ground Valley Infill R.Irk (Category 5c)
- Made Ground Railway Sidings (Category 6)
- Made Ground Commonwealth Site (Category 7)
- Worked Ground (Category 8)
- Infilled Ground (Category 9)

Figure 15 Artificial deposit typology

	Category	Thickness	Composition
Made Ground	1 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.
	2 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 (Gray, 2000). Organic and inorganic domestic refuse also proved by drilling. Infilling of the River Irwell pre-dated 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.
	3. 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 southern most sewage works.	Oily sandy ash with common organic refuse (60 boreholes)
	4. Trafford Park Industrial Estate	1 to 2 m but commonly 3 to 7 m. Over 8m in the eastern part of the Park.	Material associated with extensive post-war industrial development that 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
	5a. 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)
	5b 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)
	5c Valley infill River Irk	Typically 1 to 4 m but occasionally reaches up to 7m, particularly in the south-west of the area.	Railway land of the Manchester, Whitefield & Radcliffe line running out of Victoria Station, numerous textiles factories and dye works and spoil from former brick pits and sandstone quarries. (70 boreholes or trial pits)
	6. Railway sidings Gorton, east of Manchester city centre	1 to 4 m Borehole control is limited to the central part of this area, however.	Made Ground related to an extensive network of railway sidings, goods depots and locomotive works associated with Ancoats Junction situated at the the junction of the Crewe & Manchester and the Manchester, Sheffield & 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)
	7. 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 2 Characteristics of made ground deposits by area

	Category	Thickness	Composition
Worked Ground	8. 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 the Liverpool and the River Mersey. Both bedrock and natural superficial deposits were excavated to a depth of approximately 8m 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 study area show that the base of the canal terminates in superficial deposits of glacial or post-glacial age, but in places is excavated directly into bedrock.
Infilled Ground	9. 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 the workings is uncertain. Over 90 boreholes prove artificial ground infilling the selected former worked ground areas. Most commonly, the fill material comprises re-deposited natural material from the workings with common ask, clinker and brick fragments. For example, the fill material of the former Strangeways brick pit is proved in borehole SJ89NW425 and comprises over 1 m of sandy clay with common ash, clinker and brick. The thickness of the fill material is extremely variable across the study area, ranging from 1 m to over 15 m in the former Sherwood Sandstone quarry at Little Bolton (378400; 398500). Some former brick works and quarries are partially filled while others are completely backfilled. For example, Crofts Bank Brick Works (376000; 395800), opened 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 (378400; 398500) 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, preserving a 5 to 7m high sandstone escarpment from the former quarry.

Table 3 Characteristics of worked and infilled ground by area

6 Hydrogeology

6.1 INTRODUCTION

The current 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 and preliminary results are presented below. The support provided by the Agency for this work is here acknowledged. The aquifer area studied for the Agency extends the original project area southwards to the River Mersey (Figure 16).

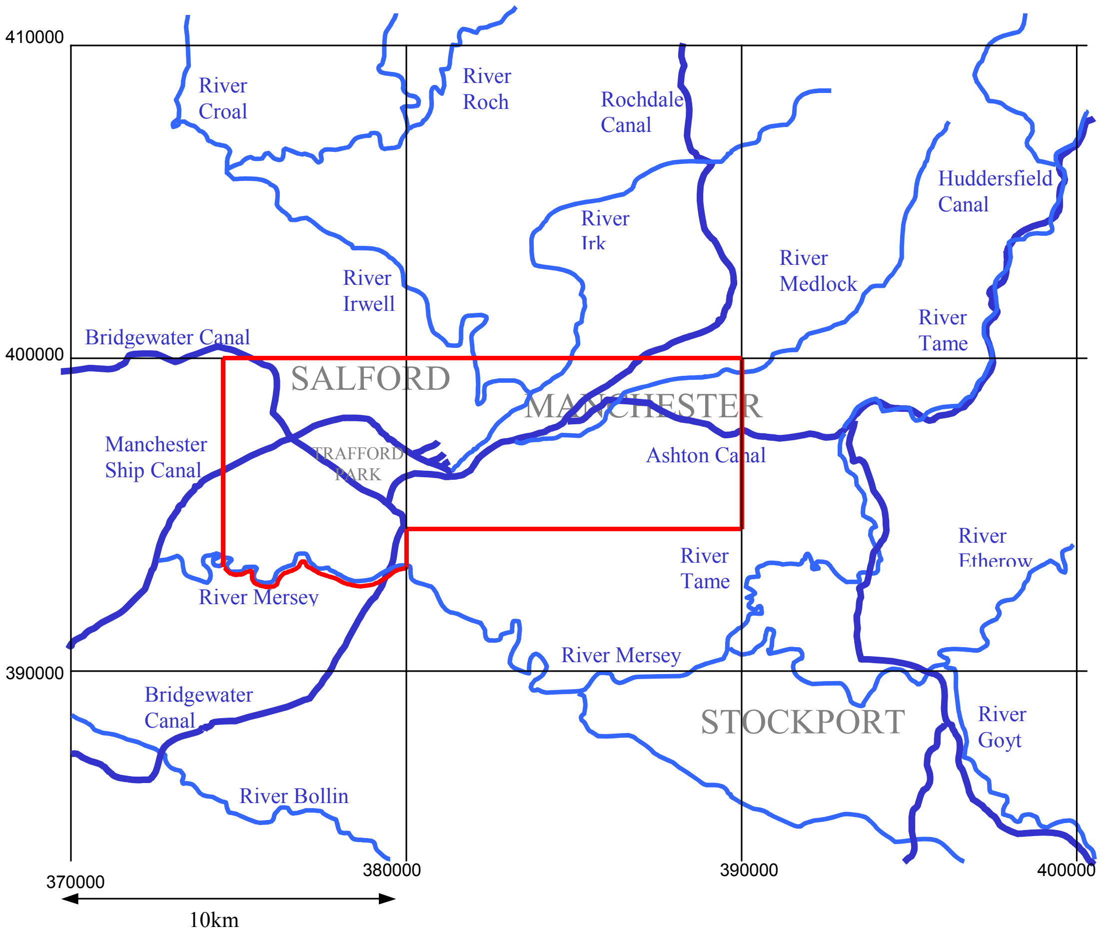


Figure 16 Principal rivers and canals in the project area (highlighted)

6.2 HYDROGEOLOGICAL ISSUES

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 Marl Formation. A number of regional studies have shown that flow in the sandstones is by a combination of fissure and intergranular flow (e.g. Ingram, et al 1981, Walthall and Ingram, 1984, Campbell 1982). The aquifer provides baseflow to the rivers and also groundwater for industrial abstractions. Sandstone units within the Coal Measures crop out in the north and east of the district and are also significant water-bearing units.

The river and major canal network is shown in Figure 16. 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.

6.2.1 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 groundwater supplies in the study area itself but Source Protection Zones (SPZs) have been defined for some of the larger abstractions in Manchester used mainly for brewing.

6.2.2 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 licenses 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 and 2000). The contours for 2000 are included in Figure 17. 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 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 70s 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 more than 1m across the aquifer.

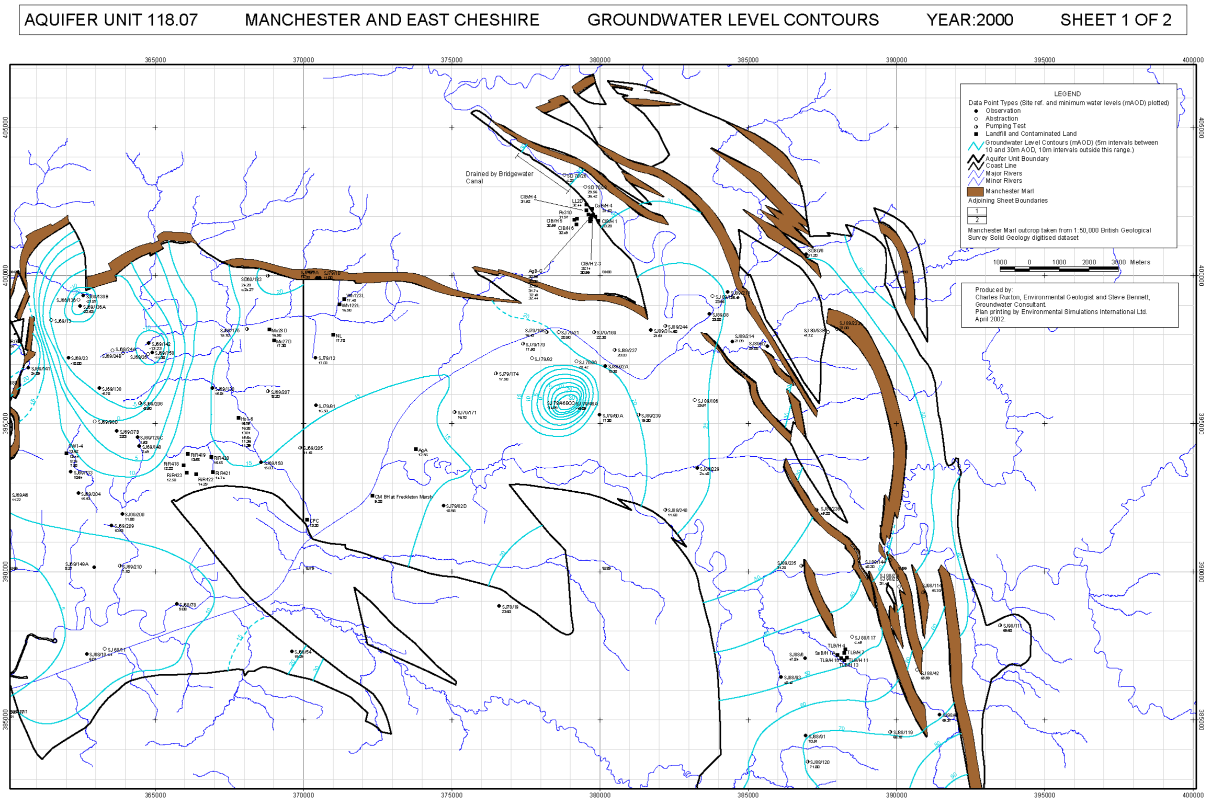


Figure 17 Groundwater level contours Manchester and East Cheshire (Environment Agency (Ruxton and Benne, 2000)

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 [380400; 401000] 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 [388000; 400300] 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 (ESI 2001).

6.2.3 Discharges

Measurements of discharge to surface waters from sewage treatment works for the months 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.

6.2.4 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 Baseline Aquifer Chemistry Project (Environment Agency/British Geological Survey, 2003) for the Manchester and East Cheshire aquifer 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 and Chat Moss areas [370700; 396100]. Patches of more recently recharged groundwater, especially along lengths of the Manchester Ship Canal, show lower hardness values and the effects of flushing of old, saline waters are not so apparent.

To the east of the Manchester Marls the groundwater chemistry suggests that, although discontinuous, the Manchester Marls compartmentalise groundwater units 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. at [378300 398100]. 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) and 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 NaCl, although the other major cations (Ca Mg and K) 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. Stansbury (1994) re-evaluated the distribution of saline groundwaters and noted a correlation with the area of thicker drift in the Didsbury Depression, thought by Grayson (1972), to be an extension of the Worsley Fault. It was suggested that the raised mound of more saline water might be the result of incomplete flushing of older saline waters or preferential flow of saline waters from depth moving along the Worsley Fault.

6.3 AQUIFER VULNERABILITY AND RECHARGE

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 Agency through a two-tier approach. Public water supply abstractions are protected from polluting activities by *Source protection Zones.* 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 first generation of these maps, published in the late 1990s, at relatively large scale of 1:100,000, have limited account taken of superficial deposits and in particular in urban areas soils are always assigned a 'worst case' vulnerability. For these reasons the maps are of limited use for site assessment.

The current project addresses these deficiencies by developing a more robust vulnerability model that takes account of the geometry, lithology and inferred transmissivity of the superficial deposits. [This research was carried out in collaboration with the Agency North West Region]

In England and Wales, the Groundwater Vulnerability series of maps produced by the Environment Agency provide an estimate of vulnerability. 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 vulnerability model prepared for central Manchester and Salford goes some way to developing these methodologies further. The model, which is based on 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 dealt with in a later iteration through inclusion of soil geochemistry and first strike water data.

6.3.1 Hydrogeological properties of the superficial deposits

Hydraulic conductivities were assigned to each of the modelled units as indicated in Table 4. The figures are taken from published sources (Brassington, 1998; Todd, 1980; Allen et al, 1997) 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 portion of superficial deposits. 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 often below the 0.1 to 3 mm limits for the formula (Fetter, 2001), the calculated values fell within the estimated ranges but are not tabulated.

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

The **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 **glaciolacustrine sands and silts** (glld_s) are relatively homogenous and in consequence are given a relatively narrow hydraulic conductivity range.

The **alluvial overbank** deposits (alv_1**)** comprise mainly silts 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 have the lowest hydraulic conductivity estimate.

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

The deposits are classified as permeable or weakly permeable based on the estimated hydraulic conductivity ranges. These definitions are based solely on the lithological description of each unit and take no account of other factors, such as weathering or fracturing that may increase the permeability of the deposit.

Model unit/notation	**Lithology**	**Inferred permeability**	**Estimated hydraulic conductivity range (md^{-1})**
Alluvial overbank deposits (alv_1)	Silt, clay, peat	Weakly permeable	$10^{-5} – 10^{-2}$
Alluvial 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 & gravel	Permeable	$10^{-4} – 10^{3}$
Glaciolacustrine deposits (glld_1)	Laminated silts and clay	Weakly permeable	$10^{-6} – 10^{-4}$
Glaciolacustrine sands and silts (ice-contact) (glld_s)	Loose, fine sands overlying laminated silts	Permeable	$10^{-2} – 10^{1}$
Till deposits (till_1)	Till, interbedded sands, impersistent laminated clays	Generally weakly permeable but some permeable lenses	$10^{-4} – 10^{1}$
Basal sand and gravel deposits (gfdu_b)	Clayey sand & gravel	Permeable	$10^{-5} – 10^{3}$

Table 4 Inferred hydraulic properties of modelled units

6.3.2 Sections and Plans

Eleven cross-sections (see Appendix 1 and Map 1) derived from the geological model show the relationships of the superficial deposits across the district. The sections show the changing character of the superficial cover across the district and illustrate the superficial-bedrock relationships along key linear features, such as the Manchester Ship Canal. Sections in the Trafford Park area are located in areas of particular interest to the Environment Agency.

The sections are annotated to indicate where potential pathways from ground surface to an underlying aquifer are likely to exist, and where pathways are likely to be restricted due to weakly permeable deposits. The annotations identify:

- direct pathways to bedrock (i.e. rockhead at outcrop);
- pathways via permeable superficial strata (as identified in Table 4);
- lateral potential 'drainage' pathways in perched permeable strata and artificial ground

The pathways are drawn on the following assumptions:

- All weakly permeable deposits less than 5 m in thickness may still offer a potential pathway due to weathering or discontinuities and are classified as permeable;

- Made ground is highly heterogeneous and of variable thickness, therefore its impact on vulnerability and recharge is difficult to define, and consequently it is treated as permeable to give a 'worst case' scenario;
- Permeable strata situated on greater than 5 m of low permeability strata (e.g. glaciolacustrine clay) are classified as perched.
- Pathways take no account of groundwater head gradients

Because groundwater head gradients have not been considered in detail, the potential pathways indicated where 'perched' water may be present should be considered more as 'drainage pathways in these deposits. Despite this, the groundwater levels within the Permo-Triassic aquifer for 2000 (Ruxton and Bennet, 2000) have been added to the sections for information.

The basal architecture of the identified permeable superficial deposits has been annotated to indicate potential lateral pathways (Map 2). 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 underlying strata (i.e. permeable, or weakly permeable) and prevailing hydraulic conditions. These plans are to be used in conjunction with the cross-sections to give an indication of the 3D relationships.

Together, the cross-sections and plans allow a better understanding of the likely vulnerability to the underlying aquifer associated with principal features and areas of interest:

Manchester Ship Canal

Cross-section 8 follows the Manchester Ship Canal and indicates that the feature is predominantly in contact with the Permo-Triassic sandstone. There are small patches of river channel deposits along the canal, and are associated with the former River Irwell. Till wedges occur at the western extent of the canal and near to Salford Quays, and may have the effect of locally reducing aquifer vulnerability and recharge. Cross-sections 1 and 2 identify rockhead at outcrop, or covered by thin till, to the north of the canal with the aquifer likely to be highly vulnerable in this area. The till thickens to the east (cross-section 3) and is dominant to the south of the canal, with outwash deposits perched above. There are several lenses of sand and gravel identified within the till, however the extent and connectivity between these lenses are not clearly defined.

The groundwater surface in the Permo-Triassic sandstone aquifer is above the base of the canal (cross-section 8) and it is likely that they are hydraulically connected (except where the canal base is excessively silted, or if it has 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, and requires detailed investigation.

River Mersey

Varying thicknesses of overbank alluvium and river channel deposits occur along the River Mersey (cross-section 10); however it is likely that the majority of the river is in hydraulic contact with the underlying Permo-Triassic sandstone aquifer, except where thick till is identified below the alluvium. The groundwater level within the sandstone occurs within the alluvial deposits; however an accurate river water level is required to indicate if the aquifer is recharged by, or discharges to, the river.

River Medlock

Cross-section 5 follows the course of the River Medlock, and identifies thin superficial deposits on a rockhead high (Coal Measures, and Permo-Triassic sandstone) to the east, with aquifer recharge and vulnerability likely to be high in this area. In the west the superficial deposits thicken with outwash deposits and River Terrace deposits mainly on till. The till deposit reduces the aquifer vulnerability, but may result in perched groundwater within the overlying permeable superficial deposits, possibly with lateral movement, based on basal architecture of the deposits, to the west.

Groundwater levels in the Permo-Triassic sandstone are below the base of the River Medlock and indicate that aquifer recharge may occur along this feature. However, the River Medlock is largely culverted downstream of Bradford, which is likely to reduce recharge.

East Manchester

There is a thickening of till strata in the east of Manchester (cross-sections 6 and 7), which are likely to reduce the vulnerability, and recharge to, the underlying aquifer. Several permeable sand and gravel lenses have been identified within the till which may act as perched aquifers; however the connectivity of these units from ground surface to aquifer is uncertain.

Trafford Park

The Trafford Park area is mostly covered by till, glaciolacustrine clay, and perched outwash deposits (cross-sections 2, 9, and 11). Several sand and gravel lenses are identified within the till strata, however the connectivity between these units is uncertain. There is a rockhead high to the north of Trafford Park with a thin till and outwash deposit cover. Aquifer vulnerability is likely to be greatest at this rockhead high, and decreasing to the south due to thick till and glaciolacustrine clay deposits. However, the large cone of depression centred in Trafford Park has the effect of locally making the aquifer unconfined beneath the till, where naturally it would be generally 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 could indicate hydraulic connection between the aquifer and the canal, however the pumping rate at this location is not currently known.

The cross-sections and plans have given an indication of the likely aquifer vulnerability along linear features (i.e. Manchester Ship Canal), and the potential lateral pathways within the permeable superficial strata (based only on the deposit architecture). However the purpose of the geological model has been to give a 3D understanding of the environment. In order to identify the changes in aquifer vulnerability spatially, based on the superficial strata, a series of hydrogeological domains have been created.

6.3.3 Hydrogeological domain mapping

The use of domain mapping in this context is now well established, particularly at catchment scale or larger (McMillan et al, 2000). The domain concept is used to identify if pollutants, or potential recharge, are able to migrate to the regional major aquifer (Permo-Triassic sandstone) or minor aquifer (Coal Measures) or are impeded by impermeable strata. The domain concept utilises the classification of superficial deposits and their inferred permeability to define their likely vulnerability.

6.3.3.1 Domain Methodology

The hydrogeological domains have been created to identify the likely level of aquifer vulnerability and are ranked in order of increasing potential recharge/decreasing vulnerability

(Table 5). The greatest aquifer recharge potential and vulnerability is assigned where a bedrock aquifer (major or minor) is at outcrop (Domain 1). Decreasing recharge and vulnerability is assumed where one or more layers of permeable superficial strata overlie the aquifer. These domains have been placed into Groups according to whether they overlie a major aquifer (Permo-Triassic sandstone), or minor aquifer (Coal Measures).

The occurrence of permeable strata overlying thick weakly permeable strata, or on non-aquifer bedrock (Manchester Marls) is defined as perched permeable strata. This group is ranked below the major and minor aquifer group as there is a lower likelihood of a vertical pathway to an aquifer, and consequently the aquifer is less vulnerable. The lower vulnerabilities are assigned to weakly permeable deposits (Aquitard group) as defined by estimated hydraulic conductivity values (Table 5), and the non-aquifer (Manchester Marls) domain.

The domains have been divided into sub-domains based on the type of superficial deposit included within each domain (i.e. alluvial river channel deposits, river terrace deposits, outwash sheet deposits, basal sand and gravel deposits, and glaciolacustrine sand and silt deposits) and have been ranked in order of decreasing aquifer vulnerability according to hydraulic conductivity range estimates (see Table 4).

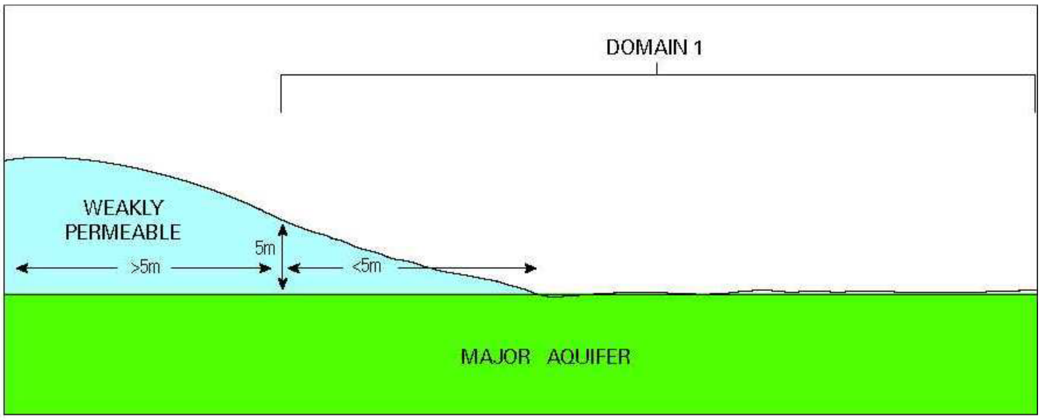
The domains have been created by interrogating grid data for the main superficial strata using the spatial analyst extension in Arc-8 to determine the vertical connectivity between lithological units, and to identify potential pathways to the underlying aquifer. The domains adhere to the same "rules" outlined earlier, whereby low permeability strata less than 5 m in thickness is still a potential pathway, and all made ground is classified as permeable. The DTM has been adjusted to the elevation of the base of made ground as there is currently no made ground domain due to its highly heterogeneous nature, and a lack of detail regarding composition and permeability. It should also be noted that leakage through sewers, water pipelines and soakaways may form a large proportion of the water balance of perched aquifers within the superficial deposits and may result in point or line source recharge which may not relate to the hydrogeological domains.

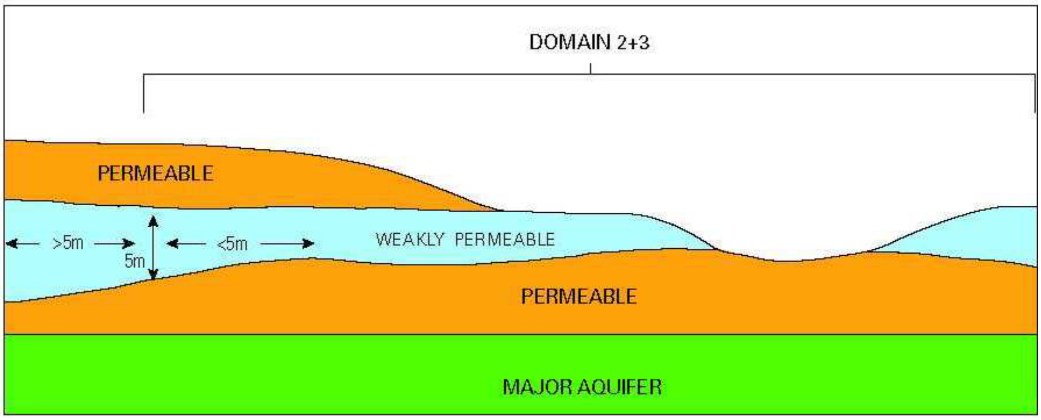
6.3.3.2 Domains

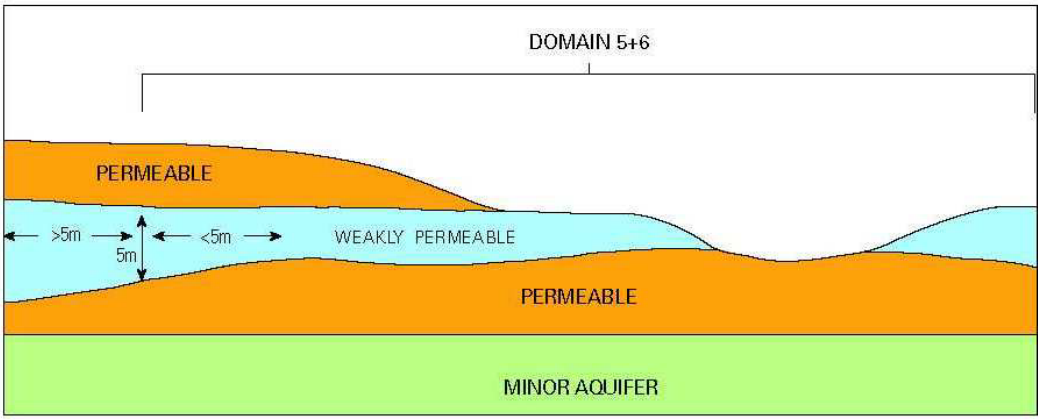
A total of nine hydrogeological domains and 25 sub-domains have been created for the project area. The nine hydrogeological domains are listed in Table 5, explained in Figure 18 and portrayed schematically in Figure 19 and Map 3.

	Group	Domain		Sub-Domain	
Highest	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 Late glacial flood gravels)
				2d	Basal gravel deposit
				2e	Glaciolacustrine sands and silts
		3	Multiple permeable superficial deposits	3a	River channel deposits and basal gravel deposit
				3b	River terrace deposits and basal gravel deposit
				3c	Outwash sheet deposits basal gravel deposit
				3d	Glaciolacustrine sands and silts and basal gravel deposit
Decreasing potential recharge and aquifer vulnerability	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 deposit
				5d	Glaciolacustrine sands and silts
		6	Multiple permeable superficial deposits	6a	Glaciolacustrine sands and silts and basal gravel deposit
	Perched aquifer	7	Perched permeable superficial strata	7a	River channel deposits
				7b	River terrace deposits
				7c	Outwash sheet deposits
				7d	Glaciolacustrine sands and silts
	Aquitard	8	Low permeability superficial strata	8a	Alluvium (overbank deposits)
				8b	Till
				8c	Glaciolacustrine clay
Lowest	Non Aquifer	9	Non-aquifer bedrock strata	9a	Manchester Marls formation

Table 5 Hydrogeological domains


DOMAIN 1
WEAKLY
PERMEABLE
5m
>5m
<5m
MAJOR AQUIFER


DOMAIN 2+3
PERMEABLE
>5m
<5m
5m
WEAKLY PERMEABLE
PERMEABLE
MAJOR AQUIFER


DOMAIN 5+6
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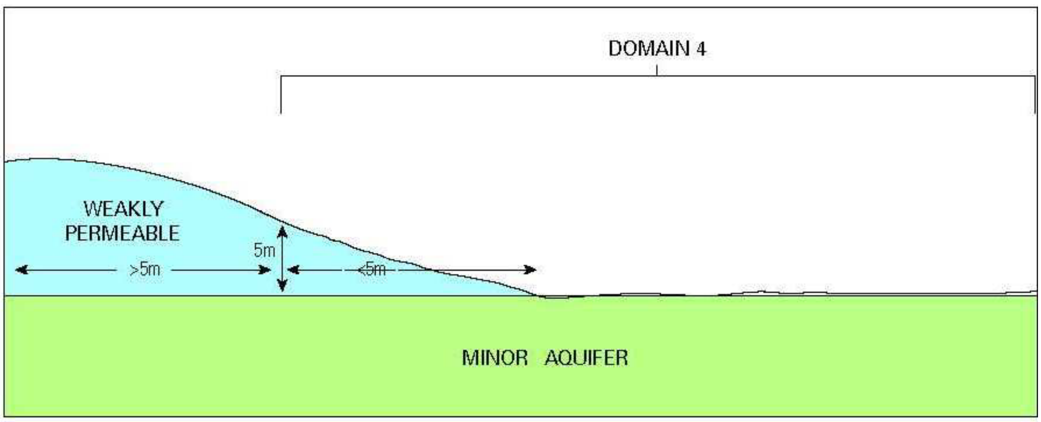
5m
WEAKLY PERMEABLE
PERMEABLE
MINOR AQUIFER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PERMEABLE
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MINOR AQUIFER

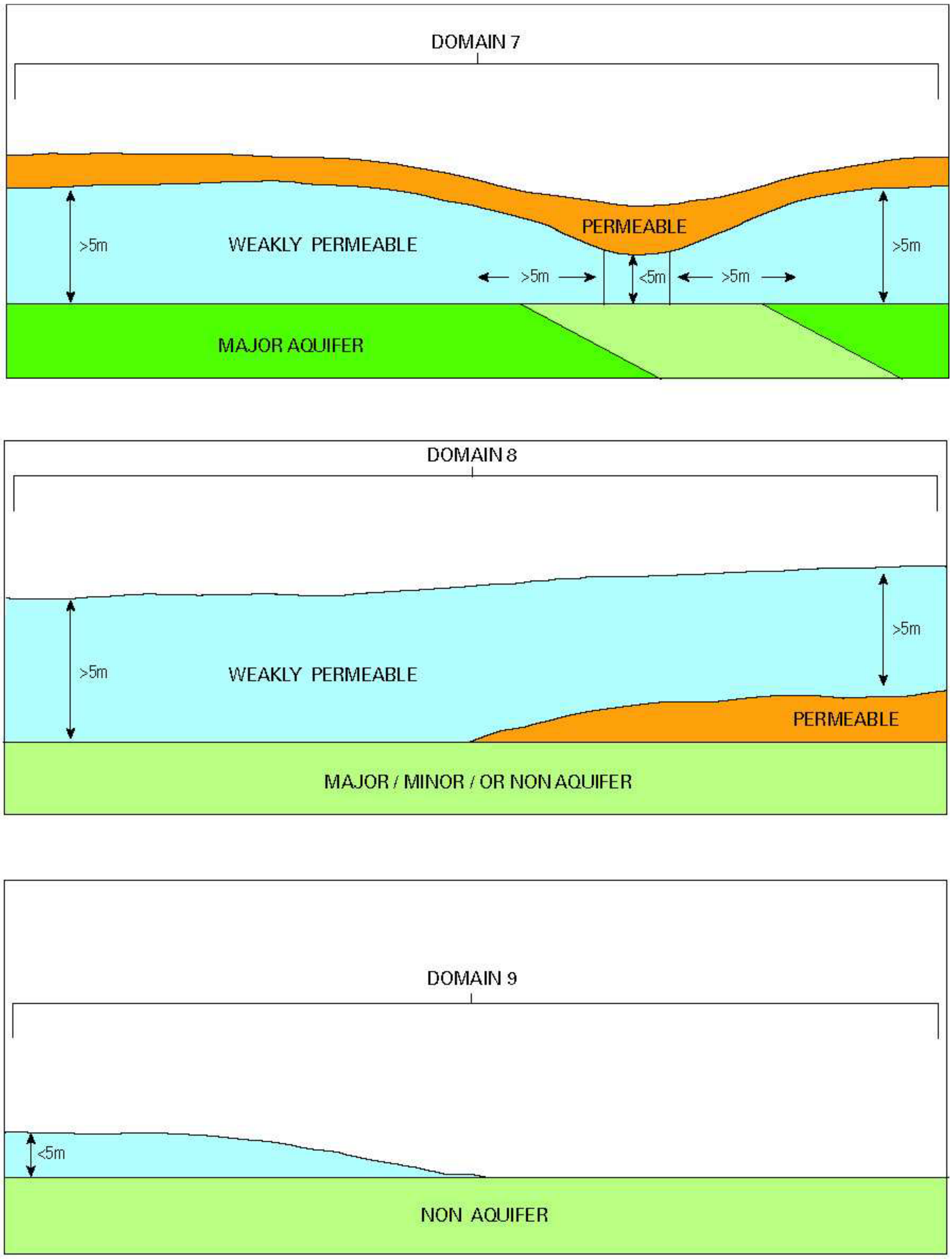

Figure 18 Hydrogeological domains (schematic)

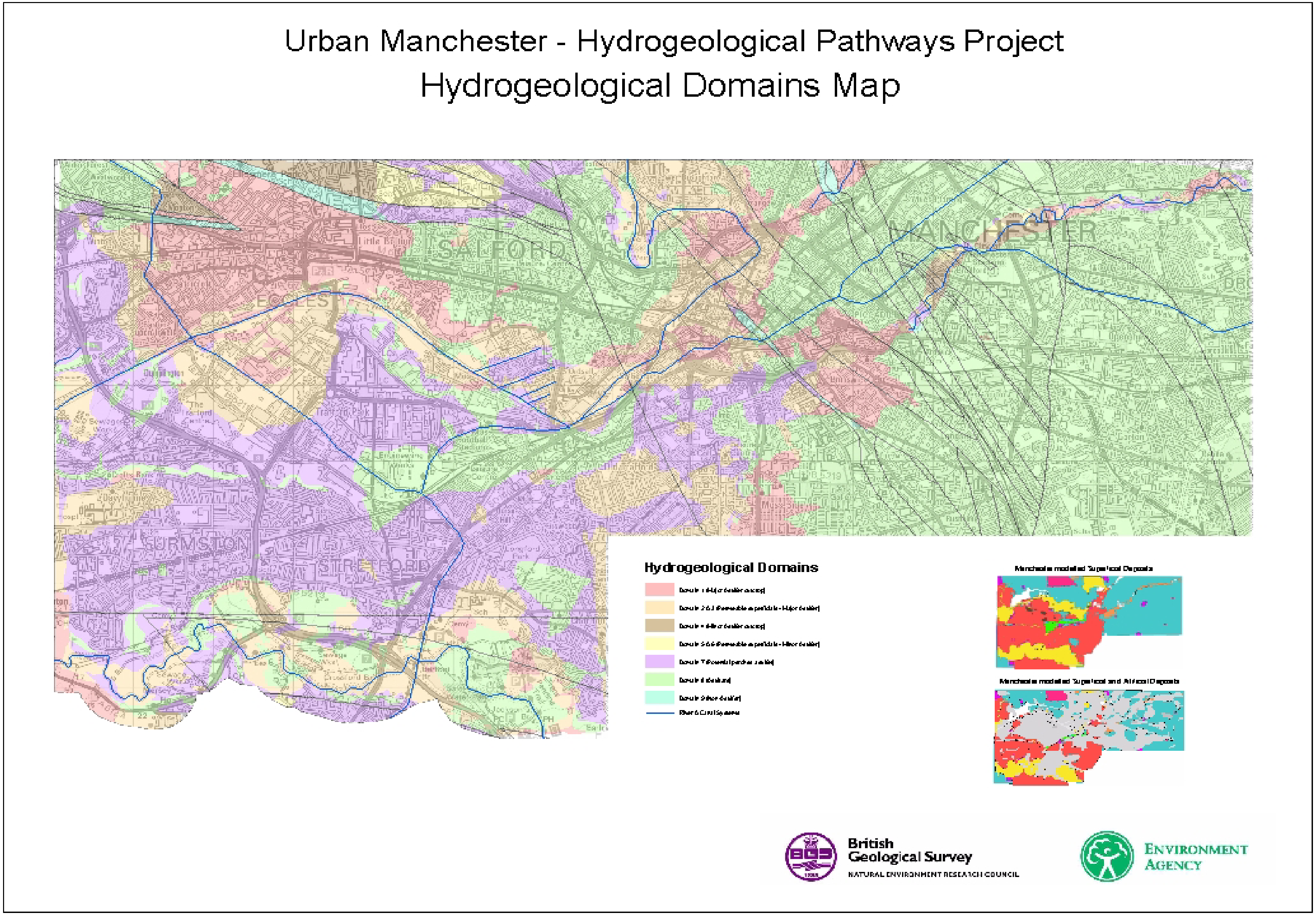

Figure 19 Hydrogeological domains in Manchester area

Domain 1: 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, in this domain. This domain is most extensive in 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 10-15 m below ground level (see cross-section 2) on higher ground to the north of the canal. The water level within the canal and its variation has not been measured as part of this study and no attempt has been made to identify if this feature is recharging, or being recharged by, the aquifer (see section 8).

Further smaller outcrop areas are identified to the east in the city centre and are associated with rockhead highs, and an absence of alluvium and river terrace deposits.

Domain 2 and 3: Major Aquifer, permeable superficial deposit and multiple permeable superficial deposits

Permeable superficial strata in contact with, or less than five metres above, bedrock are commonly associated with alluvium in the incised River Irwell and River Mersey valleys. Outwash sheet deposits (lgfg) are generally above thick till or lake clay deposits; however they are directly on (or less than 5 m above) bedrock on a rockhead high to the north of Trafford Park and also to the north and south of the city centre. River Terrace deposits are in contact with (or less than 5 m above) bedrock within the River Medlock valley, however these are mainly small areas with the majority of the valley directly in contact with bedrock (Permo-Triassic sandstone and Coal Measures). The glaciolacustrine sands and silts (glld_s) are mainly situated on Coal Measure strata; however there is a small area that is on Permo-Triassic sandstone. The deposit is largely underlain by thin till, and the steep basal architecture of the deposit may promote lateral pathways, depending on till integrity. The buried valley channel fill deposits are always in contact, or less than 5 m above, bedrock, but these deposits are rarely less than five metres below the ground surface (taken from the base of the made ground) and generally occur as small patches, for example adjacent to the River Irwell valley to the north of the city centre.

Multiple permeable strata occur where permeable deposits overlap, for instance, basal sand and gravel deposits (gfdu_b) below river channel deposits (alv_2), as occurs around Salford Quay. The multiple permeable superficial deposits may reduce the aquifer recharge and vulnerability compared to single permeable strata as there could be up to five metres of low permeability strata between permeable features, and vertical pathways may be longer; however, at this stage they are joined into one domain for the domain map.

Domain 4, 5, and 6: Minor aquifer, outcrop, permeable superficial deposit

The Coal Measures minor aquifer is found as two east-west wedges in the northwest of the project area, and a large north-south wedge in the east. Bedrock is mainly at outcrop in the west, except where thick till and glacial lake sands are identified. Glaciolacustrine sands and silts (glld_s) are partly in direct contact with bedrock, however, as identified in Domain 2, the deposit is largely underlain by thin till, and the steep basal architecture of the deposit may promote lateral pathways, depending on till integrity.

The wedge of Coal Measures strata in the east is extensively covered by thick till, except along the River Medlock where bedrock is at outcrop or covered by intermittent river terrace deposits. There is an additional outcrop of Coal Measures strata at the northern edge of the project area associated with the River Irk.

Domain 7: Perched permeable superficial deposits

This domain comprises of alluvial river channel deposits (alv_2), outwash sheet deposits (lgfg), glaciolacustrine sands and silts (glld_s), and river terrace deposits (rtdu). The outwash deposits form the most extensive strata as they are largely underlain by glaciolacustrine clays and/or till.

It is assumed that in perched domains there is likely to be little vertical recharge to the underlying aquifer and that migration is likely to occur laterally. The pathways are estimated based on the architecture of the deposit base, in the absence of groundwater head data. The base of the outwash deposits slope gently to the west, with slight deviations towards river valleys (River Mersey, and Bent Lanes Brook).

Alluvial river channel deposits occasionally rest above weakly permeable deposits along the River Irwell where till wedges occur (e.g. Salford Quays and at the western boundary to the project area). It is likely that lateral pathways will exist from these areas to areas where alluvium is in direct contact with bedrock (not accounting for groundwater head gradients). More extensive alluvium is located at the margins of the River Mersey valley, with lateral pathways are likely to be orientated towards the river, where pathways exist to bedrock.

The northern and eastern margin of the glaciolacustrine sands and silts rest on bedrock, with lateral pathways likely to be towards permeable strata in contact with bedrock (principally Coal Measures), except in the east where pathways may be onto weakly permeable deposits.

The river terrace deposits are perched only in the north adjacent to the glaciolacustrine sands and silts, and intermittently along the River Medlock.

The lack of accurate data about perched groundwater levels within superficial strata means that it is not possible to accurately predict lateral pathways. However it can be assumed that pathways in perched alluvial aquifer on the edge of valleys are likely to be towards the associated river, based on the base architecture of the deposit (this does not account for groundwater head gradients). Also, groundwater is likely to form a contiguous surface in connected alluvial bodies regardless of the domain (i.e. groundwater is likely to be connected between alluvial bodies which are in direct contact with bedrock).

Pathways in the relatively flat outwash deposits are less easily defined and are likely to be reliant on groundwater head gradients in these deposits.

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 reduce vertical recharge and promote runoff. The glaciolacustrine clay deposit comprise laminated, stone free, clays, however they are generally less than five metres in thickness and are largely covered by outwash deposits. Consequently there are only small isolated areas where the glacial lake clay is greater than five metres in thickness and not overlain by outwash deposits.

Thick (>5 m) overbank alluvium occurs intermittently along the River Irwell valley, and extensively along the River Mersey valley. Runoff is likely to be orientated towards the associated river (not accounting for land drains etc) and permeable deposits in contact with the underlying aquifer.

Till is the most extensive weakly permeable deposit and is up to 45 m thick in the east of the project area. The till composition generally comprises stiff sandy clay, however is highly variable and there are also ice contact sand and gravel lenses within the till. The heterogeneity of the till and the presence of sand and gravel lenses gives a level of uncertainty in the assumption that the till is weakly permeable. The lateral extent, and potential connectivity between the sand and gravel lenses has not been delineated sufficiently for them to be treated as separate units. It is likely that greater than 5 m of till is likely to significantly reduce recharge, however it is possible for pathways to exist through interconnected sand and gravel lenses within the till.

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 (see section 3.1). Domain 9 has been created to identify where the Manchester Marls are at outcrop, with small outcrop in the northwest and central parts of the district. In the central area of the district there are also permeable superficial deposits (i.e. lgfg) overlying the Manchester Marls. This is essentially a perched aquifer (permeable deposit on weakly permeable deposits) and has been included in the perched permeable superficial deposit domain (Domain 7). The extensive Manchester Marls sliver in the east of the district has not been included within Domain 9 as it is overlain by thick till deposits (Domain 8).

6.3.4 Uncertainty

In Section 4.6 the uncertainty associated with building the model was introduced. There is likely to be further uncertainty associated with the delineation of the hydrogeological domains. Borehole densities have been calculated for each domain (Table 6), which give an indication of the number of available boreholes used to construct each domain. A distinction is drawn between boreholes that partially penetrate each domain and those that fully penetrate. The domain map is likely to be suitable for planning decisions at catchment and sub-catchment scale.

	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
Domain 9	N/A	N/A	N/A	N/A	N/A	N/A*

Table 6 Borehole density by domain

* no statistics were available for Domain 9

7 Land Use

Land use studies were undertaken to assist in determining the likely distribution of potentially contaminated ground.

7.1 PRESENT-DAY LAND USE

The project area 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) (Figure *). The scheme is hierarchical and based on 13 main land use types, or 'divisions' but allows for a further 51 'classes' and 431 'subclasses' to be defined. The Manchester district was classified to division level, but further subdivided in two classes (recreation, and industrial and commercial) to aid interpretation of other related data (Table 7).

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 7 Present-day land use classification scheme

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 (Andrew Taylor, 2001).
- From air photographs 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 x 50 m) was used to enable effective coverage of the area. Only those watercourses indicated on OS base-maps by a double line with a water-fill on a 1:50 000 scale basemap were not digitised. Only roadways designated as motorways or A-roads were extracted. Railways were taken to include the full extent of the embankment and/or cutting.

The current land use map of the area shows a concentration of industrial and commercial land uses concentrated in the Trafford Park, Weaste, Manchester city and Strangeways, Bradford and Openshaw districts. Residential areas are for the most part restricted to the periphery of the area. 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.

7.2 PAST POTENTIALLY CONTAMINATIVE LAND USE

The past potentially contaminative land use for three eras have been produced (Figures 20–22), with snapshots covering the late Victorian (1890s), inter-war (1920s) and immediate post-war (1950s) periods. The survey involved a trawl of legacy 1:1250 and 1:2500-scale Ordnance Survey data, 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 use into 20 categories and 57 sub-categories (Table 8).

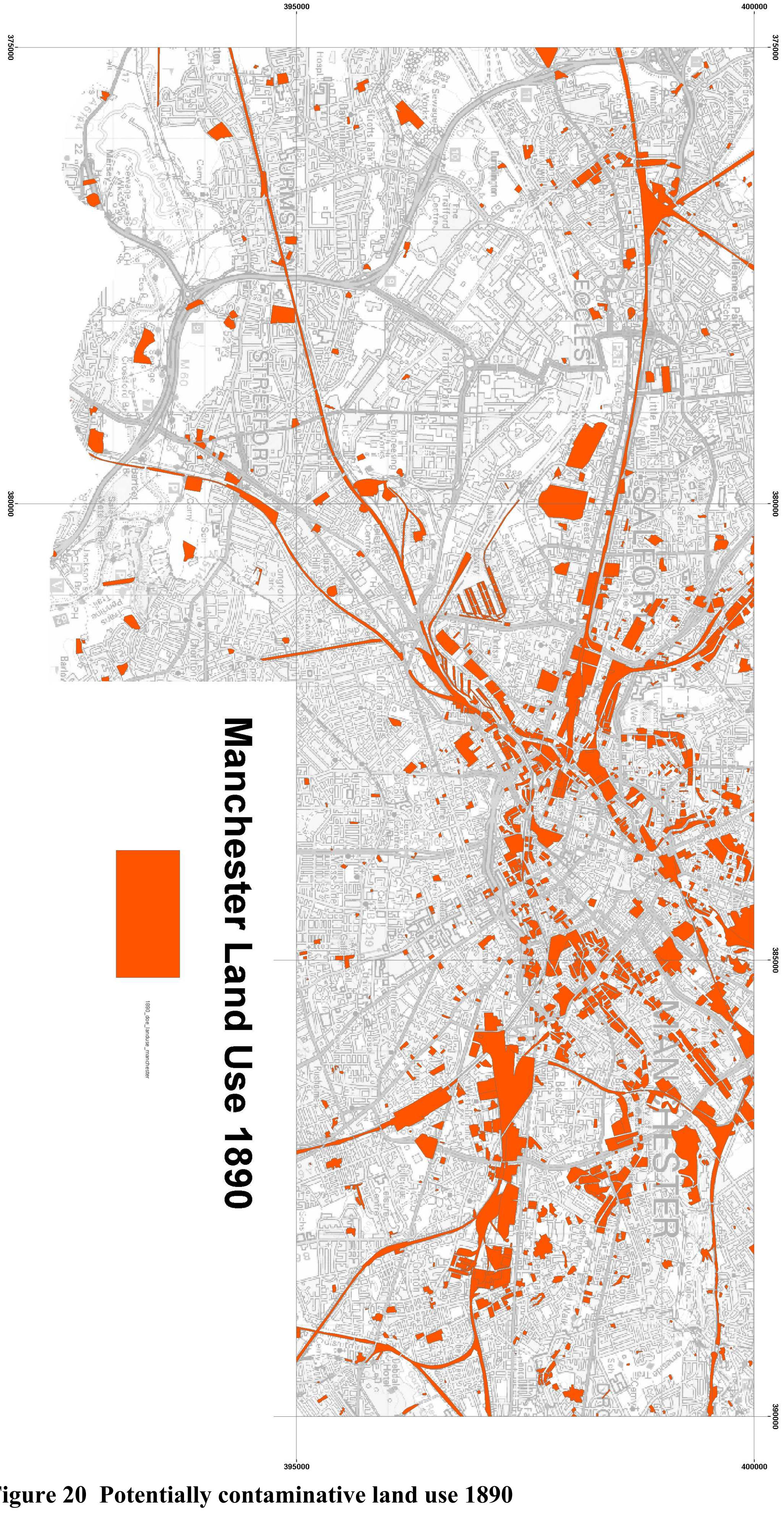

Figure 20 Potentially contaminative land use 1890

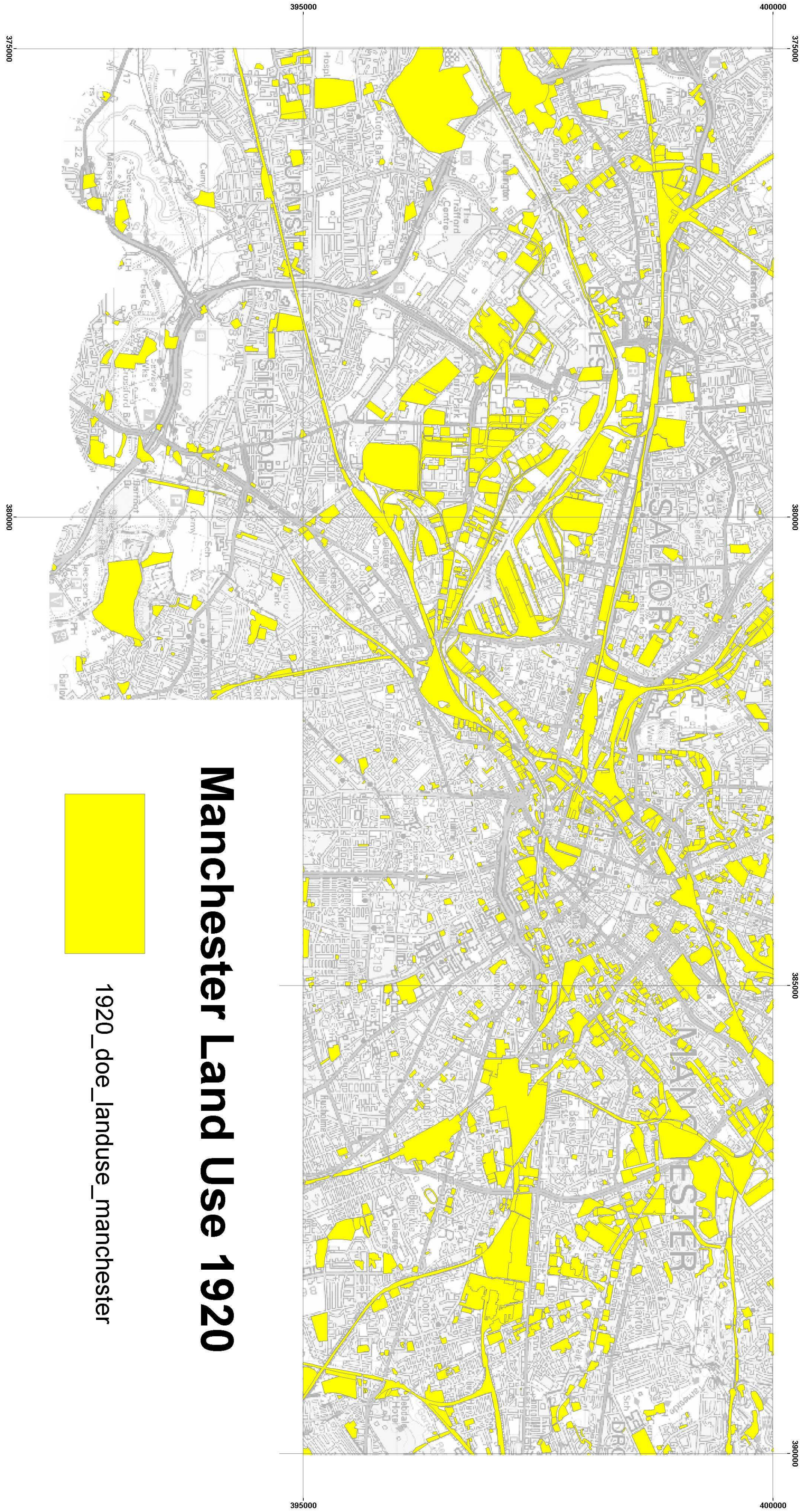

Figure 21 Potentially contaminative land use 1920

Figure 22 Potentially contaminative land use 1950

In addition to a land use category and sub-category, all sites identified were assigned a site 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 (Figure 20) 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 (Figure 21), Trafford Park had begun to develop, along with the Ordsall and Weaste areas north of the Ship Canal, in response to the opening of the Ship Canal. To the north of the city, the Strangeways area was becoming industrialised. In the south-west, the Davyhulme Sewage Works complex was opened in 1894, coinciding with the opening of the Ship Canal. The 1950s map (Figure 1950) shows a general expansion in industries across the area, but concentrated in the Eccles, Pendleton and St. George's-Hulme areas.

Table 8 Classification of past potentially contaminative industries

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

8 Conclusions and Recommendations

The 3D geological model of the intricate geometries of the superficial deposits provides a powerful, new approach to investigate the potential for aquifer recharge and gives an indication of aquifer vulnerability.

Study of this model has indicated that in the Manchester conurbation the potential pathways for pollution and recharge are mainly located along the Manchester Ship Canal and adjoining areas where bedrock is at outcrop or close to surface.

Thick till and, largely concealed glaciolacustrine (glacial lake deposits) clays and silts largely protect the major aquifer below Trafford Park, however, there is the potential for lateral migration via the outwash sheet deposits which are locally in contact with the aquifer.

The east of Manchester is dominated by thick tills, which are likely to reduce recharge and vulnerability, however, incised rivers in direct contact with bedrock may offer recharge pathways. The infilling of these valleys with made ground may result in flushing of associated contaminants into the aquifer. The model also identifies large areas of thick (up to 12 metres) man-made deposits especially around Salford Quays, near the Peel Green Road Sewage works and near the River Mersey.

In order to make best use of the outputs from this study, there is a need for a more detailed investigation into the distribution of shallow groundwater in the permeable superficial deposits. In the first instance attention this could be focussed in key areas.

The water levels in rivers and canals, in particular the Manchester Ship Canal, need to be related to surrounding groundwater levels, perhaps using selected modelled sections. More detailed studies of the potential leakage from or to the drainage and sewerage system also need to be undertaken.

There is considerable potential using soil geochemistry in combination with the made ground model and the historic land use data, to further develop site vulnerability assessments on the basis of a 'source- pathway- receptor' principle.

Future work in BGS will mainly focus on 3D property modelling. This will include attribution of the model with engineering and hydrological properties and an analysis of uncertainty. Work will also continue to finalise the GSI3D Analyst, which will enable the customer to view the model, derive predictive boreholes, slice and dice the model to specific requirements, and export grids and maps for further manipulation in other software.

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10 Appendix

Eleven computer generated cross-sections through the Manchester model

Map 1	Compilation of computer generated cross-sections
Map 2	Geometry and conceptual pathways of Superficial Aquifers
Map 3	Hydrogeological Domain Map

Inferred pathways in superficial deposits

Superficial Deposits	Inferred permeability
Artificial ground	Permeable
Alluvium (silt & clay)	Weakly permeable
Sub-alluvial gravel & gravelly sand	Permeable
Glaciofluvial sand & gravel	Permeable
Glaciolacustrine clay, silt & sand	Weakly permeable
Till	Weakly permeable
Ice contact undivided (till, clay, sand & gravel)	Unknown permeability

Bedrock	Aquifer Group
Sherwood Sandstone Group	Major aquifer
Manchester Marls Formation	Non-aquifer but included in major aquifer
Collyhurst Sandstone Formation	Major aquifer
Halesowen Sandstone Formation	Minor aquifer
Etruria Formation	Non-aquifer
Coal Measures Group	Minor aquifer

Modelled piezometric surface/water table in the Sherwood Sandstone Group [2000]

Direct pathway to aquifer

Pathway via permeable superficial deposits to aquifer

Pathway via <5m weakly permeable superficial deposits

Inferred pathway within permeable superficial deposits

Lateral pathway out of page

Lateral pathway into page

Permeable deposits on >5m weakly permeable deposits. Lateral migration based on base architecture of unit.

Key to fold-out sections

Conceptual pathways in Superficial deposits Manchester Section 1

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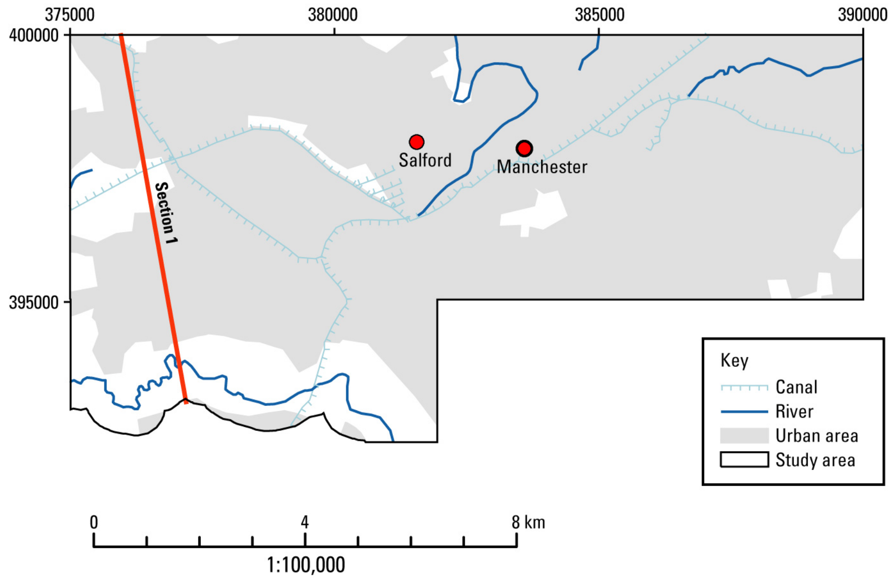

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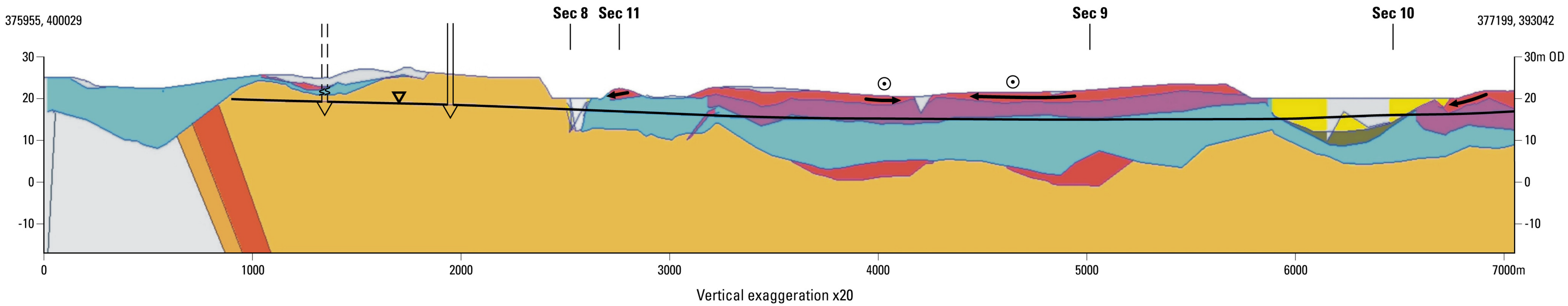

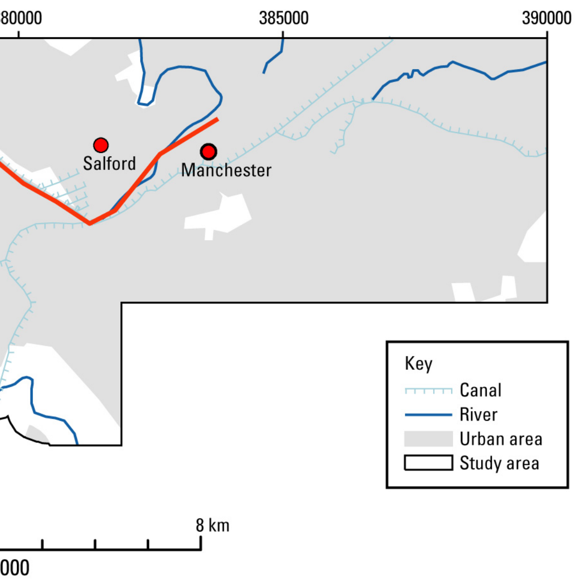

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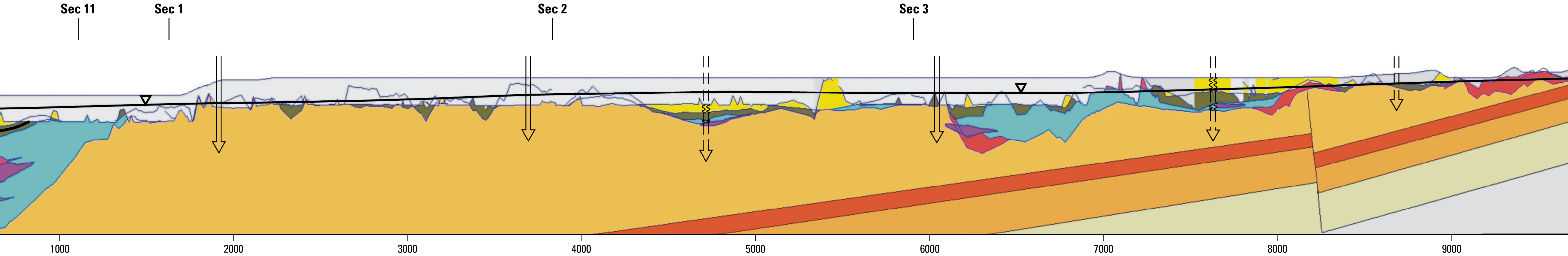

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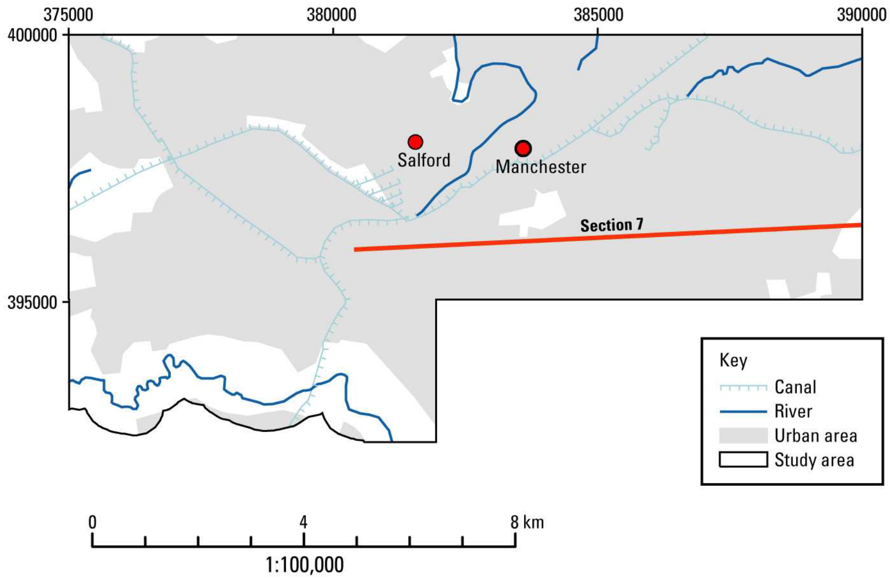

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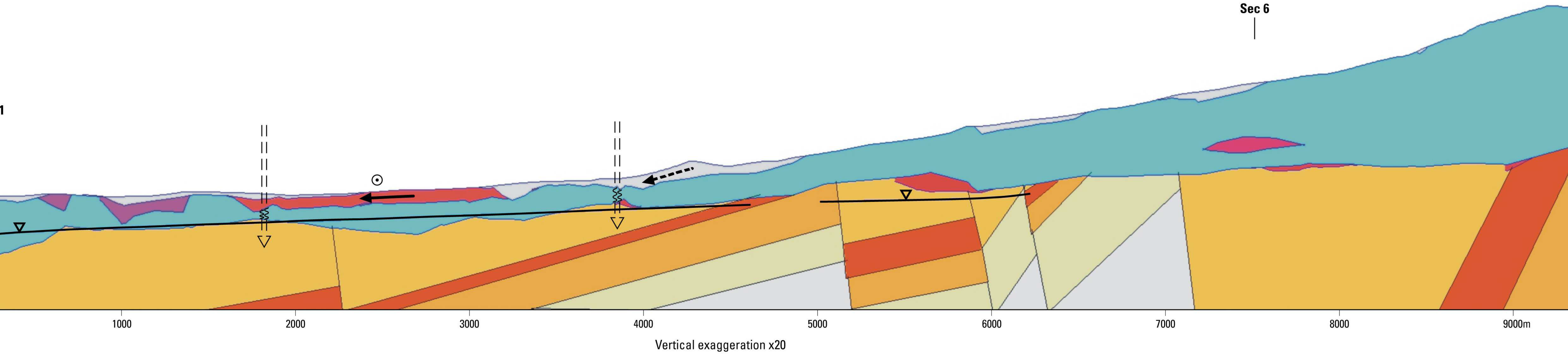

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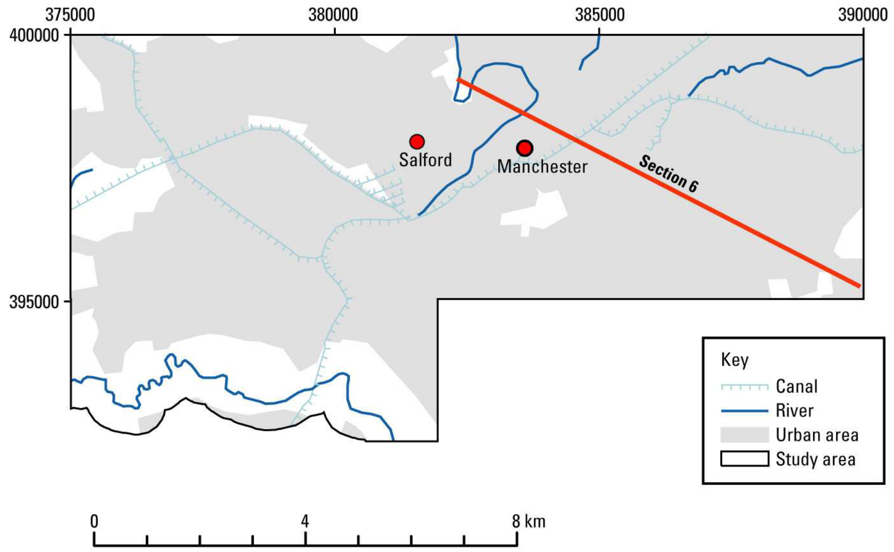

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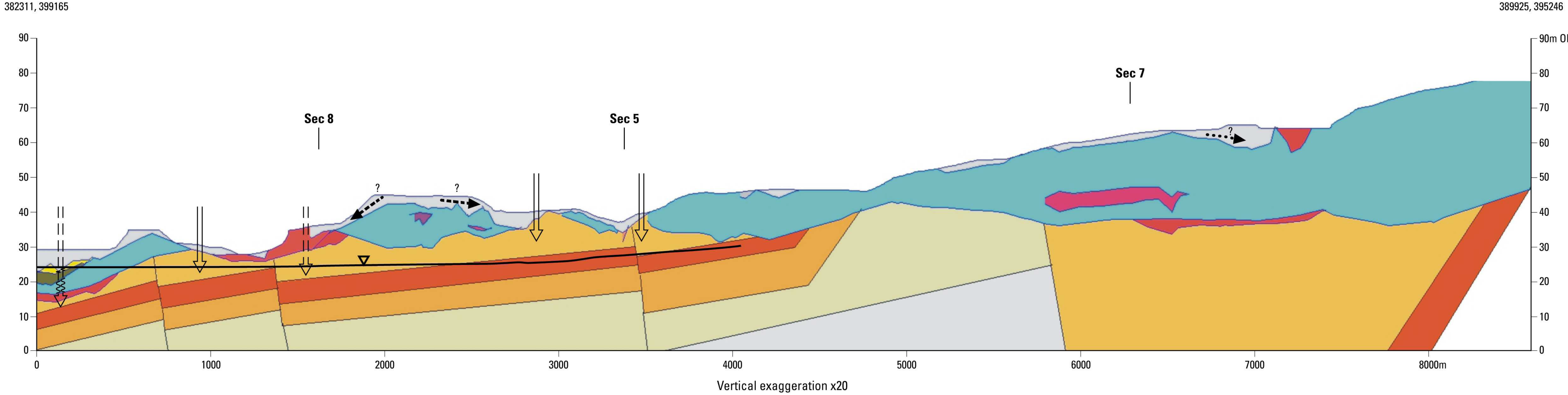

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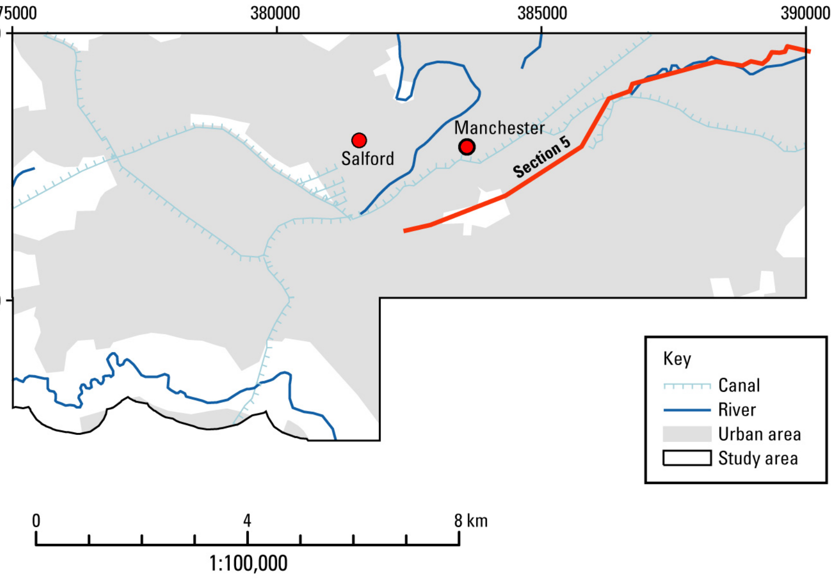

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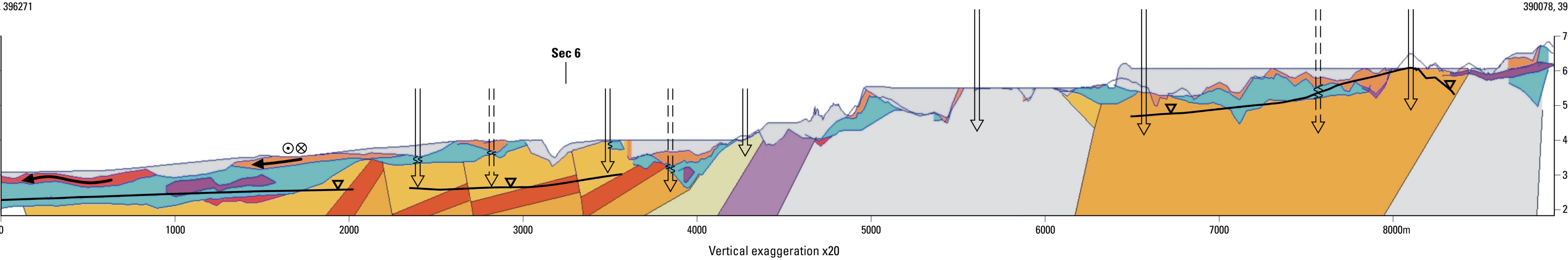

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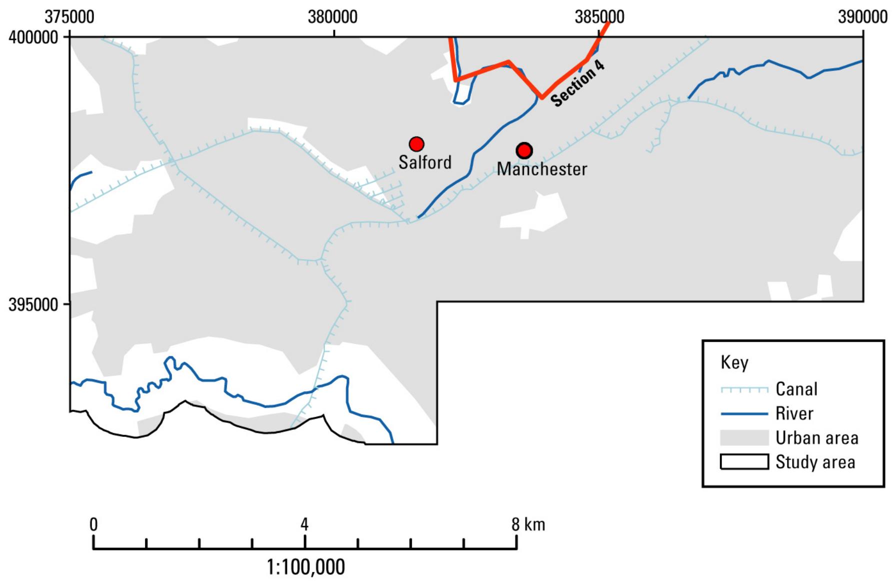

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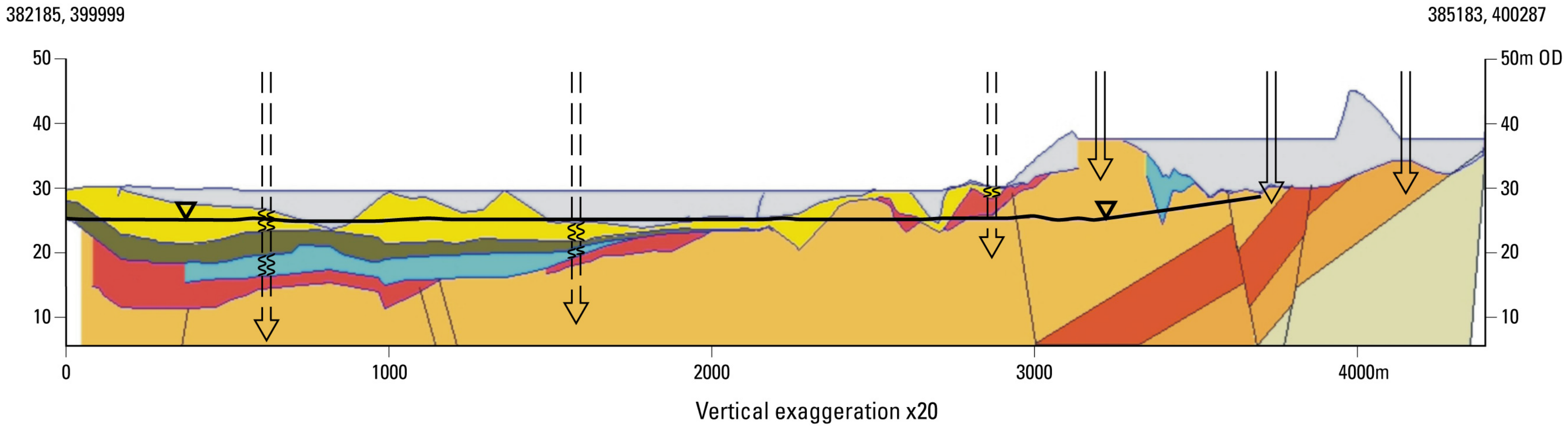

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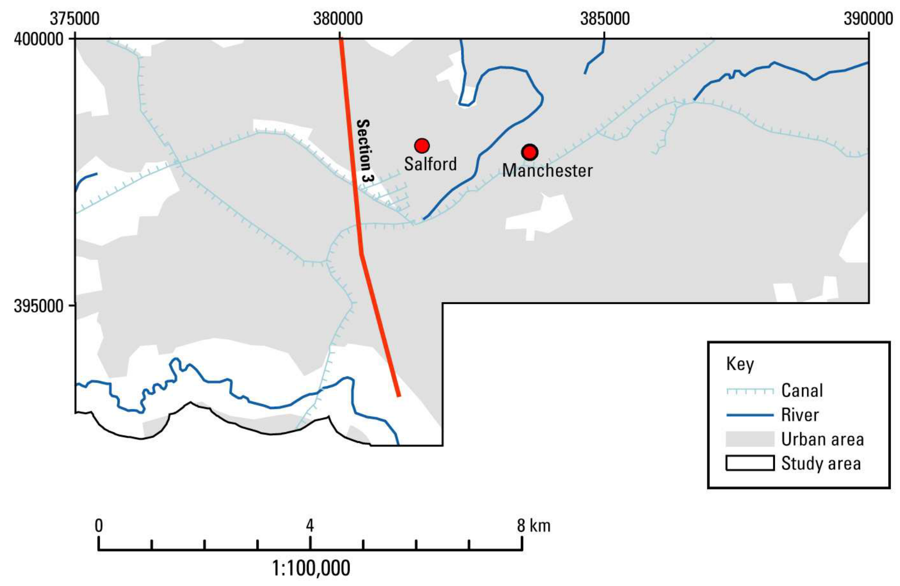

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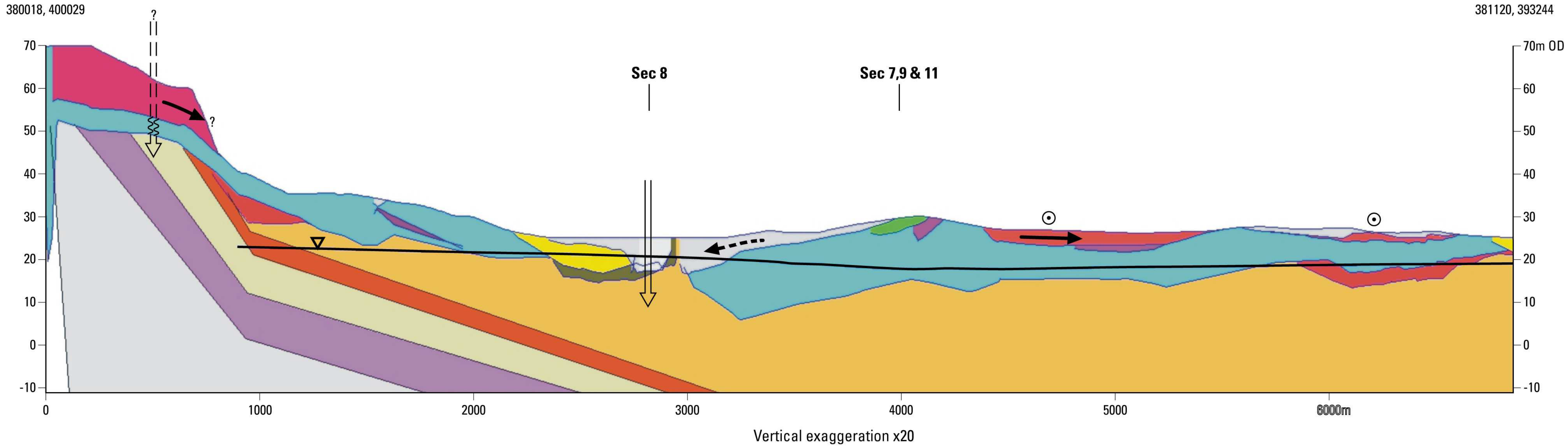

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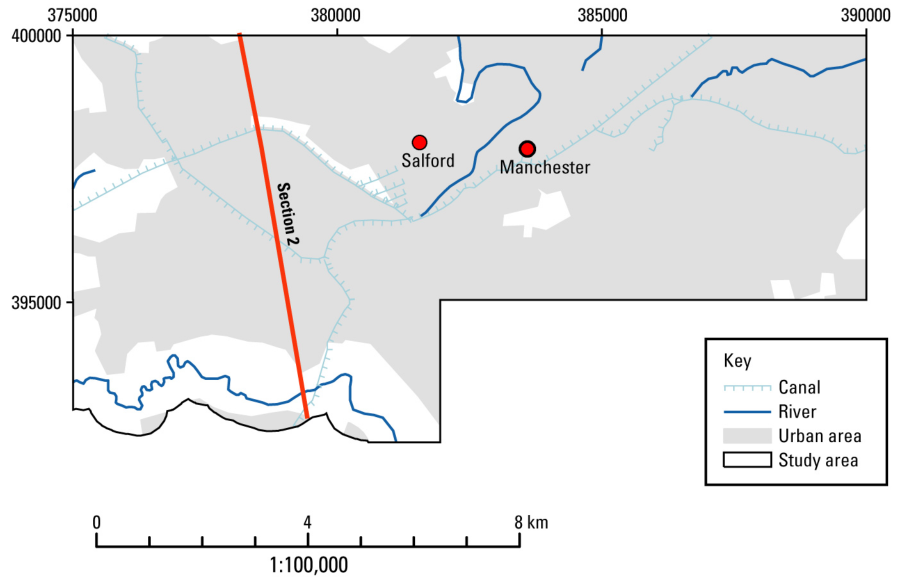

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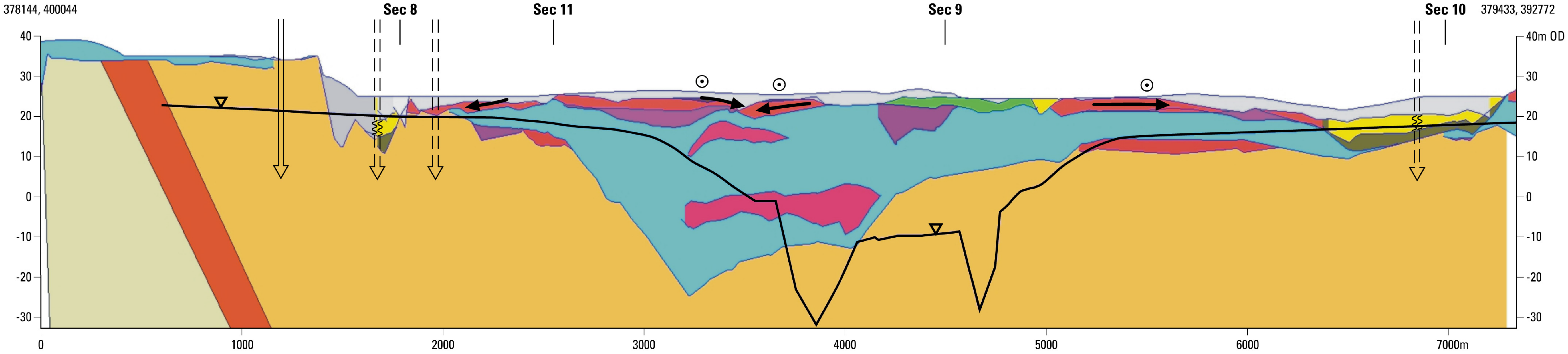

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Conceptual pathways in Superficial deposits Manchester Section 9

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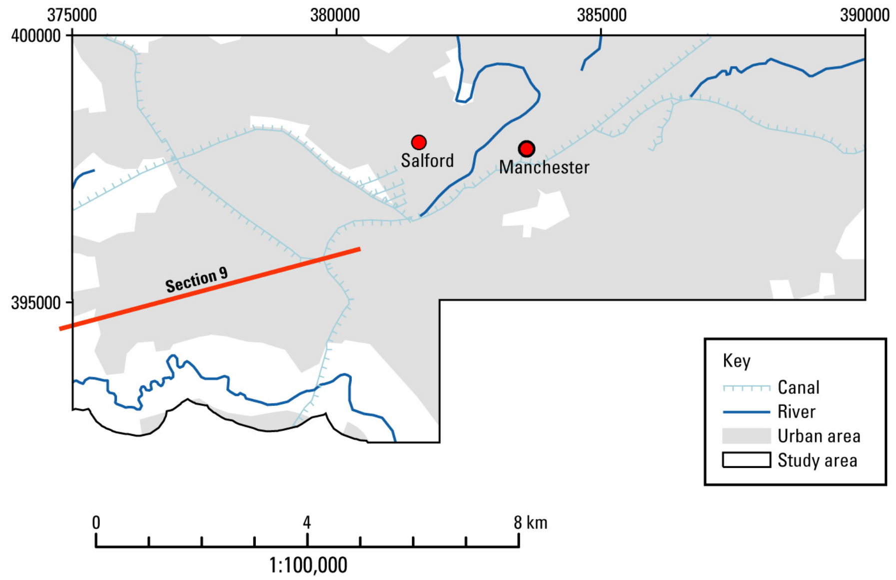

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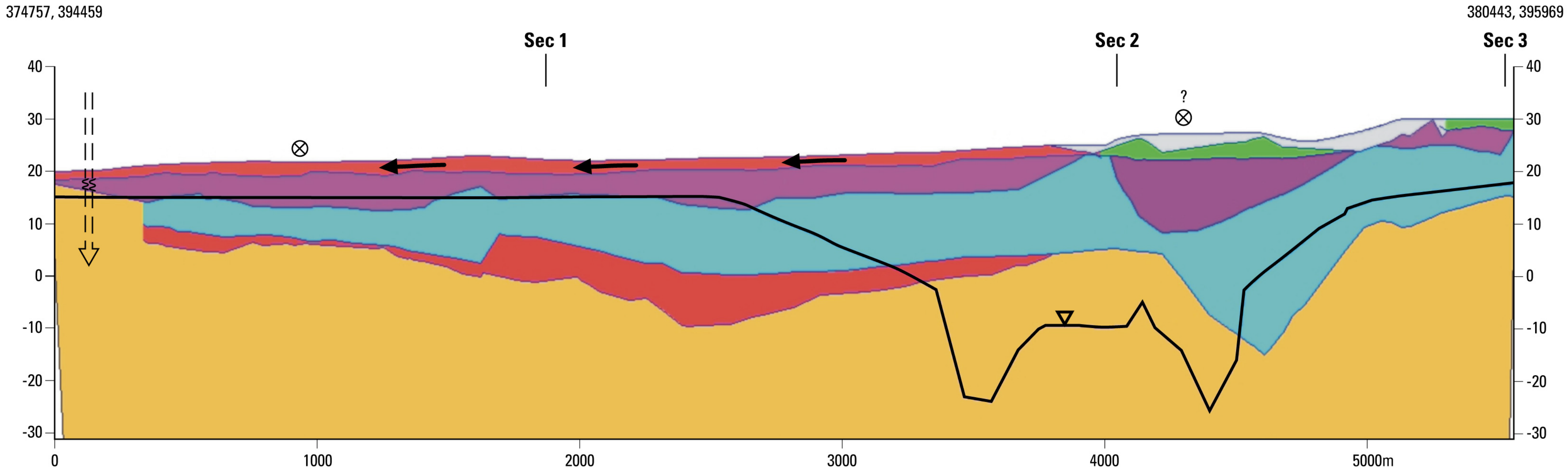

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Conceptual pathways in Superficial deposits Manchester Section 10

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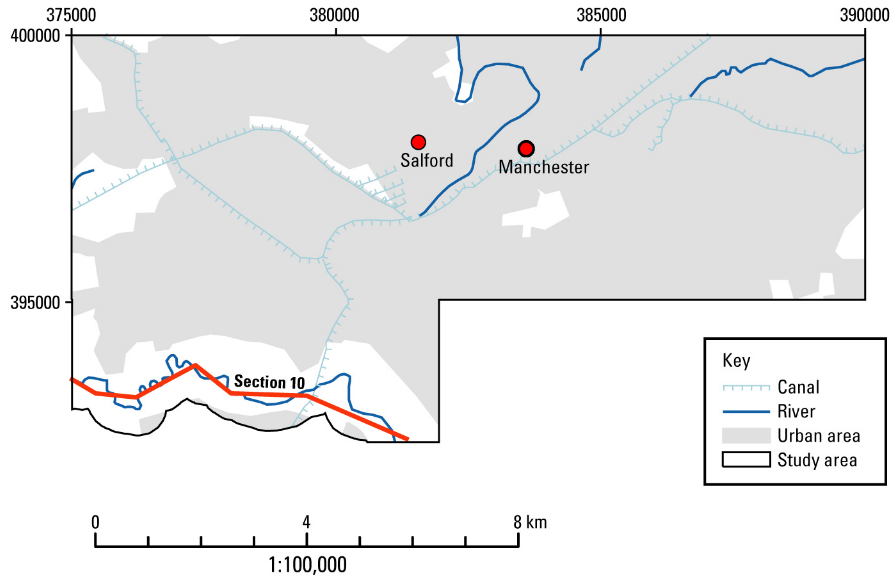

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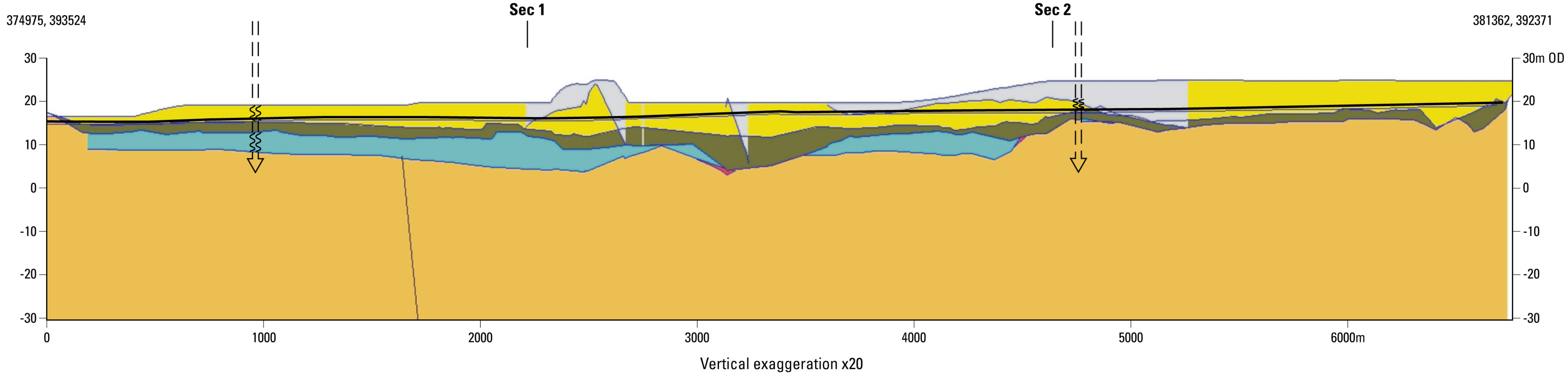

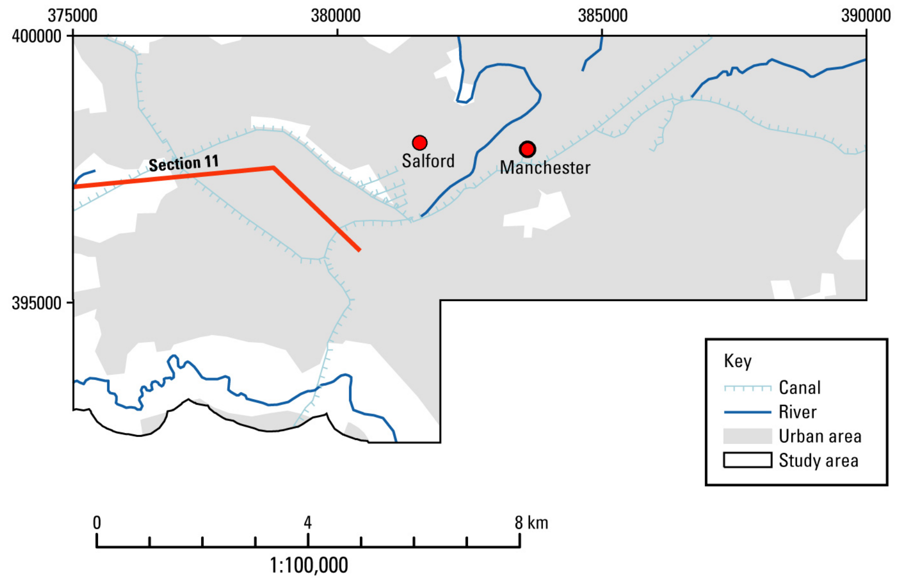

Conceptual pathways in Superficial deposits Manchester Section 11

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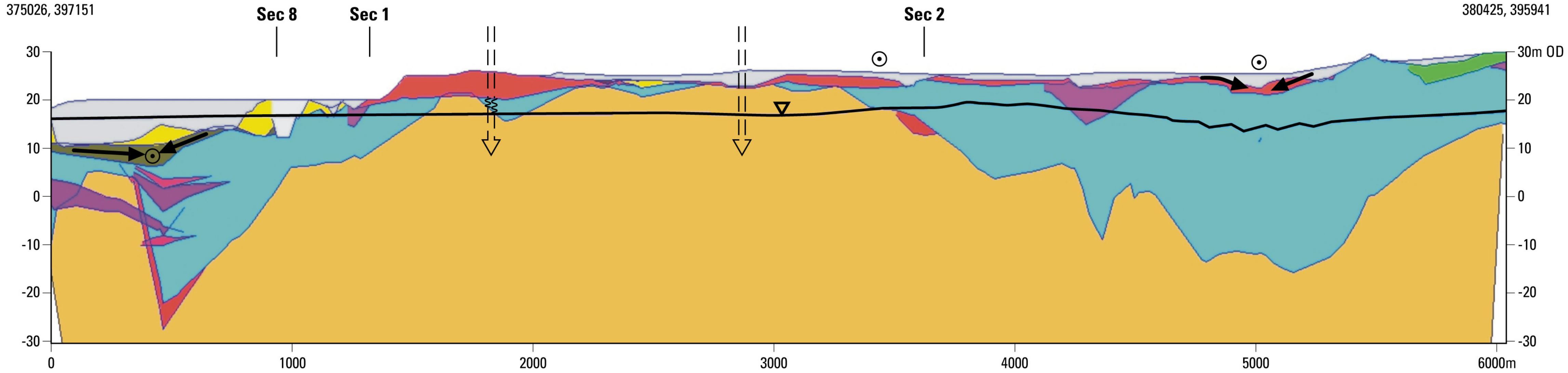
Manchester Section 11



Vertical exaggeration x20

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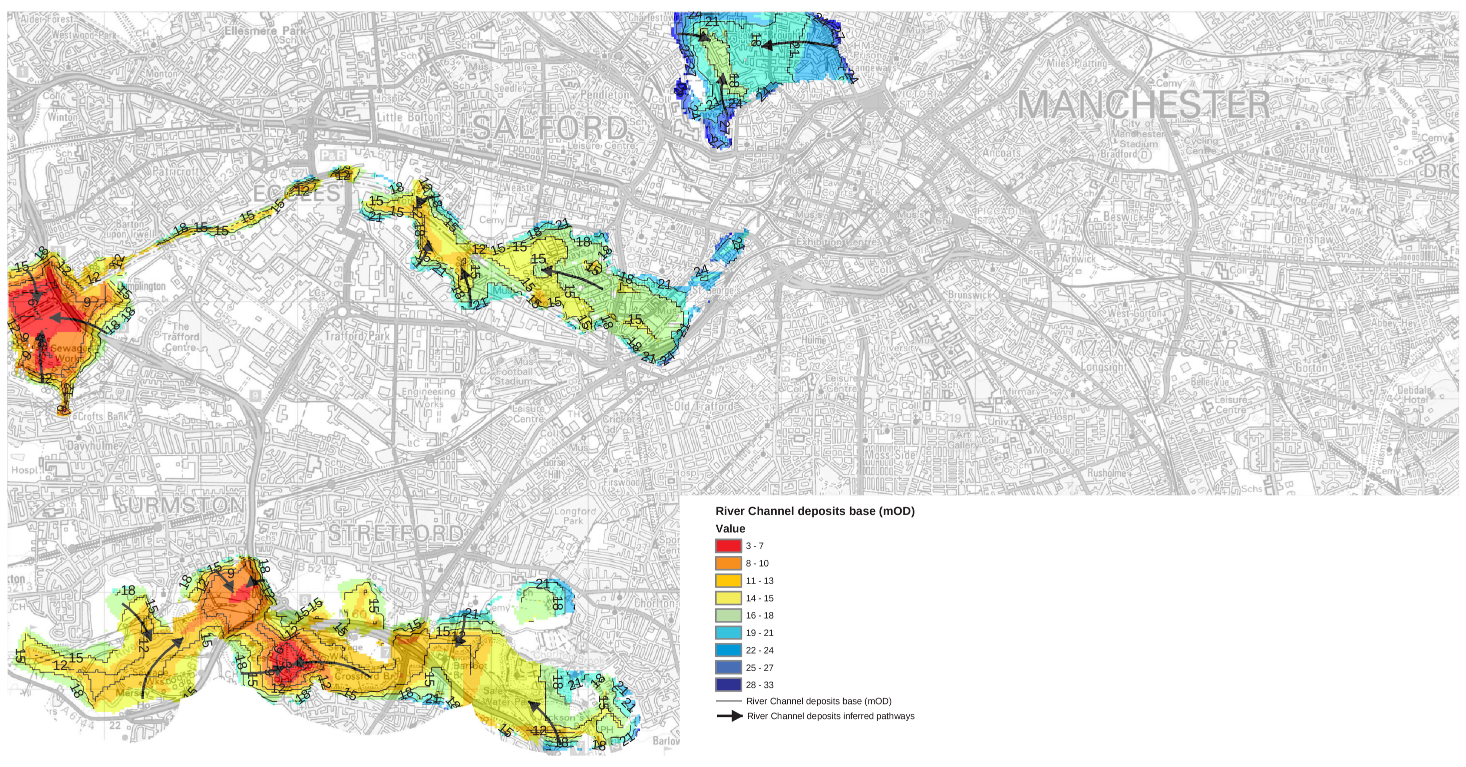
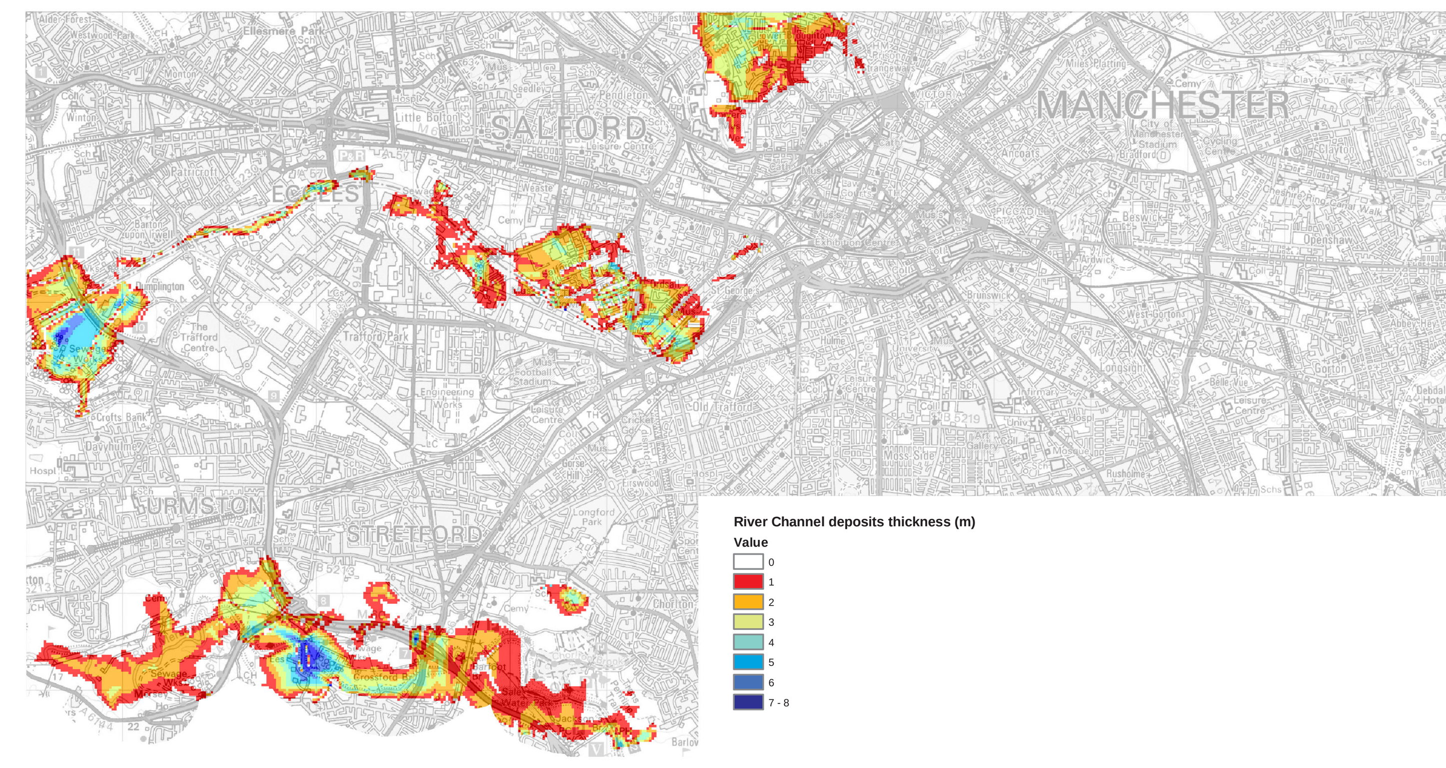
Map 2 Geometry and conceptual pathways of Superficial Aquifers

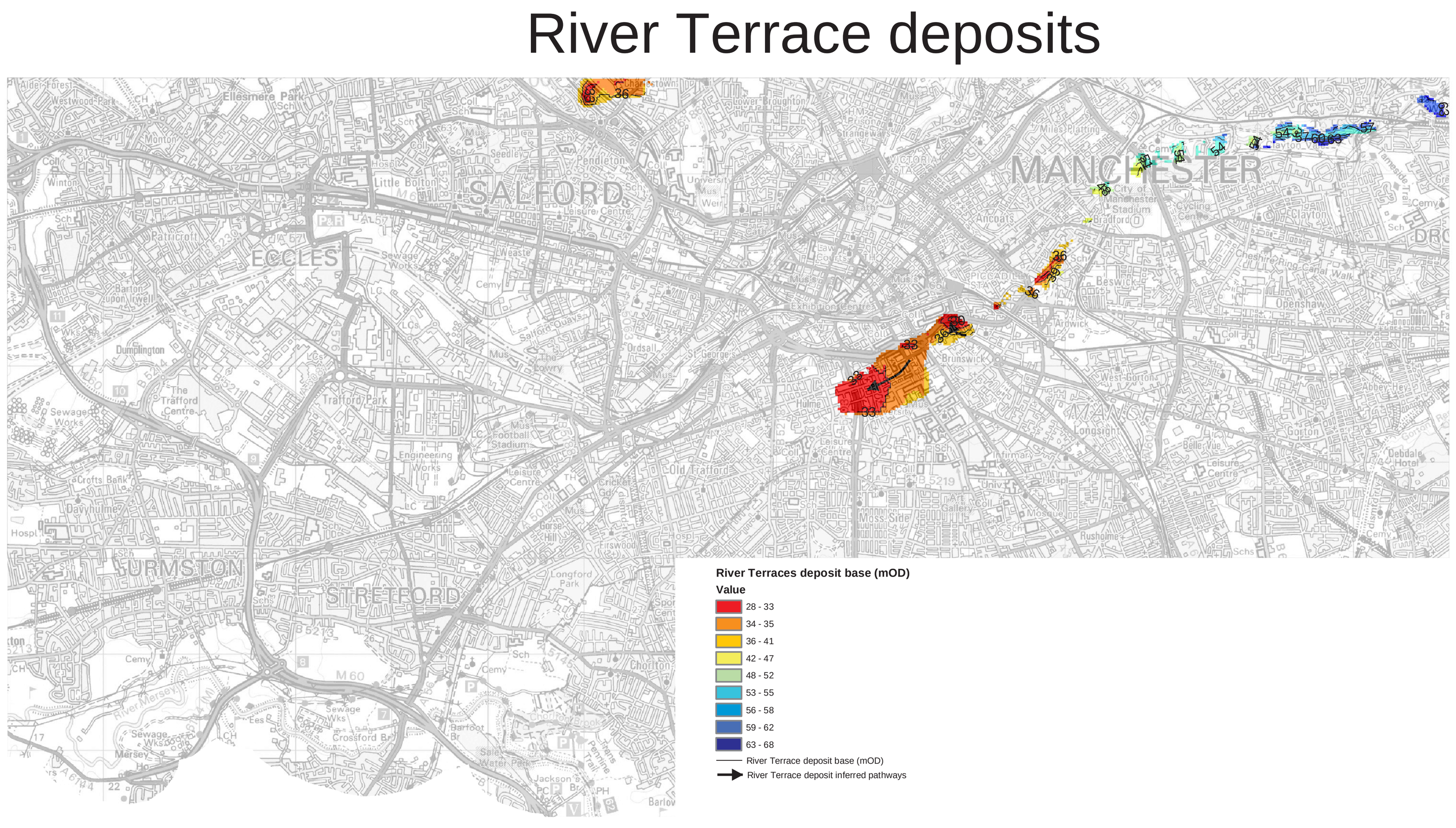
River Channel deposits



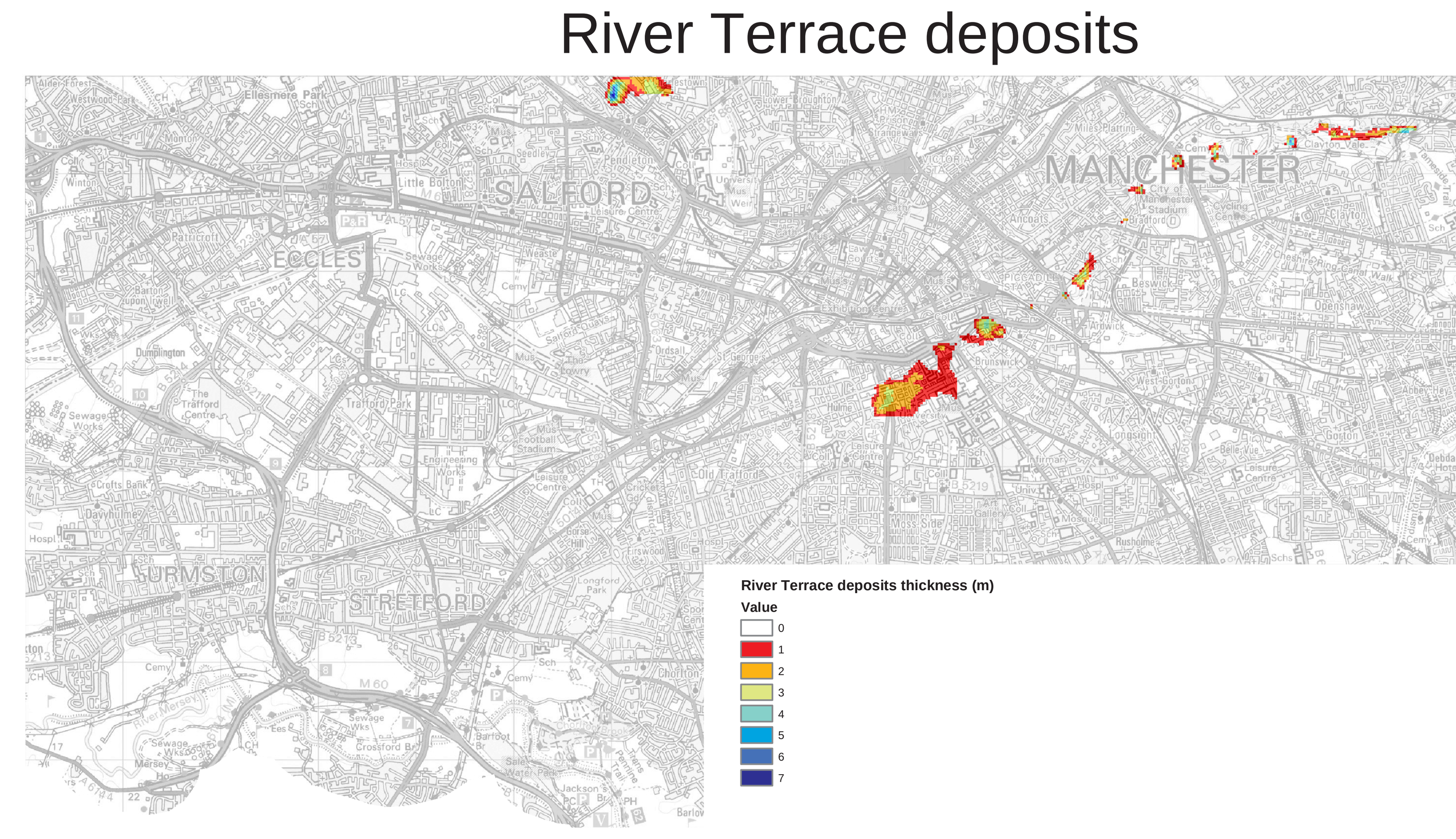
River Channel deposits



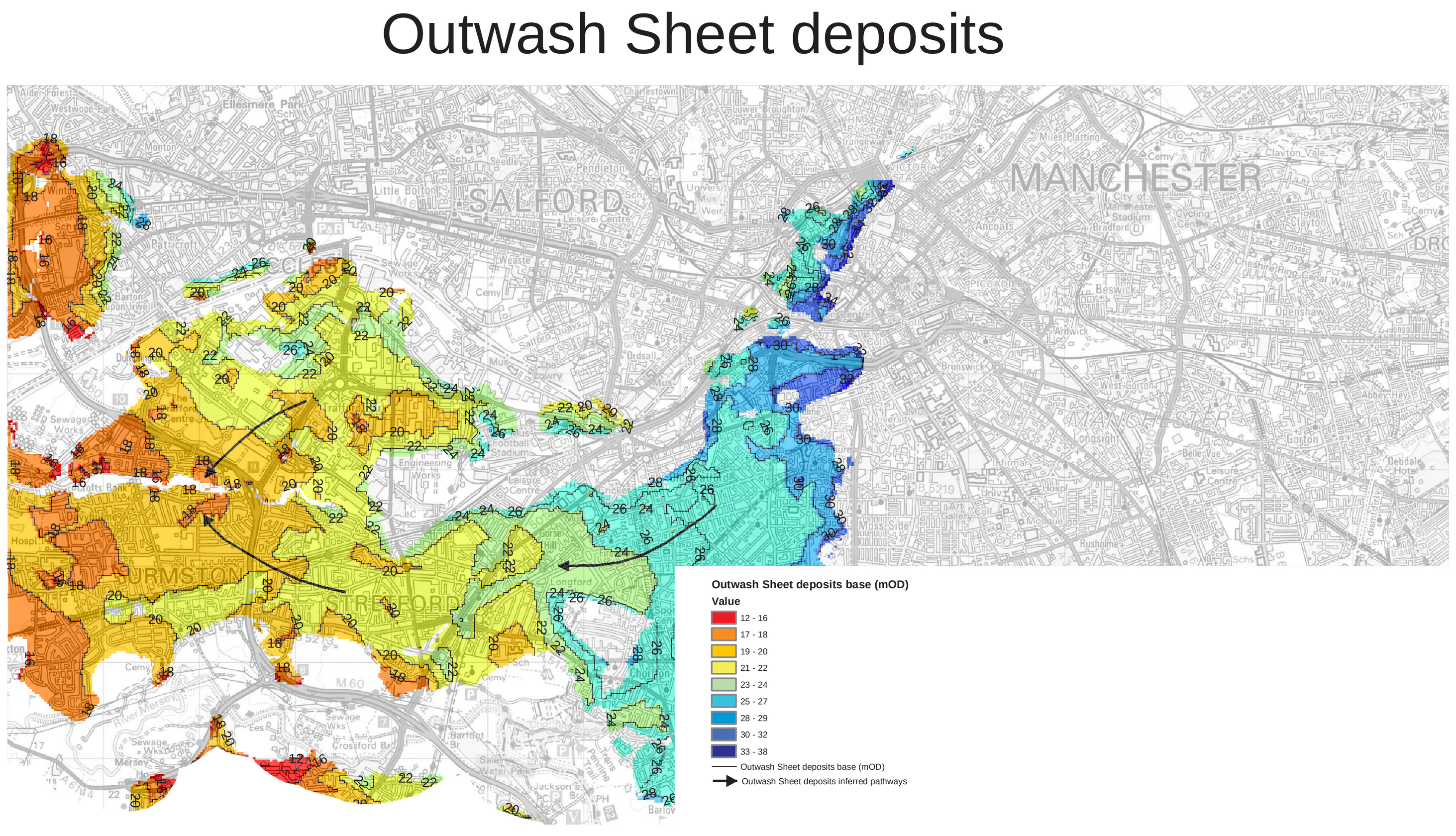
River Terrace deposits



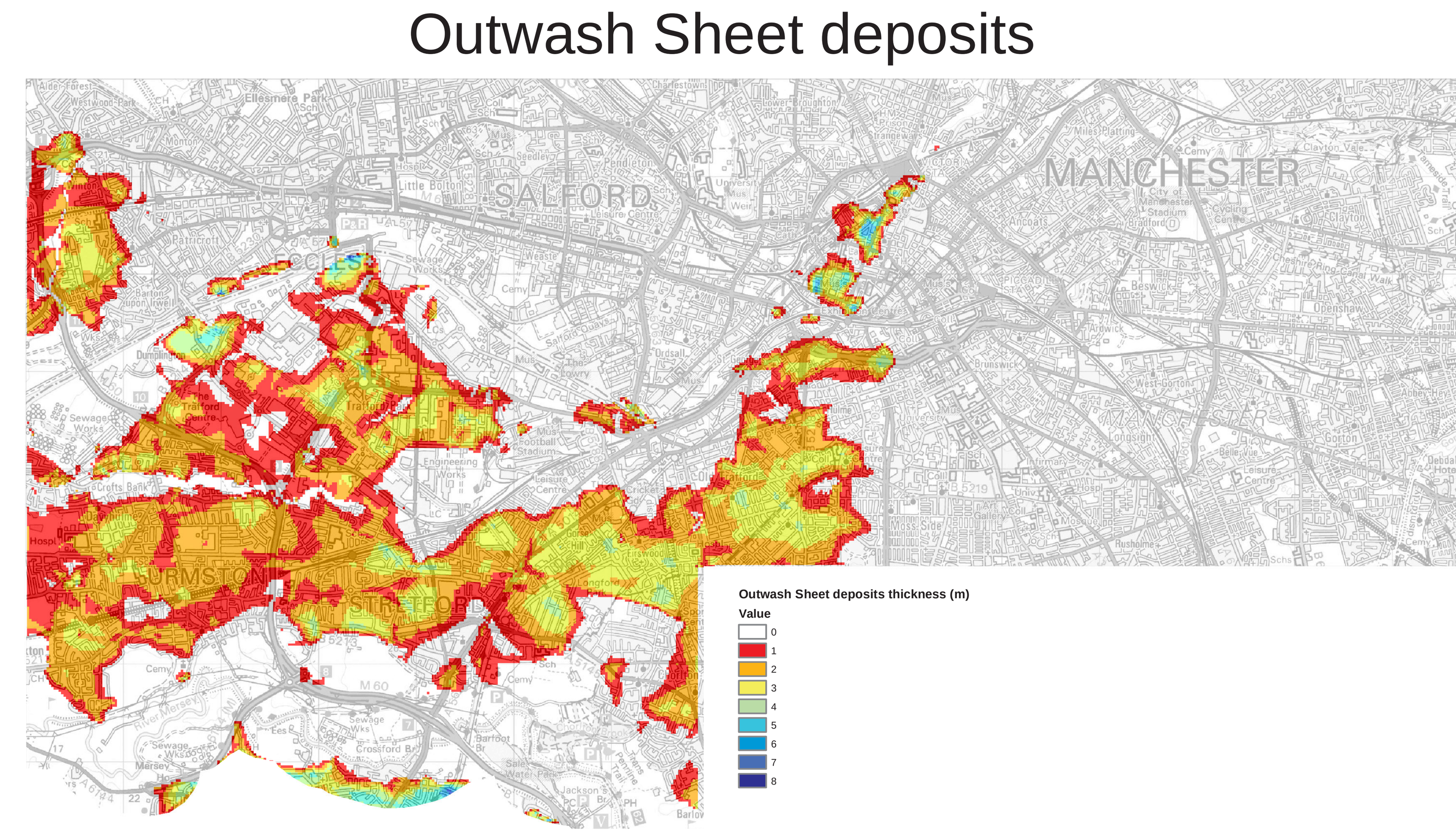
River Terrace deposits



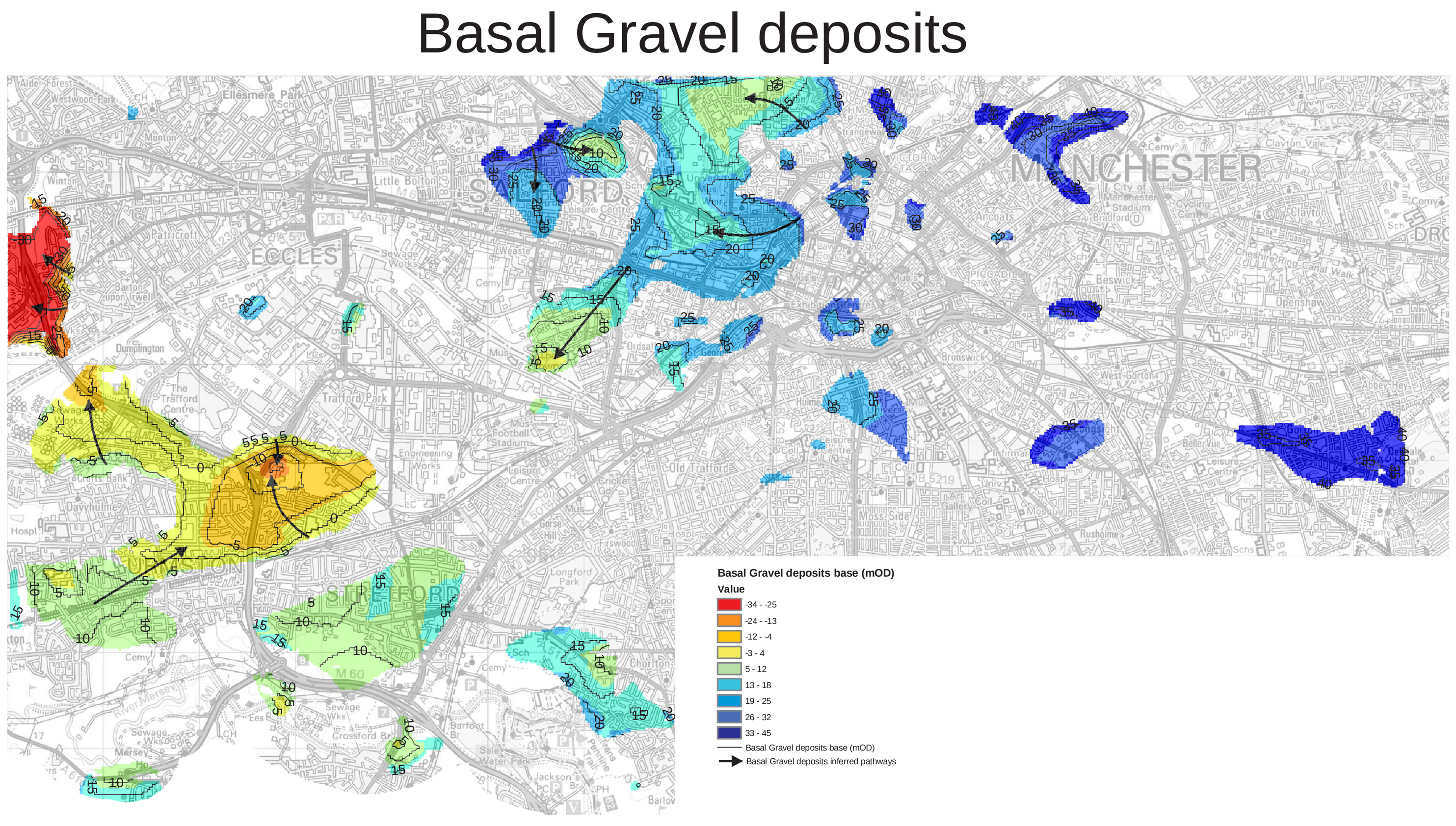
Outwash Sheet deposits



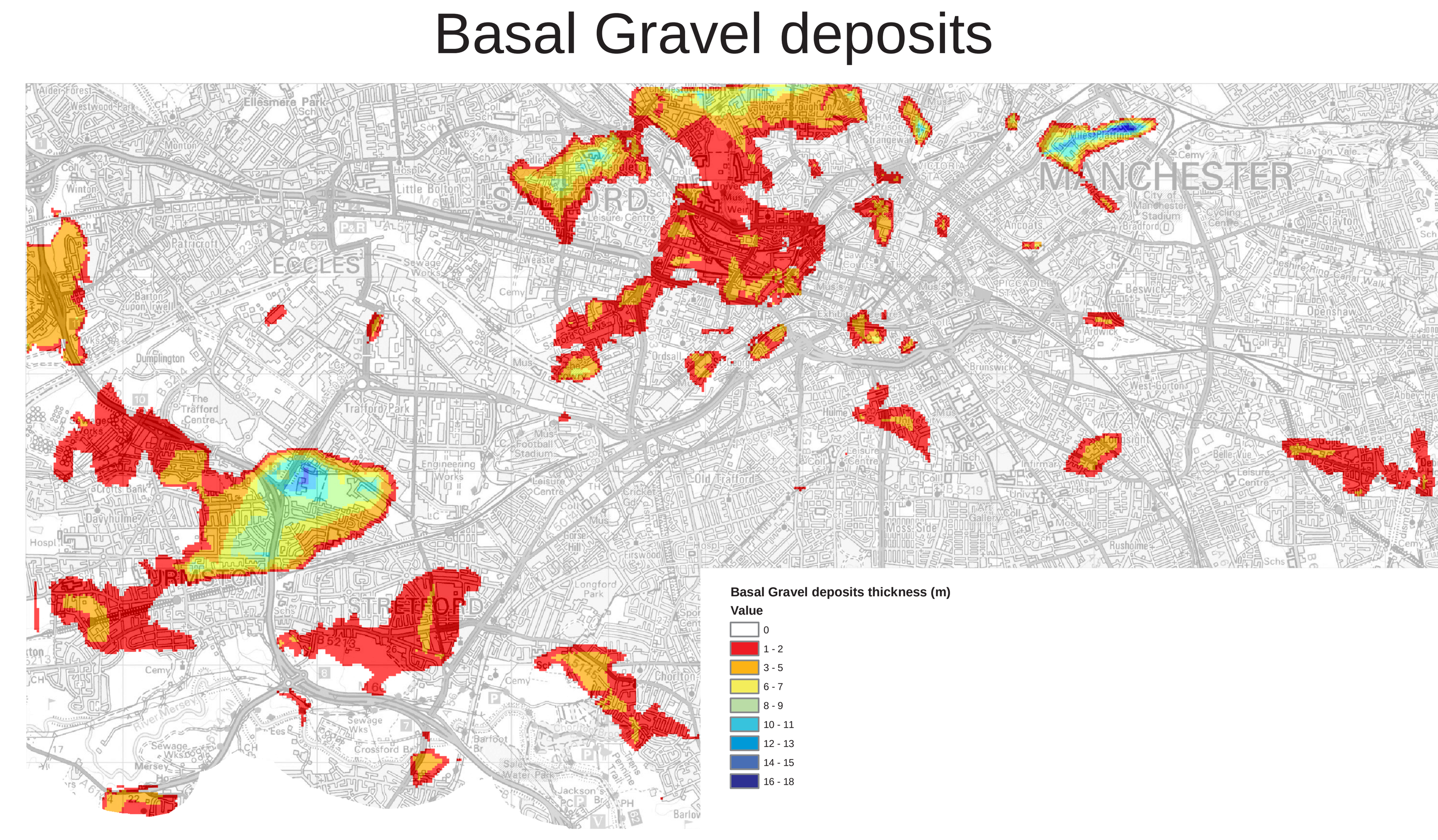
Outwash Sheet deposits



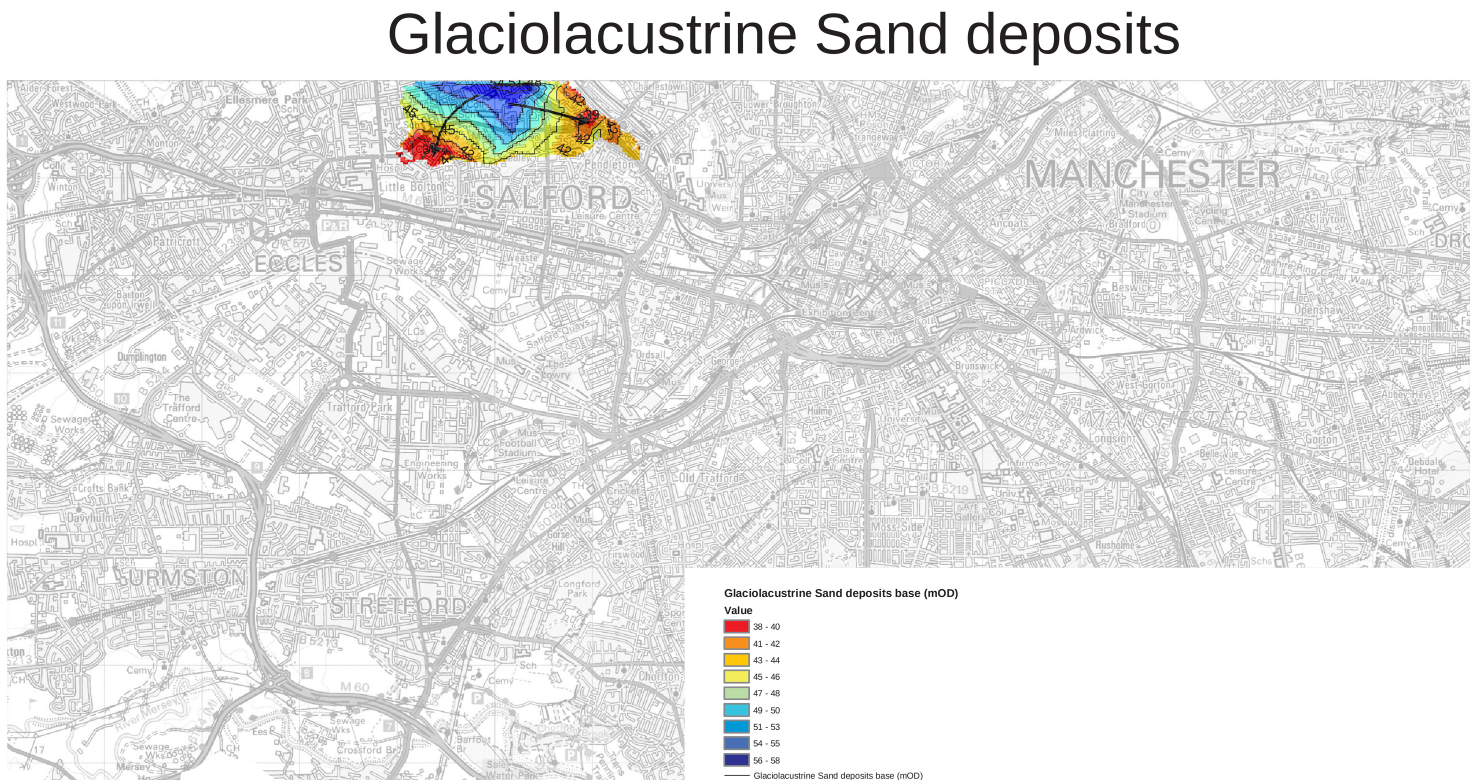
Basal Gravel deposits



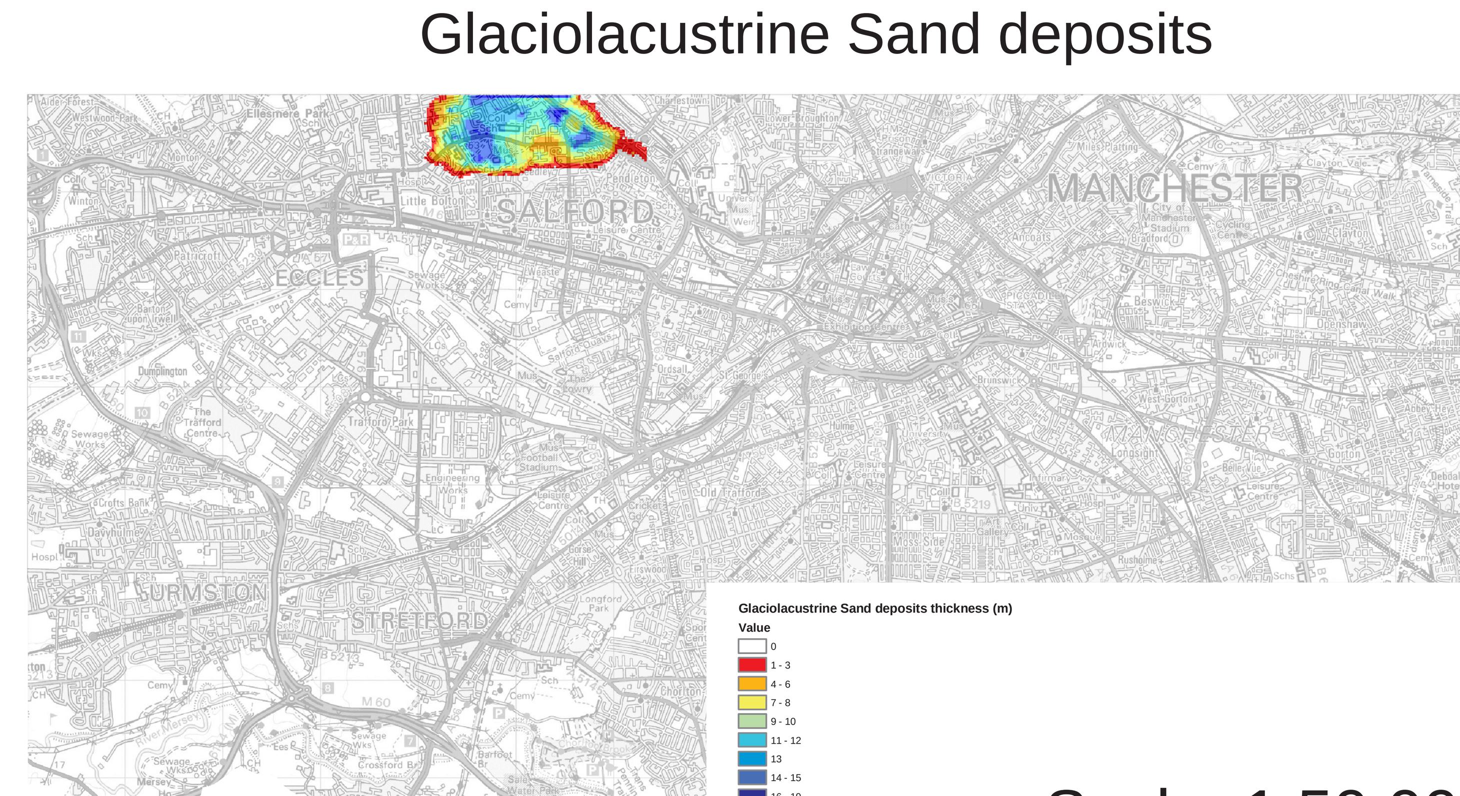
Basal Gravel deposits



Glaciolacustrine Sand deposits



Glaciolacustrine Sand deposits



Scale: 1:50,000

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MAP 3: Hydrogeological Domains Map

Hydrogeological Domains

- Domain 1 (Major Aquifer outcrop)
- Domain 2 & 3 (Permeable superficials - Major Aquifer)
- Domain 4 (Minor Aquifer outcrop)
- Domain 5 & 6 (Permeable superficials - Minor Aquifer)
- Domain 7 (Potential perched aquifer)
- Domain 8 (Aquitard)
- Domain 9 (Non-Aquifer)
- River & Canal systems

Manchester modelled Superficial Deposits (1:100,000)

Manchester modelled Superficial and Artificial Deposits (1:100,000)

Scale: 1:15,000

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