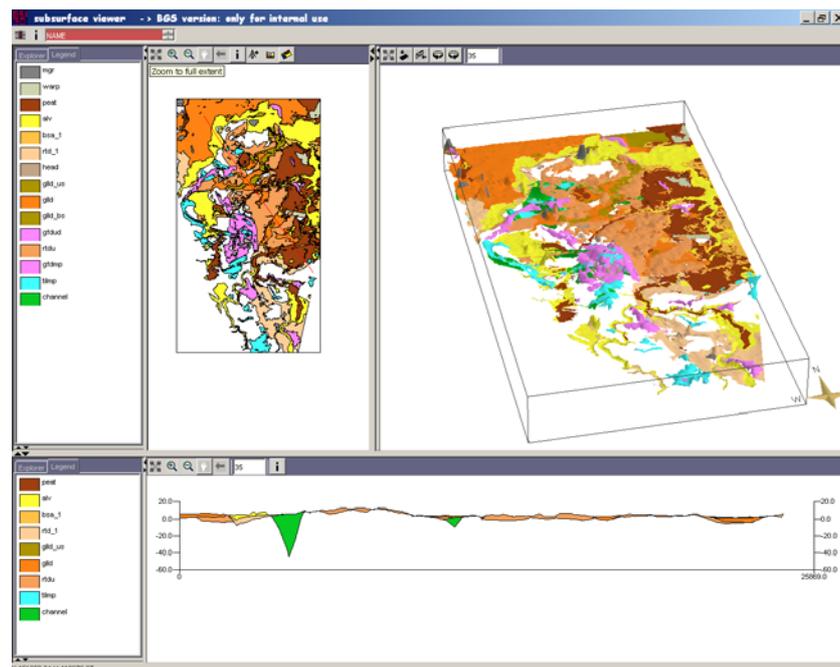




3-D hydrogeological characterisation of the superficial deposits between Doncaster and Retford

Report prepared for the Environment Agency by the British Geological Survey

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BRITISH GEOLOGICAL SURVEY

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) on behalf of Dr Martin Shepley, Senior Technical Specialist (Hydrogeology) at the Environment Agency, West Midlands Region. The help and assistance of all staff involved is greatly acknowledged and in addition, the report authors would like to thank Matilda Beatty of Yorkshire Water and Ben Fretwell of Entec.

Executive Summary

A 3-D geological model of the area between Doncaster and Retford was created in order to characterise the thickness and distribution of superficial deposits to allow hydrogeological domains to be derived above the Sherwood Sandstone aquifer. The overarching aim of the study was to use a domains approach, derived from the output of the 3-D model to assess potential recharge to the Sherwood Sandstone aquifer. The results of the study are intended to help the Environment Agency meet its regulatory requirements under the Water Framework Directive and Catchment Abstraction Management Strategy (CAMS) and form part of its overall East Midlands – Yorkshire Sherwood Sandstone Groundwater Study.

The 3-D model revealed a complex sequence of pre-glacial, glacial and post-glacial sediments deposited on a rockhead surface that extends in places to –26mOD as a result of deep incision into the bedrock. These channels are orientated north-west, south-east or east-west. The sequence of superficial deposits is generally less than 10m thick, increasing to 25m in places to the east and southeast of the project area.

The area from Hatfield Moors in the north-east to Misson in the south-east is characterised by a sequence of peat, variably underlain by Blown Sand, Glaciolacustrine silt and clay and “Older River Gravel”. The Glaciolacustrine silt and clay is most thickly developed beneath Hatfield Moors, but is laterally discontinuous. Elsewhere, to the west of the study area, the superficial deposits comprise sand, gravel and till of limited extent and are generally less than 10m thick, except in some fluvial valleys.

Seven hydrogeological domains were identified from the 3-D model and other published data sources. The domains were defined in terms of the potential for recharge to occur either directly into the Sherwood Sandstone or through the sequence of superficial deposits. Each of the units making up the superficial deposits in the area was classified according to its inferred hydrogeological properties.

A hydrogeological domains map produced via a series of GIS rules and queries using the digital output from the model reveal that the potential for recharge is greatest in the western and central parts of the project area, with only limited potential recharge occurring to the east.

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Summary

This report presents the result of a study commissioned by the Environment Agency West Midlands Region to characterise the superficial deposits between Doncaster in the north-west and Retford in the south-east. The area covers over 500km² and incorporates the regionally important Sherwood Sandstone aquifer and Hatfield Moors, which is a designated Site of Special Scientific Interest. The 3-D model was used to derive hydrogeological domains in the superficial deposits overlying either bedrock aquifers or aquitards.

1 Introduction

This report presents the results of a study commissioned by the Environment Agency West Midlands Region to characterise the superficial deposits between Doncaster and Retford in terms of their hydrogeological domains overlying the regionally important Sherwood Sandstone aquifer. It forms part of an overarching Environment Agency study that aims to develop a

unified, regional groundwater model of the East Midlands – Yorkshire Sherwood Sandstone Aquifer that addresses current water resource issues. The results of the study will enable the Environment Agency to support its requirements under the Water Framework Directive (WFD) and Catchment Abstraction Management Strategy (CAMS)

In order to meet these requirements a hydrogeological domains approach was developed to understand the nature of the superficial deposits overlying the Sherwood Sandstone aquifer. In order to apply these domains, a 3-D model of the superficial deposits was constructed. The outputs of the model in the form of digital grids comprising the elevation of the top and base of each geological unit and its thickness were queried within a GIS to derive hydrogeological domains.

1.1 LOCATION AND TOPOGRAPHY

The area investigated covers an area of over 500km² from Doncaster and Askern in the north-west to Retford in the south-east (Figure 1). The rivers Don, Idle and Torne cross the area and flow north-eastwards towards the Humber Estuary. These rivers have been subjected to significant drainage diversion initiated in the 1620s. Artificially induced alluvium (warp) has also been created, especially in the eastern part of the area. The area is generally low lying and is defined by an escarpment of Permian rocks in the west and the Isle of Axholme ridge in the east.

Hatfield Moors, designated a Site of Special Scientific Interest (SSSI), is located to the north-east of the project area.

2 3-D modelling

The 3-D model of the superficial deposits between Doncaster and Retford was constructed using the GSI3D software tool and methodology. GSI3D uses a Digital Terrain Model (DTM), surface geological linework and interpreted downhole geological borehole information to enable a series of cross sections to be constructed from on-screen correlation of each geological deposit. The 3-D model is calculated from this series of correlated cross sections to produce a stack of surfaces corresponding to each of the geological units.

2.1 DATA AND INFORMATION SOURCES

The 3-D geological model was constructed from a combination of diverse data and information sources, including coded boreholes, 2-D geological maps, field observations to the north of the project area in Selby and other published datasets and local knowledge.

Important published information included the geological memoir for sheets 79 and 88 (Gaunt, 1994) and British Geological Survey Industrial Mineral Assessment Unit Sand and Gravel reports (Clayton, 1979, Price & Best, 1982, Thomas, 1981 and Thomas & Price, 1979). Where possible, sections showing the thickness and interrelationships of the superficial deposits within these reports have been incorporated into the 3-D model.

Interpreted borehole data was entered and retrieved from BGS corporate databases, which contained primary geological information on lithology, thickness and lithostratigraphy. This included boreholes coded for the project in addition to existing boreholes within the database, principally from BGS sand and gravel resource assessments. Additional geological information

was provided for some Environment Agency monitoring boreholes and where possible this data was transferred to the project borehole databases and used in the 3-D model.

2.2 CROSS SECTION CONSTRUCTION

The correlated cross sections that provide the framework for the 3-D model were built by selecting individual boreholes. In general, this involved the selection of the best quality borehole but also took into account the location of Environment Agency observation boreholes, Yorkshire Water public supply boreholes and newly acquired boreholes drilled by Entec on behalf of Yorkshire Water. In addition, at least three cross sections were tied to existing regional cross sections further north to ensure geological consistency in the area (Ford *et al*, 2004).

The geological succession proved in each borehole was used to constrain the correlation lines of each geological unit. In some areas borehole density was high but in others was low. In all cases other published information such as cross sections in IGS sand and gravel reports (Clayton, 1979, Price & Best, 1982, Thomas, 1981 and Thomas & Price, 1979) were used to help constrain the correlations in areas where borehole coverage was sparse.

The location of the main cross sections is shown in Figure 2. Other ‘helper’ sections were constructed in subsequent model iterations to help constrain the superficial geology model further. Helper sections are constructed to help in the removal of ‘spikes’ resulting from initial errors in the model calculation and wide node spacing on the correlated cross sections. In total, 177 sections were used to produce the 3-D superficial geology model.

2.3 ENVELOPE CONSTRUCTION (DISTRIBUTION OF UNITS)

The envelope of a geological unit defines its surface and subsurface distribution. In general, the surface distribution is initially constrained by existing geological linework. However, more recent boreholes may provide additional information and the surface linework may be amended on the basis of such information. For the purposes of this project BGS DiGMapGB-50 scale, superficial geology linework was used as the base dataset from which the geological envelopes were constructed. The envelope for each geological unit in turn was then edited to reflect the correlation of that unit along the lines of section.

Although the envelopes were constructed based on original 1:50 000 scale data, some polygons for geological units were excluded from the 3-D model. This mainly related to very small areas of Alluvium, Peat, Blown Sand and Glaciolacustrine Silt and Clay where the small polygons were not visible at the regional resolution of the model. The effect of this was to produce a simplification of the distribution of geological units appropriate to the regional scale and suitability for use of the 3-D model and its derived output at 1:50 000 scale or less.

The subsurface distribution of each geological unit is defined mainly by its presence in boreholes and its spatial correlation. In other areas it is constrained from other published information and map sources. For example, the distribution of the glaciolacustrine sediments is constrained by figure 42 in Gaunt, 1994.

2.4 MODEL CALCULATION

The model was calculated in GSI3D to produce a series of stacked Triangular Irregular Network (TIN) surfaces corresponding to the top, base and thickness of each geological unit. The model

algorithm starts from the DTM at the top and calculates downwards through progressively older units.

The model was calculated using a minimum node distance along the envelope boundaries of 15 m, except along the RTDU (Older River Gravel) unit where a minimum node distance of 50 m was used. Using a minimum node distance was necessary to take account of the large project area and the resulting large number of nodes along each geological boundary.

The result of using this edge-cleaning algorithm is that some small gaps appear between the edges of very thin, non-overlapping units when the model is converted from a TIN stack to grids. This principally occurs between Alluvium and Peat. It will be noticeable therefore in the resulting grids, that small gaps will be evident between some geological boundaries, where the units are thin. The grids were exported at 50 m cell size and used to derive the hydrogeological domains using a series of GIS algorithms developed for the project.

3 Geological Summary

3.1 BEDROCK

The bedrock beneath the area comprises Permian rocks in the west and Triassic rocks in east; the whole sequence dips gently to the east. The Permian rocks rest unconformably on the Carboniferous and comprise the Cadeby Formation (a significant dolomite aquifer), the Edlington Formation (mainly gypsiferous mudstones), the Brotherton Formation (a thin dolomite aquifer) and the Roxby Formation (gypsiferous mudstones). The overlying Triassic rocks comprise the Sherwood Sandstone Group, the main aquifer followed by the Mercia Mudstone Group (mudstone, gypsiferous mudstone and some sandstone).

The elevation of the rockhead surface, derived from the 3-D model is shown in Figure 3.

3.2 SUPERFICIAL DEPOSITS

The superficial deposits in the area mainly represent the deposits from at least the last two ice-ages and the intervening interglacial deposits. The landscape has been subjected to several episodes of erosion and several episodes of deposition. The superficial geological sequence is shown in Table 1. The total thickness of the superficial deposits derived from the 3-D model is shown in Figure 4.

Table 1 The sequence of superficial deposits in the Doncaster – Retford area. Numbers in the name column are used for clarity and reference in subsequent sections and figures.

Age	Generic Name	Thickness	Details
Recent	Made Ground (1)	Variable	Anthropogenic deposits.
	Warp (2)	Up to 1m	Made ground formed by flooding land and the artificial deposition of laminated silt and clay.
Flandrian	Peat (3)	0-4.5m	Peat
	Alluvium (4)	3-8m	River flood plane deposits
	Blown Sand (5)	0- 4m, 8 in places	Fine-grained wind-blown sand that commonly underlies peat in the east of the area
Probably late Devensian	River Terrace Deposits (6)	0-8m, 15 in places	Sand and gravel with some clay
Devensian (glacial and pro-glacial deposits)	Head (7)	0-3m	Generally sandy and gravelly clay, dependent on the surrounding deposits, caused by solifluction during and at the end of the last glacial interval.
	Glaciolacustrine Deposits (sand) (8)	0-1m	Sand with silt and clay deposited in the Pro-glacial Lake Humber or when the lake had just drained.
	Glaciolacustrine deposits (silt and clay) (9)	0-8m	Also called the Hemingbrough Formation or 25ft Drift (silt and clay) Pro-glacial lake deposits formed in Lake Humber when the present estuary was blocked with ice.

	Glaciolacustrine deposits (basal sand) (10)	0-3m	Silty and clayey sand
	Glaciofluvial deposits (11)	0-5m	Sand and gravelly sand with silt and clay interdigitating with the Glaciolacustrine deposits in places.
Ipswichian	Older River Gravel (Doncaster area) (12)	5-15m	Sand and gravel
Pre-Ipswichian possibly Anglian	Glaciofluvial deposits (13)	0-16m generally 0-10m	Well-sorted sand and gravel with abundant pebbles derived from the Sherwood Sandstone Group bedrock.
Possibly Anglian	Older Till (Doncaster area) (14)	0- 9m	Bouldery, cobbly and gravelly sandy clay deposited from ice.
Pre-Anglian or Anglian	Buried Channel Deposits (15)	Up to 58m	Deposits filling deep incised buried valleys; mainly sand and gravel at base overlain by thick laminated silt and clay.

3.3 PRE-ANGLIAN OR ANGLIAN GLACIAL DEPOSITS

3.3.1 Channel Deposits (15)

The bedrock of the area is traversed by a number of deep buried channels that are only proved in boreholes. These were recognised by Gaunt (1981 and 1994) and due to their uneven floors, which rise and fall along their length, they are interpreted as sub-glacial tunnel valleys, produced from the action of meltwater beneath advancing glaciers. Nine of them are orientated approximately north-west to south-east and the two southern ones are orientated approximately east-west. The valleys range in depth to minus 58m below present OD. The fill in the valleys is generally silty or gravelly sand overlain by laminated silt and clay. Some of these channels were identified and named by Gaunt (1981 and 1994). Approximately from north to south the channels are: Barnby Dun Station Channel, Arksey Channel, Armthorpe Channel, Wheatley Park Channel, Bessacar Channel (very small and not intersected by any cross-section), Rossington Channel, Blackwood Channel, Loversall Channel, Hunster Grange Channel, Lim Pool Channel and an unnamed channel in the south of the area. Gaunt (1981 and 1994) interprets all these channels as being pre-Ipswichian and most probably related to the Anglian glacial event.

3.3.2 Till (14)

Patchy glacial till has been mapped throughout the western part of the area and as small relics in the central-southern part of the area. These deposits are mainly relics sitting on slightly elevated bedrock and therefore cap hills and ridges of Sherwood Sandstone bedrock. On the flanks of the hills they are commonly much thinner and in the low ground they have not been recognised, presumably they have been eroded away. In some places, such as at the western end of section WE_2, the till overlies the valley fill deposits described above.

The till is interpreted as Anglian in age as the Devensian glacial front is now recognised (BGS work in progress on the Selby area) to lie at the Escrick Moraine at the village of Escrick. The

till commonly comprises sandy clay or clayey sand with clasts of local and erratic material. In places it can include laminated clay, sand and gravel deposits. Gaunt (1994) records that in places it is overlain by the glaciofluvial deposits described below.

3.3.3 Pre-Ipswichian, possibly Anglian Glaciofluvial Deposits (13)

The glaciofluvial deposits occur in four main concentrations within the area. In the north they comprise the capping to the Doncaster ridge, the area around Rossington including the Rossington ridge (Clayton, 1979) the area around Ranskill/Scrooby and eastwards, plus the area just north-east of Retford. All these deposits rest on bedrock, or in a few places on the underlying till. In most places, they cap the bedrock highs in the same way as the glacial till, but in a few places they are also incised into the bedrock (i.e. Section WE_5). The deposits mainly comprise sand and gravel, and clayey pebbly sand.

3.4 IPSWICHIAN DEPOSITS

3.4.1 Older River Gravel (12)

Large spreads of Older River Gravel are present in the north and east of the district. They form a terrace-like area with an elevation of up to 12m above OD and contain sedimentary structures indicative of deposition from a fluvial environment. The palaeocurrent directions and variations in composition suggest that the deposits in the north were deposited by fluvial activity via the Don Valley, while those deposits in the south appear to be associated with the valleys of the rivers Idle and Torne. In the Don Valley the deposits form a 15m thick linear ridge comprising sand and gravel. In places the deposits are incised and are commonly overlain by younger glaciolacustrine deposits. The large spread to the south-east of Doncaster is generally around 5m thick, reaching 9m in places.

Figure 5 shows a map of the thickness and elevation of the base of the Older River Gravel produced from the 3-D model.

3.5 DEVANSIAN DEPOSITS

3.5.1 Glaciofluvial Deposits (11)

In the north-east of the area there are a few small patches of sand and gravel interpreted to be glaciofluvial deposits. These typically form relic deposits up to about 5m thick capping bedrock hills (i.e. Near the eastern end of line WE_6) and beneath later deposits (also near the eastern end of line WE_6).

3.5.2 Glaciolacustrine Deposits (basal sand) (10)

Two small patches of sand at the base of the glaciolacustrine deposits have been modelled. The largest of these deposits on section NS_2 comprises up to 3m of very clayey sand. A small area has also been mapped to the north-west of here.

3.5.3 Glaciolacustrine Deposits (silt and clay) (9)

The Glaciolacustrine silt and clay forms extensive very flat spreads in the north-east of the area. The deposit is generally laminated clay and silt with subordinate layers of fine-grained sand. It represents the deposits in the distal end of the main Vale of York pro-glacial lake during the

Devensian ice-age. The deposits were formerly called the silts and clays of the 25ft Drift (Edwards, et al., 1950, Gaunt 1981 and 1994), but have now been designated the Hemingbrough Formation (Thomas, 1999). In the north-east of the district the deposit is only a few metres thick, resting on the Older River Gravel. However, in the east (Section WE_2), it thickens to around 8m. Similarly on section NS_2 the silt and clay is around 1.5 to 2m thick in the south, but thickens to around 8m in the largest outcrop in the far north-east of the area.

Figure 6 shows a map of the thickness and elevation of the base of the Glaciolacustrine silt and clay produced from the 3-D model.

3.5.4 Glaciolacustrine Deposits (sand) (8)

This sand is closely associated with the Glaciolacustrine silt and clay deposits, it is rarely more than a metre or so thick and forms a spread of generally fine-grained sand at the surface (i.e. near the northern end of section NS_1).

3.5.5 Head (7)

The Head deposits are mainly associated with the older deposits in the area or with exposed bedrock. They are generally clayey gravels of reworked local material or reworked glacial and glaciofluvial material. The deposit forms in valley bottoms and generally represents re-deposition of material probably by freeze and thaw (solifluction) in a periglacial environment. The deposits are usually only a few metres thick.

3.5.6 River Terrace Deposits (6)

River terrace deposits are present in the north-west of the area and in large spreads in the south. In the north they are associated with the River Don and are incised by the later river course and alluvium. Here the deposits comprise a basal gravel overlain by sand. In the south the deposits are widespread in the vicinity of Retford, where they are associated with the valley of the River Idle. Here they are composed of pebbly and gravelly sand overlain by sand. Many of the River Terrace Deposits are considered to be likely correlatives of the Glaciolacustrine silts, clays and sands.

3.6 POST-GLACIAL DEPOSITS

3.6.1 Blown Sand (5)

Blown sand is extensive in the north-east of the district, where it forms thin spreads of fine-grained silty sand. In the east of the area it commonly rests directly on bedrock and in flat or low-lying areas. Where it is present in the lower ground it overlies large areas of Glaciolacustrine silt and clay and in the same areas it is largely concealed beneath later peat deposits, particularly in the area between Hatfield Moors and Misson (eastern end of WE_6 and WE_3).

3.6.2 Alluvium (4)

Alluvium is represented by Holocene overbank deposits comprising mainly fine-grained sediments, as shown on BGS geological maps. The coarser component of Alluvium, typically a basal gravel lag that may be correlated with River Terrace Deposits, is included within the River Terrace Deposits unit for the purposes of this project.

Extensive areas of alluvial deposits are present in the area associated with all the main drainage courses. In the Doncaster area it is associated with the River Don, but also spreads out into low-lying area of Potter Carr to the south of Doncaster. Along the River Don, the alluvium is up to around 6m thick with its base in section WE_6 lying just below present sea level. By comparison, the large ponded areas of alluvium are only 3 or 4m thick and are mainly concentrated in a belt along the junction between the Sherwood Sandstone Group and the gypsiferous Roxby Formation.

A narrow strip of meandering alluvium is associated with the River Ryton in the south-west, which drains another large enclosed area. In the south-east the area north of Retford is drained by the River Idle, which has a wide flood plane, but only a thin alluvial sequence comprising a few metres of silt and clay resting on sand and gravel (Thomas, 1981). In the north-east of the area the alluvium associated with the east of Hatfield Moors is much thicker than the other rivers of the area and reaches around 6-8m on section WE_2.

3.6.3 Peat (3)

Peat is extensive in the east of the area, where it forms spreads resting on the flat Glaciolacustrine deposits. It is also commonly associated with present and past drainage courses in the centre and west of the area. The peat is rarely more than a few metres thick, but on Hatfield Moors, where it has been extensively worked, it is in excess of 3m thick (Price & Best, 1982). Along the River Idle, east of Misson, it is in excess of 4m thick (Thomas & Price, 1979).

Figure 7 shows a map of the thickness and elevation of the base of the Peat produced from the 3-D model.

3.6.4 Warp (2)

Warp is a form of made ground developed by building flood banks around field areas and artificially flooding the ground so that layers of clay and silt are built up (Gaunt 1994). Over time the land can be raised by a metre or so. In several places on Hatfield Moors “cartwarp” has been deposited. This term refers to the process of raising the level of the land manually by transporting material into the fields and spreading it out (Gaunt, 1994).

3.6.5 Made Ground (1)

Made Ground and other types of artificial ground has not been included except where it forms a major feature evident on the Digital Terrain Model (DTM) used in the study. Four areas are shown, the two southern ones are up to 3 or 4m thick, the northern ones only a metre or so thick.

3.7 LIMITATIONS AND RESOLUTION OF THE 3-D MODEL

It was not possible to quantify the overall confidence of the 3-D model. However, model confidence is generally higher in areas with a high borehole density (Figure 2). The age, quality and purpose for which the boreholes were drilled all affect confidence in the borehole record itself.

Published interpreted maps and 2-D geological maps have all been used to improve model confidence in areas where borehole data is limited and the distribution of geological units is poorly understood. This is particularly important in relation to the subsurface distribution of Glaciolacustrine sediments, where borehole control over a large area is limited.

The model resolution was developed to be broadly comparable with a 1:50,000 scale geological map and to be an appropriate resolution to derive hydrogeological domains for an area covering over 500km². As a result, any output from the model should use a minimum cell size of 50m. It would not be appropriate to use a cell size any less than this. The model and its derived output, including the hydrogeological domains, should be used for regional scale (1:50 000 or smaller) studies only. It would not be applicable to use the model for site-specific (e.g. 1:10 000 scale or larger) studies or ground investigation.

As a result of the effect of the minimum node distance, edge-cleaning algorithm described in the modelling methodology section, along boundaries of thin, non-overlapping units, small gaps occur between these units in the exported grids. These gaps represent areas of uncertainty along these boundaries where the units may be thin and in the grids appear as areas of bedrock at surface. It would be possible to reduce the effect of this using further “helper” sections along these boundaries but it was beyond the scope and resources of the project to do so.

The NEXTMap digital terrain model at 125 m cell size was used in the calculation of the model and construction of the cross sections. In places, the dataset contains errors that are represented by anomalous spikes (higher elevation) or cuts (lower elevation) into the DTM. The effect of this would be to artificially result in thickness increases or decreases in some geological units that occur at the surface. It is not possible to quantify the magnitude of these potential errors but it is expected that such effects would be minimal.

4 HYDROGEOLOGY

4.1 INTRODUCTION

Development of the hydrogeological component of the model is based on an initial assumption that the bedrock falls into two categories; namely Major Aquifer dominated by the Sherwood Sandstone Group and Aquitard dominated by the Mercia Mudstone Group, largely comprising interbedded mudstones and siltstones. The Permian rocks that underlie the western side of the model have been grouped with the Sherwood Sandstone, as Major Aquifer and the Jurassic strata to the east have been included with the Aquitard.

4.2 HYDROGEOLOGICAL PROPERTIES OF THE SUPERFICIAL DEPOSITS

The Superficial Deposits have been classified in terms of their relative permeability (Table 2). The classification has been derived from an assessment of the gross lithology of each of the units as summarised in Table 1. No attempt has been made to designate actual hydraulic conductivity ranges to the units, although it is considered that the weakly permeable units are likely to have hydraulic conductivity values of less than 10^{-1} m/day. Many of the units are laminated and therefore are likely to exhibit high horizontal to vertical hydraulic conductivity ratios.

Table 2 Superficial deposits: permeability classification. Numbers in the name column refer to the geological deposits described in Section 3.

Generic Name	Permeability classification	Further hydrogeological observations
Made Ground (1)	Permeable	Considered permeable because of heterogeneity
Warp (2)	Weakly permeable	Primarily cohesive silt and clay, forming a surface layer of the order of 1 to 2 m in thickness. Where other weakly permeable strata underlie the warp it is considered to be effective in reducing recharge to the underlying aquifer. Being primarily clay and silt the warp exhibits limited storage potential.
Alluvium (3)	Weakly Permeable	River flood plain deposits are inherently variable. Limited testing (Klingbeil & Sears, 2001) indicates hydraulic conductivities to be in the range 4.55×10^{-5} to 2.75×10^{-3} m/day. In central parts of the main river channels this may be absent and gravel (rtd_1) exposed but the identification of this using bathymetric data was beyond the scope of the project.
Peat (4)	Weakly permeable	Hydraulic conductivities, determined from boreholes in Hatfield Moors, were in the range 4.06×10^{-4} to 1.12×10^{-1} m/d when derived from falling head tests and 4.75 to 8.55×10^{-5} m/d when laboratory determined from core samples, representing vertical hydraulic conductivity (Klingbeil & Sears, 2001)
Blown Sand (5)	Permeable	Where this deposit is thick enough it may locally conduct a reasonable amount of lateral groundwater flow, generally overlain by peat and alluvium.
River Terrace Deposits (6)	Permeable	Sand and gravel with some clay, locally derived from the Glaciolacustrine Deposits, therefore relatively fine grained, but locally may conduct a reasonable amount of lateral

Generic Name	Permeability classification	Further hydrogeological observations
		groundwater flow where they are thick enough.
Head (7)	Permeable	The heterogeneity of the Head deposits (both Devensian and Holocene deposits) warrant that they be classified as permeable.
Glaciolacustrine Deposits (sand) (8)	Permeable	Sand with silt and clay, commonly forming discontinuous, low ridges and generally less than 2.5m in thickness, therefore only locally utilised for water supply.
Glaciolacustrine Deposits (silt and clay) (9)	Weakly permeable	The structured nature of the laminated clays, silts and sands renders them effective as an aquitard.
Glaciolacustrine Deposits (basal sand) (10)	Permeable	The deposits generally comprise bedded and well-sorted silty and clayey sand, which is up to 4m in thickness and locally may conduct a reasonable amount of groundwater.
Glaciofluvial Deposits (11)	Permeable	Sand and gravelly sand with silt and clay interdigitating with the Glaciolacustrine Deposits in places.
Older River Gravel (Doncaster area) (12)	Permeable	Sand and gravel, possibly locally confined.
Glaciofluvial Deposits (13)	Permeable	Well-sorted sand and gravel with abundant pebbles derived from the Sherwood Sandstone Group, likely to be in hydraulic continuity with the bedrock.
Older Till (Doncaster area) (14)	Permeable	The Older Till generally comprises weathered and decalcified bouldery, cobbly and gravelly sandy clay, which has a limited effect on inhibiting recharge.
Buried Channel Deposits (15)	Permeable	The deposits filling the channels comprise granular basal deposits overlain by consolidated laminated clays. It is reported (Gaunt, 1994) that the granular deposits increase in thickness towards the eastern ends of the channels, thus at their base they have the potential to conduct a reasonable amount of groundwater flow.

It should be noted that this information has been compiled from the literature (Gaunt, 1994, Institute of Geological Sciences, 1982); and from a consultants report (Klingbeil & Sears, 2001). It has not been derived from detailed examination of the boreholes records that form the basis of the 3-D modelling. Valuable additional information could be gained from interpretation of the groundwater level data that has been presented with the model.

4.3 HYDROGEOLOGICAL DOMAIN MAPPING

The use of domain mapping in the context of both aquifer recharge (McMillan et al., 2000) and aquifer vulnerability (Dochartaigh et al., 2005) is well established. Quaternary sediments are characterised by variable and complex lithologies and are important in determining the amount of water that will recharge the deeper groundwater system. The principle of domain mapping is the recognition of sequences of lithologies that are likely to be characterised by similar hydrogeological properties.

The domains are used to reduce the complexity of the superficial deposits for the purposes of understanding the recharge processes better. The lithostratigraphic units are grouped according to how the superficial sequence will affect groundwater flow between the aquifer (i.e. the Sherwood Sandstone) and ground surface. This means that the nature of the bedrock beneath the superficial deposits also needs consideration. For example, permeable superficial deposits over the Mercia Mudstone may enhance recharge to the Sherwood Sandstone if the permeable deposits overlap onto the Sherwood Sandstone outcrop.

It is clear from examination of Table 2 that there are a number of permeable units, which are locally capped by or interfinger with the weakly permeable units. The cross sections reveal a variety of sequences of superficial strata and it is these sequences that are reflected in the hydrogeological domains. Many of the lithological units are thin, which reduces the hydrological effectiveness of the unit. Accordingly, the designation of domains requires an assessment of the criteria that affect the hydrological effectiveness. In this context the following assumptions have been made:

- Made ground is highly heterogeneous and of variable thickness and has been designated a permeable unit to reflect the heterogeneity.
- The extensive nature of the Channel Deposits is such that they can connect a number of domains, accordingly they have been designated a separate domain, which may be capped by overlying domains.
- The ‘Sand on Clay’ domain is designated where permeable strata are situated on greater than 3m of low permeability strata such as the Glaciolacustrine clay and silt.
- The peat acts is considered to inhibit vertical flow where it exceeds 2m in thickness. Other weakly permeable superficial deposits are considered to inhibit vertical flow where they exceed 3m in thickness.

A number of sub-domains have been established (Table 3), which are grouped to form the seven domains that populate the map of hydrogeological domains (Figure 8). The domains are portrayed schematically in Figure 9. The domains themselves were generated using geological information (top and base elevation and thickness of each geological unit) derived from the 3-D superficial geology model.

Table 3 Hydrogeological Domains

Sub-domain		Domain	
1a	Sherwood Sandstone at outcrop	1	Sherwood Sandstone Group at outcrop and where Superficial Deposits <3m
1b	Sherwood Sandstone overlain by <3m of Superficial Deposits		
2a	Glaciofluvial Deposits	2	Permeable Superficial Deposits (one or more units present in excess of 3m) over Sherwood Sandstone Group
2b	River Terrace Deposits		
2c	Glaciolacustrine upper, or basal sand		
2d	Blown Sand		

2e	Till		
2f	Head		
3c	Blown Sand underlain by Glaciolacustrine Deposits >3m in thickness	3	'Sand on Clay' over Sherwood Sandstone Group
3a	Channel Deposits	3A	Channel Deposits over Sherwood Sandstone Group
4b	Glaciolacustrine Deposits over River Terrace Deposits	4	Weakly permeable Superficial Deposits (>2m peat, >3m other weakly permeable Superficial Deposits) capping permeable Superficial Deposits overlying Sherwood Sandstone Group, or Mercia Mudstone Group
4c	Alluvium over River Terrace Deposits		
5a	Alluvium >3m (>2m peat/warp)	5	Weakly permeable Superficial Deposits over Sherwood Sandstone Group and Mercia Mudstone Group
5b	>3m Glaciolacustrine Deposits		
6a	Mercia Mudstone Group at outcrop	6	Mercia Mudstone Group overlain by <3m of weakly permeable Superficial Deposits
6b	Mercia Mudstone Group overlain by < 3m of weakly permeable Superficial Deposits		
7	Mercia Mudstone Group overlain by one or more units of Glaciofluvial Deposits, River Terrace Deposits, Glaciolacustrine basal sand, Blown Sand or Till	7	Mercia Mudstone Group overlain by permeable Superficial Deposits

Domain 1: Aquifer at 'Surface'

This domain identifies where the Sherwood Sandstone (and on the western side of the superficial geology model, where the Zechstein Group) is at surface, or covered by less than 3 m of superficial deposits. This domain forms the principal domain, reflecting the generally limited thickness of the superficial deposits in the area. It is likely that the superficial deposits in this domain will have limited effect on the recharge to the aquifer.

Domain 2: Permeable Superficial Deposits over Aquifer

Typically this domain comprises those areas in which permeable superficial deposits such as the River Terrace Deposits, Till and Glaciofluvial Deposits overlie the Sherwood Sandstone through the central axis of the superficial geology model and where the granular components of the Glaciolacustrine Deposits and the Blown Sands overlie the Sherwood Sandstone on the eastern side of the superficial geology model. In these areas it is considered likely that recharge to the permeable superficial deposits will drain freely to the aquifer depending on the position of the water table.

Domain 3: 'Sand on Clay' over Aquifer

This domain largely occupies the eastern side of the superficial geology model. The 'Sand on Clay' defined in the domain comprises Blown Sand that is underlain by low permeability

Glaciolacustrine Deposits (> 3m in thickness). The groundwater level data (see e.g. Section NS_2) indicate that the Sherwood Sandstone groundwater levels are above the base of the weakly permeable deposits, showing that the domain is not perched above the Sherwood Sandstone in this area. Flow to the Sherwood Sandstone will be head-dependent, but is likely to be limited by the weakly permeable deposits. It is possible that flow to and from the Sherwood Sandstone is less restricted along the edges of this domain.

Domain 3A: Channel Deposits

The Channel Deposits have been defined as a separate domain, because these are linear features that cross a number of domains. Glacial channel deposits are inherently variable and the hydraulic conductivity may vary greatly in these channels. They form lengthy linear features and have the potential to provide a connection between otherwise disparate domains. The north-west to south-east trending channels are predominantly found in the north-western sector of the superficial geology model.

Domain 4: Weakly permeable Superficial Deposits overlying Permeable Superficial deposits

In this domain there is a potential for indirect, lateral recharge either directly to the aquifer or via another domain (e.g. the 'Sand on Clay' of Domain 3). Recharge is most likely to occur along the margins of the domain. The domain occurs in a predominantly north-west to south-east trending swathe across the north and central part of the superficial geology model.

Domain 5: Weakly permeable Superficial Deposits overlying bedrock

This domain largely comprises Alluvium and Peat or Glaciolacustrine Deposits capping the Sherwood Sandstone and minimising recharge except at the featheredge of the superficial deposits. The domain largely occurs in the northern part of the superficial geology model.

Domain 6: Mercia Mudstone at surface, or covered by less than 3 m of weakly permeable Superficial Deposits.

This comprises the domain of minimum recharge potential to the Sherwood Sandstone. Some runoff recharge to other domains may be possible given suitable topography. However, drainage (although very subdued and strongly influenced by artificial drainage systems) is largely to the east and recharge from this domain is likely to be very limited. Areas that fall within Domain 6 tend to occupy the eastern side of the superficial geology model.

Domain 7: Mercia Mudstone overlain by permeable Superficial deposits.

This domain comprises areas where one or more permeable units (Glaciofluvial Deposits, River Terrace Deposits, Glaciolacustrine basal sand, Blown Sand or Till) overlie Mercia Mudstone. There is some potential for flow from these deposits to the Sherwood Sandstone along the edge of the Mercia Mudstone.

5 Hydrogeological Uncertainty

Other superficial geology models have taken a limiting thickness of 5m to define a weakly permeable superficial deposit (e.g. Kessler *et al*, 2004). This has generally been based on the inclusion of Glacial Till as an aquitard. Tills are commonly heterogeneous and incorporate bodies of sand and gravel within them. In this area the Glacial Till has been designated a permeable lithology. The principal superficial deposit to underlie the perched aquifers in this

area is the laminated Glaciolacustrine silt and clay unit, which in the experience of both the British Geological Survey and the Environment Agency has been found to be a very low permeability unit and it is this experience that has guided the limiting thickness of 3m in the definition of the weakly permeable units.

Where specific thickness values have been used to define the domains a qualitative estimate of uncertainty associated with those values was made by producing two other domains maps to give an indication of variability associated with them. The thickness values were defined for the Glaciolacustrine silt and clay and peat units. In addition to the domains produced in Table XX, two other domains maps were produced according to the tables shown in Appendix 1.

The first map was produced by reducing the thickness values of peat and Glaciolacustrine clay and silt to 1m. The second map was produced by increasing the thickness values to 5 and 3m for Glaciolacustrine clay and silt and peat respectively. All three maps illustrate the variation in the distribution of Domains 4 and 5 related to the variation in thickness values used to define them.

Recharge is influenced by a number of contributory factors including: vegetation type, which influences evapo-transpiration and surface run-off; topography, which influences the amount of surface run-off; soil types, which also influence run-off and storage; and the depth of the unsaturated zone, which influences storage capacity and rates of recharge. Clearly therefore, there is a significant degree of uncertainty associated with ascribing numerical models to the domains without due consideration of the level of the groundwater tables and the nature of groundwater storage within the superficial deposits.

The limitations and assumptions that have been detailed in the production of the 3-D superficial geology model apply equally to the domain mapping as the domains are entirely defined by spatial queries of the 3-D superficial geological model. Furthermore, there has not been any field, or numerical verification of the domain mapping and information such as water level data has not been considered in the definition of the domains.

5.1 WATER LEVEL DATA

Water level data recorded in boreholes for key Environment Agency observation wells were provided and incorporated into the project database. Two sets of water level data were provided recording a maximum in January 2001 and a minimum in May 1997. Water level data is shown for selected observation boreholes on the cross sections shown in Appendix 1.

5.2 GIS METHODOLOGY AND CREATION OF HYDROGEOLOGICAL DOMAINS

The GIS versions of the hydrogeological domains were generated using the raster calculator in ArcGIS 9.1 (spatial analyst extension). The raster calculator manipulates gridded data and so is able to use the grids exported from the 3-D model. The grids exported for each geological unit were elevation of the top and base of the unit and its thickness.

The first stage of the process is to identify and describe each of the domains. The second stage is to define rules for each sub-domain. These rules then follow some simple spatial principles. A full description of the GIS rules is beyond the scope of this part of the report but an example of one such rule is given below.

Sub-domain 2a is defined where Glaciofluvial deposits (permeable superficial deposits comprising either pre-Ipswichian sand and gravel or Devensian sand and gravel), are present and in excess of 3m thick, overlying rocks of the Sherwood Sandstone Group. The rules defining the sub-domain were:

WHERE (gfdmp_thickness or gfdud_thickness) is greater than 3 AND is over the (Sherwood Sandstone or Zechstein Group).

Gfdmp and gfdud are codes used in the 3-D model for pre-Ipswichian and Devensian sand and gravel respectively. These rules are then translated in to commands for the raster calculator and the results saved as grids. The grids have a binary, '1' / '0', 'present' / 'not present' format.

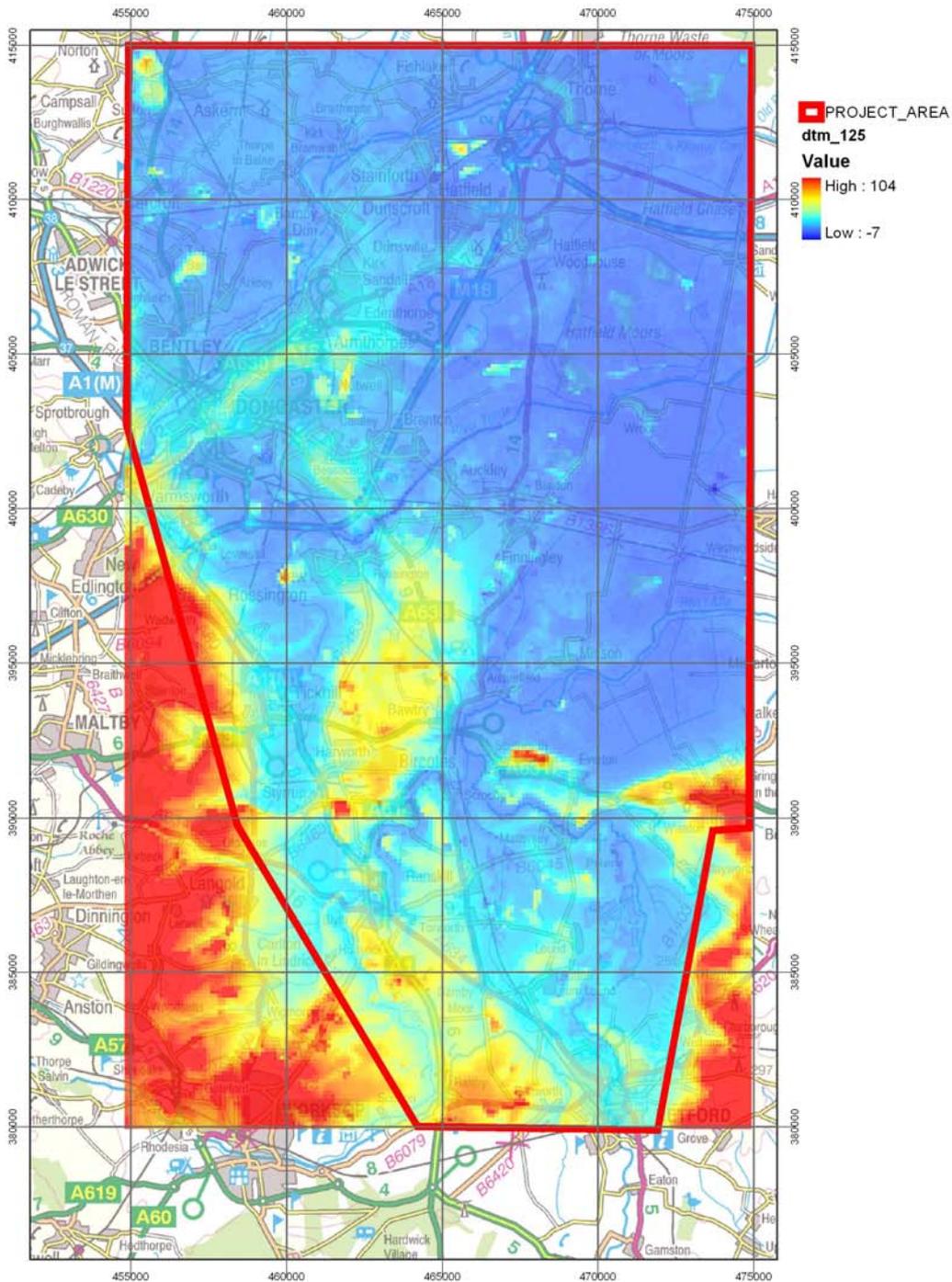
The final stage of the process is to convert the grids into vector format and remove any 0 ('not present') values from the shapefile. This leaves only the areas that satisfy the domain criteria.

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Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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Appendix 1 Figures

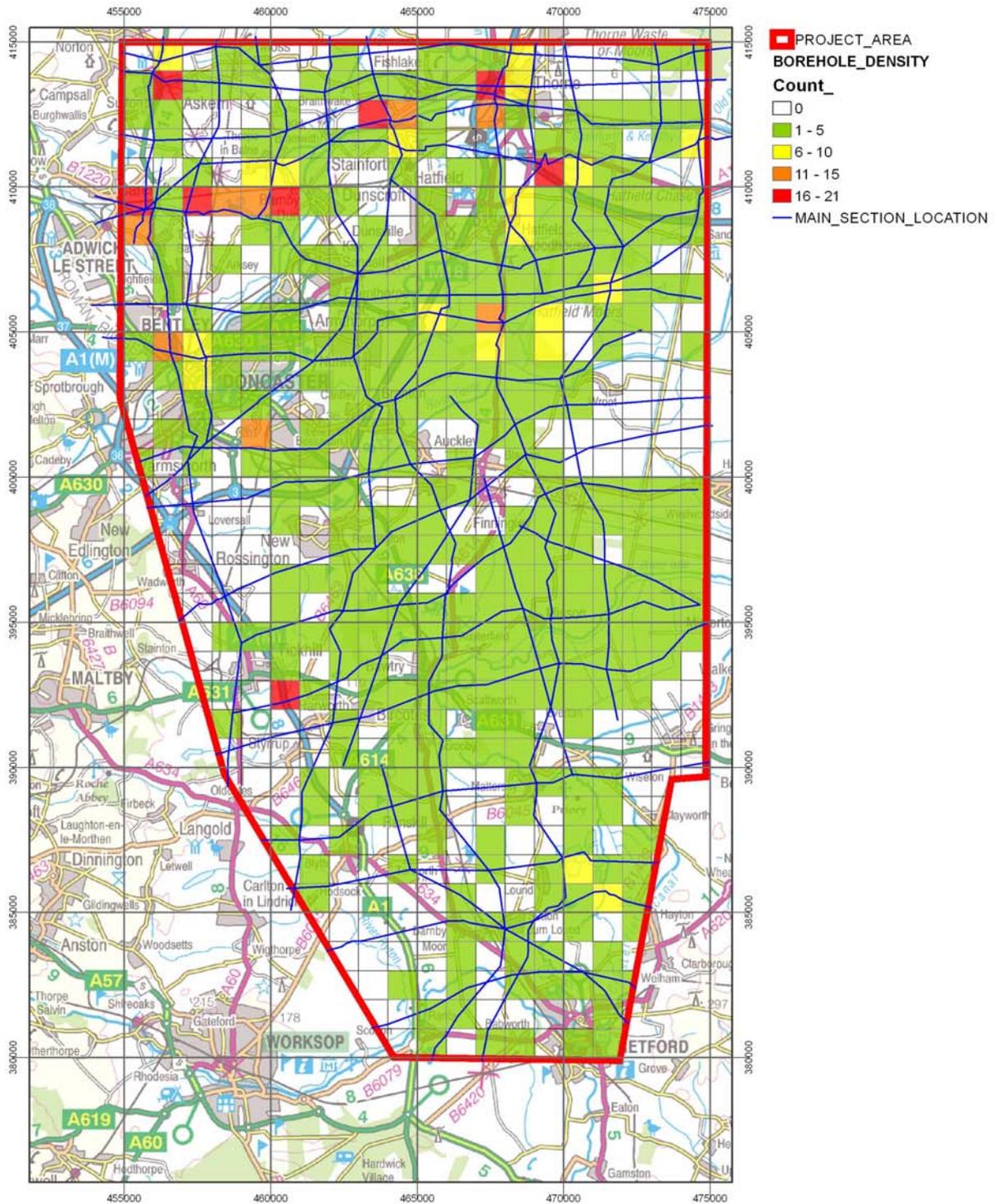


All values in metres



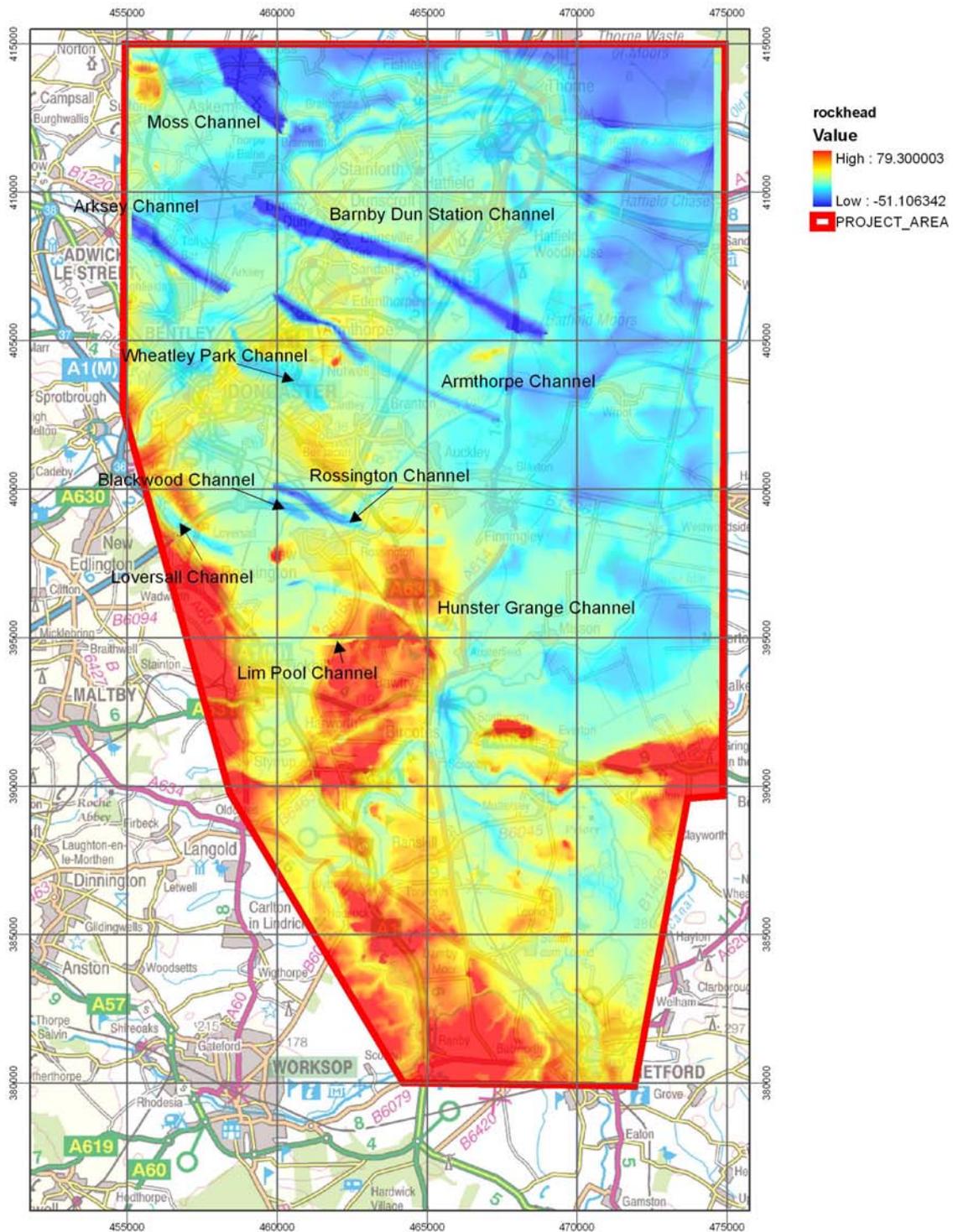
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 Topography © Crown Copyright reserved.

Figure 1 Topography within project area. NEXTMap Britain elevation data from Intermap Technologies



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Figure 2 Borehole and cross section location



Rockhead Elevation map derived from 3-D superficial geology model and NEXTMap Britain elevation data. Main buried channels shown.

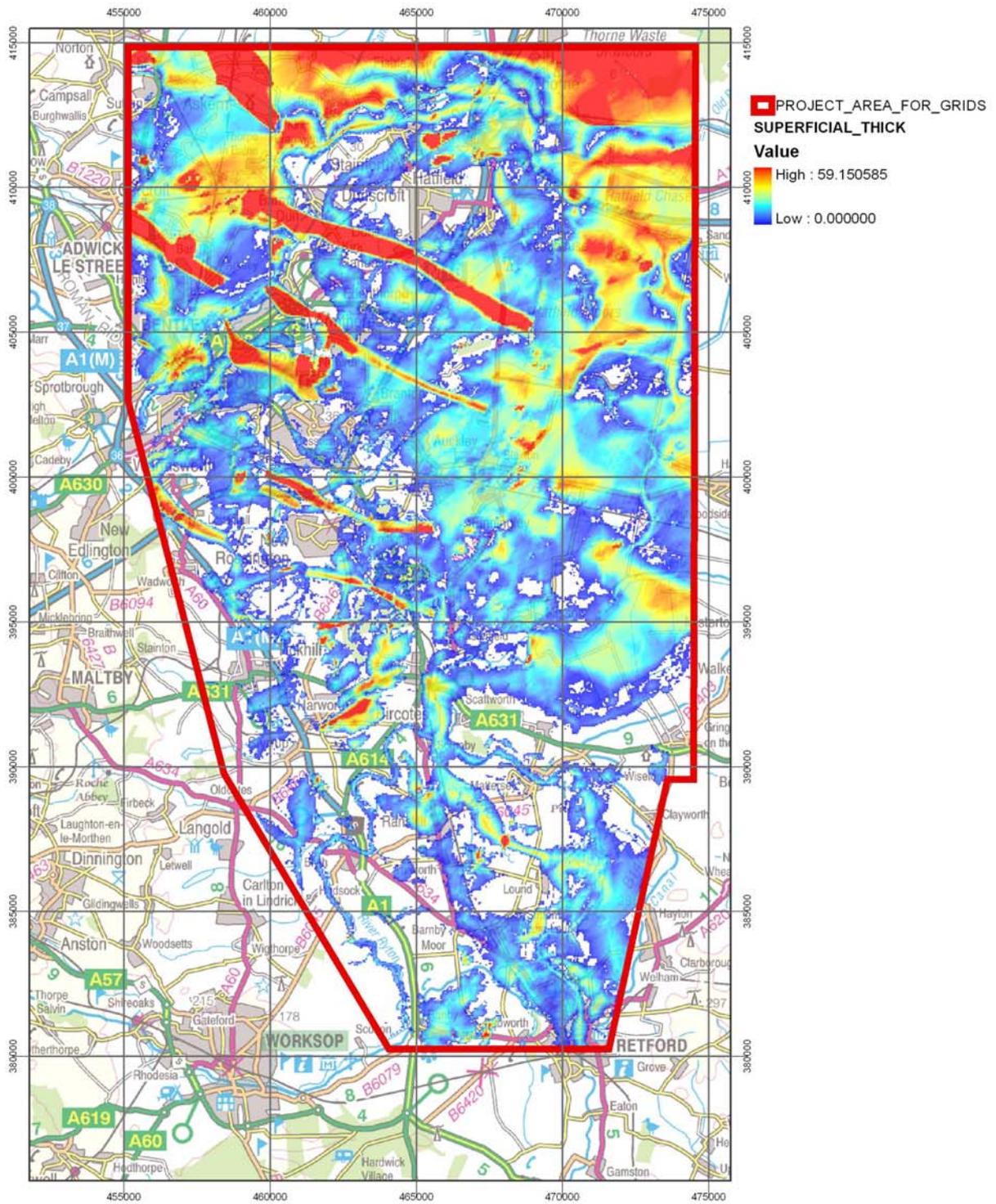
All values in metres.



NEXTMap Britain elevation data from Intermap Technologies

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Figure 3 Rockhead elevation derived from 3-D model (m)

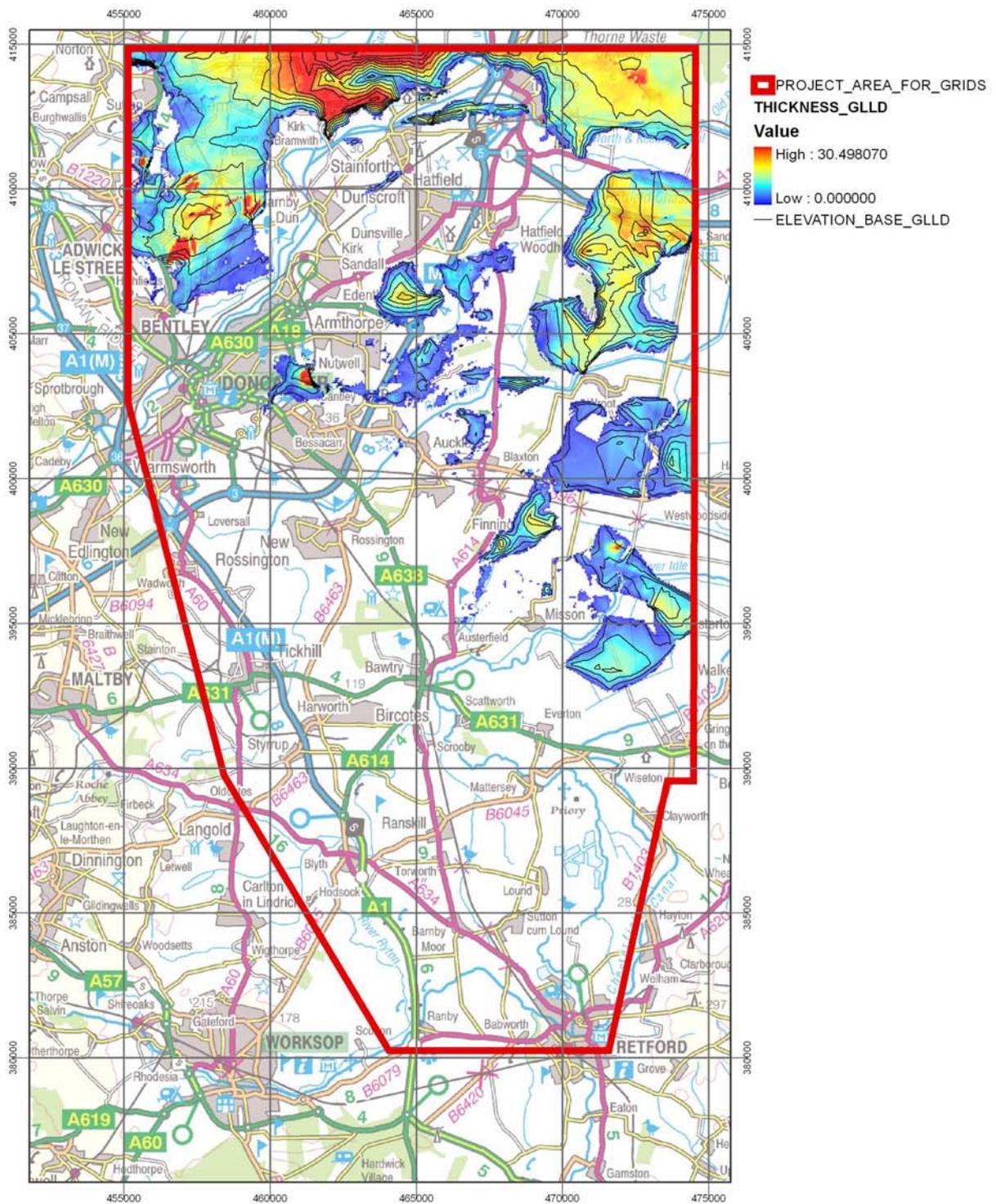


All values in metres



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Figure 4 Thickness of superficial deposits derived from 3-D model (m)

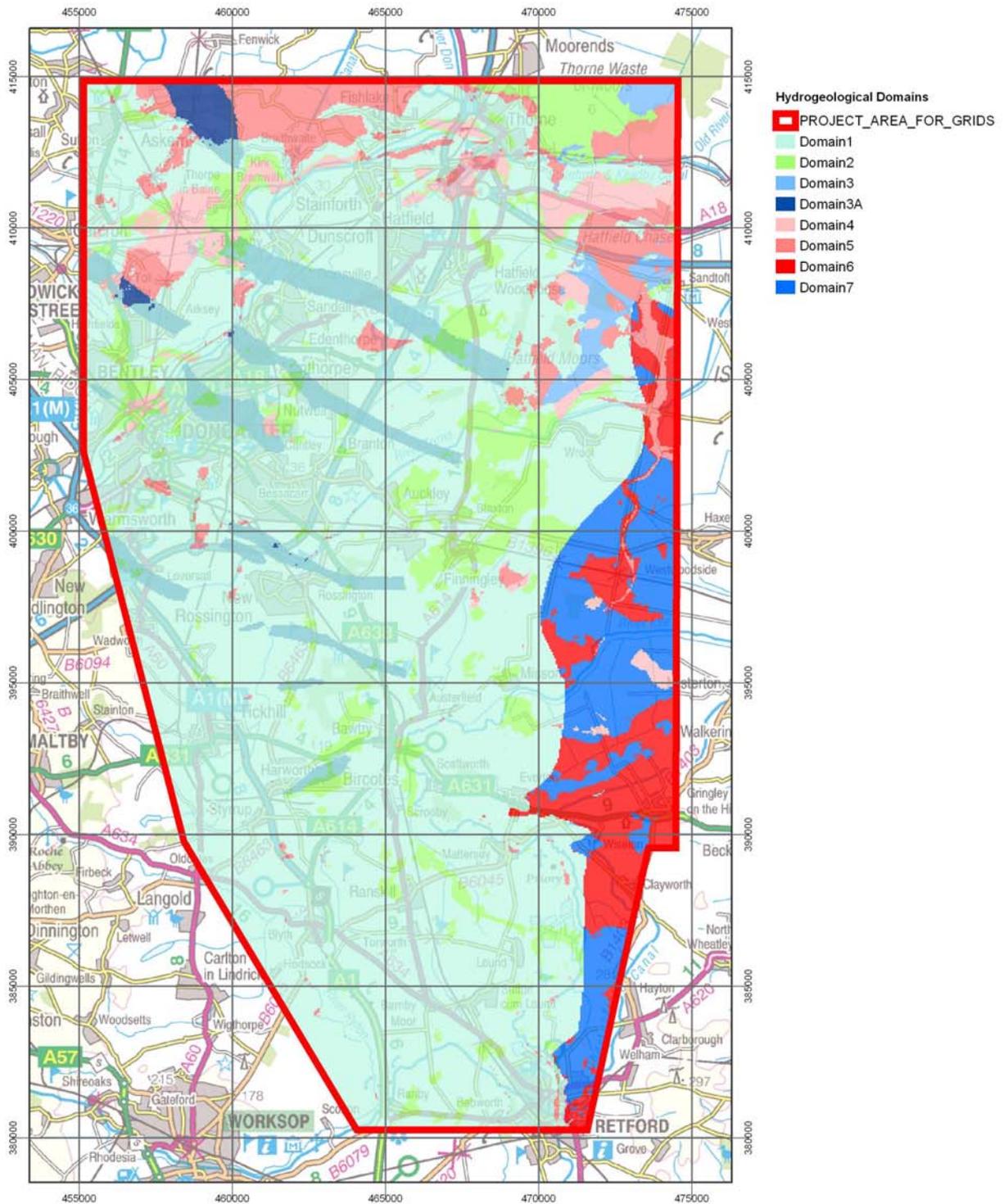


All values in metres



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Figure 6 Thickness and elevation of the base of Glaciolacustrine silt and clay (all values in m)



Hydrogeological domains increased.
 Thickness cut off values increased to 3m in Peat. Thickness in Domain1 increased to 5m to reflect increased thickness in Domains 4 and 5



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Figure 10 Thickness cut off values increased to 5m for Glaciolacustrine clay and silt and Alluvium. Thickness cut off values increased to 3m for peat. Thickness in Domain 1 increased to 5m to reflect increased thickness in Domains 4 and 5.

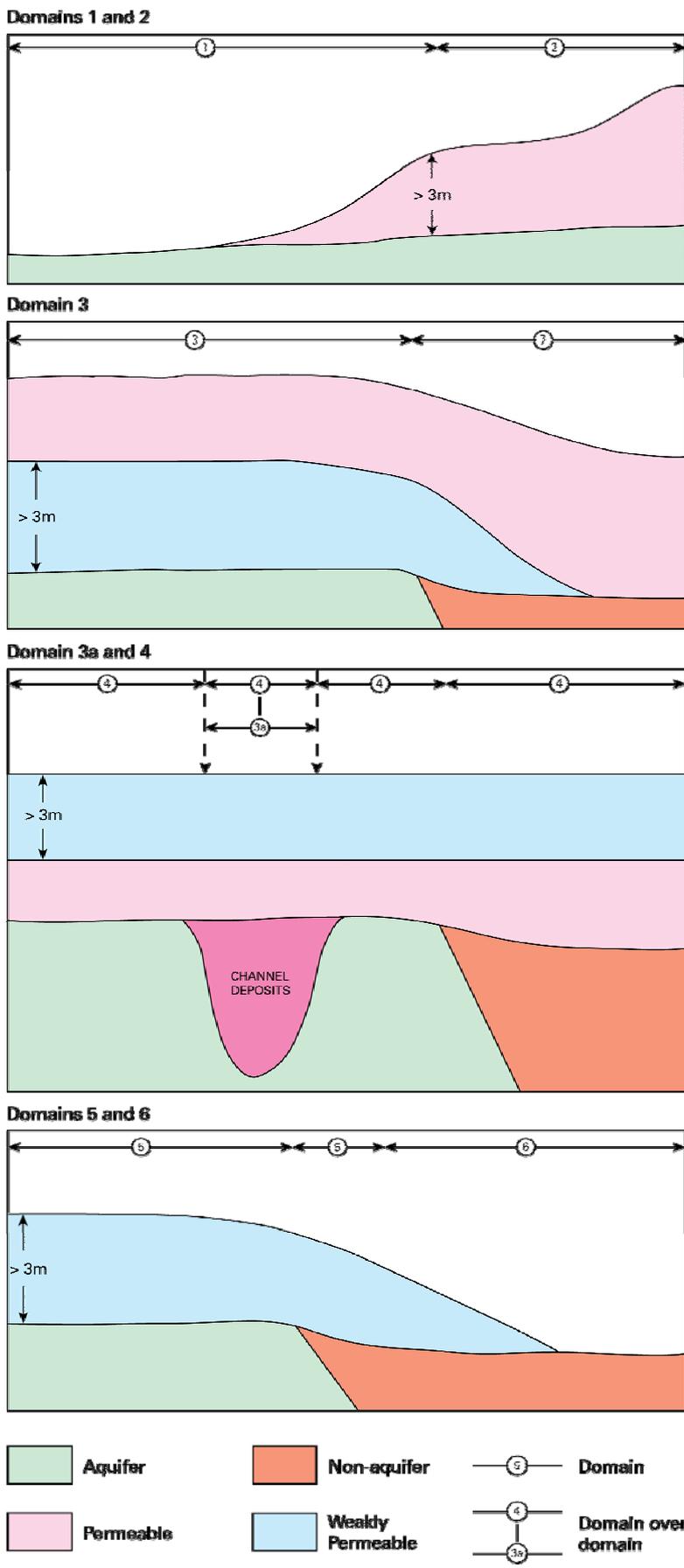


Figure 11 Schematic representation of the definition of hydrogeological domains

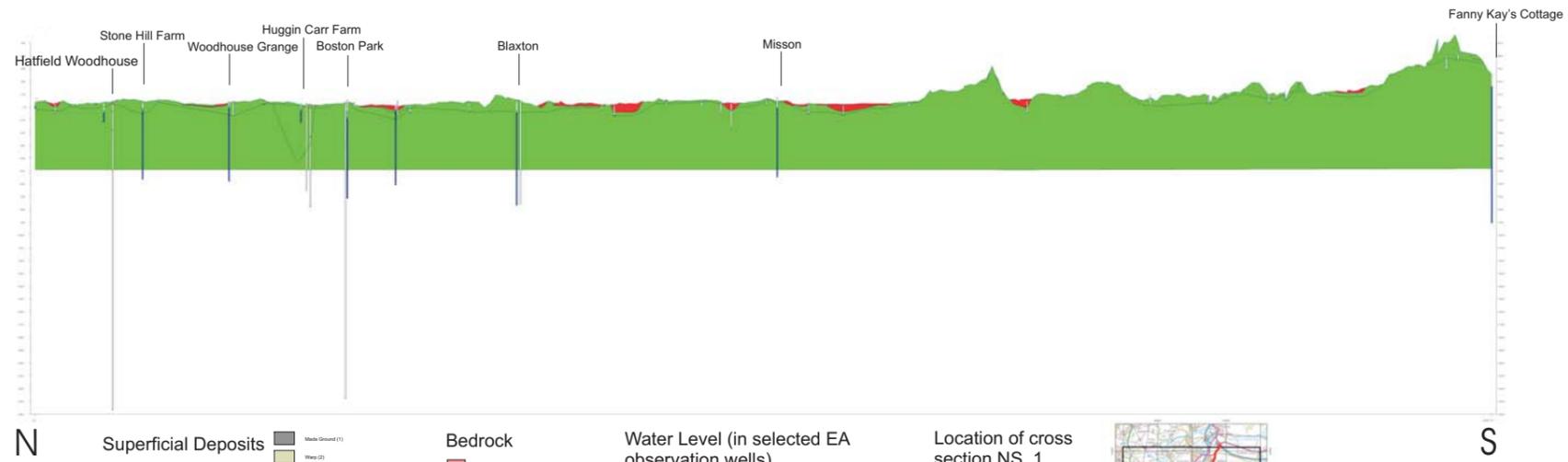
Appendix 2 Hydrogeological Domains Tables

Sub-domain		Domain	
1a	Sherwood Sandstone at outcrop	1	Sherwood Sandstone Group at outcrop and where Superficial Deposits <3m
1b	Sherwood Sandstone overlain by <3m of Superficial Deposits		
2a	Glaciofluvial Deposits	2	Permeable Superficial Deposits (one or more units present in excess of 3m) over Sherwood Sandstone Group
2b	River Terrace Deposits		
2c	Glaciolacustrine upper, or basal sand		
2d	Blown Sand		
2e	Till		
2f	Head		
3c	Blown Sand underlain by Glaciolacustrine Deposits >3m in thickness	3	'Sand on Clay' over Sherwood Sandstone Group
3a	Channel Deposits	3A	Channel Deposits over Sherwood Sandstone Group
4b	Glaciolacustrine Deposits over River Terrace Deposits	4	Weakly permeable Superficial Deposits (>1m peat, >1m other weakly permeable Superficial Deposits) capping permeable Superficial Deposits overlying Sherwood Sandstone Group, or Mercia Mudstone Group
4c	Alluvium over River Terrace Deposits		
5a	Alluvium >1m (>1m peat/warp)	5	Weakly permeable Superficial Deposits over Sherwood Sandstone Group and Mercia Mudstone Group
5b	>1m Glaciolacustrine Deposits		
6a	Mercia Mudstone Group at outcrop	6	Mercia Mudstone Group overlain by <3m of weakly permeable Superficial Deposits
6b	Mercia Mudstone Group overlain by < 3m of weakly permeable Superficial Deposits		
7	Mercia Mudstone Group overlain by one or more units of Glaciofluvial Deposits, River Terrace Deposits, Glaciolacustrine basal sand, Blown Sand or Till	7	Mercia Mudstone Group overlain by permeable Superficial Deposits

Domains uncertainty Table 1. Thickness cut off values reduced to 1m for Glaciolacustrine silt and clay, peat and alluvium.

Sub-domain		Domain	
1a	Sherwood Sandstone at outcrop	1	Sherwood Sandstone Group at outcrop and where Superficial Deposits <5m
1b	Sherwood Sandstone overlain by <5m of Superficial Deposits		
2a	Glaciofluvial Deposits	2	Permeable Superficial Deposits (one or more units present in excess of 3m) over Sherwood Sandstone Group
2b	River Terrace Deposits		
2c	Glaciolacustrine upper, or basal sand		
2d	Blown Sand		
2e	Till		
2f	Head		
3c	Blown Sand underlain by Glaciolacustrine Deposits >3m in thickness	3	'Sand on Clay' over Sherwood Sandstone Group
3a	Channel Deposits	3A	Channel Deposits over Sherwood Sandstone Group
4b	Glaciolacustrine Deposits over River Terrace Deposits	4	Weakly permeable Superficial Deposits (>3m peat, >5m other weakly permeable Superficial Deposits) capping permeable Superficial Deposits overlying Sherwood Sandstone Group, or Mercia Mudstone Group
4c	Alluvium over River Terrace Deposits		
5a	Alluvium >5m (>3m peat/warp)	5	Weakly permeable Superficial Deposits over Sherwood Sandstone Group and Mercia Mudstone Group
5b	>5m Glaciolacustrine Deposits		
6a	Mercia Mudstone Group at outcrop	6	Mercia Mudstone Group overlain by <5m of weakly permeable Superficial Deposits
6b	Mercia Mudstone Group overlain by < 5m of weakly permeable Superficial Deposits		
7	Mercia Mudstone Group overlain by one or more units of Glaciofluvial Deposits, River Terrace Deposits, Glaciolacustrine basal sand, Blown Sand or Till	7	Mercia Mudstone Group overlain by permeable Superficial Deposits

Domains uncertainty Table 2. Thickness cut off values increased to 5m for Glaciolacustrine clay and silt and Alluvium. Thickness cut off values increased to 3m for peat. Thickness in Domain 1 increased to 5m to reflect increased thickness in Domains 4 and 5.



Superficial Deposits

- Medio Gravel (1)
- Wey (2)
- Flint (3)
- Alkham (4)
- Blaxton Sand (5)
- River Terrace Deposits (6)
- Heal (7)
- Glaucouslime Sand (8)
- Glaucouslime Laminated Clay and SA, some Sand (9)
- Glaucouslime Lower Sand (10)
- Clayford Deposits (11)
- 'Old' River Gravel (12)
- Pre-Speersham Clayford Deposits (13)
- TS (14)
- Channel Deposits (15)

Bedrock

- Meria Mudstone Group
- Downed Sandstone Group
- Fensian (unlabelled)

Hydrogeology

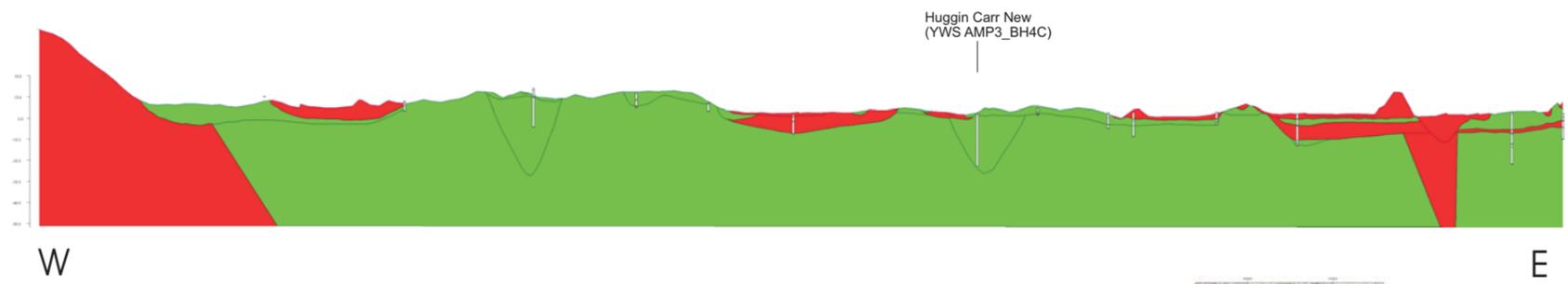
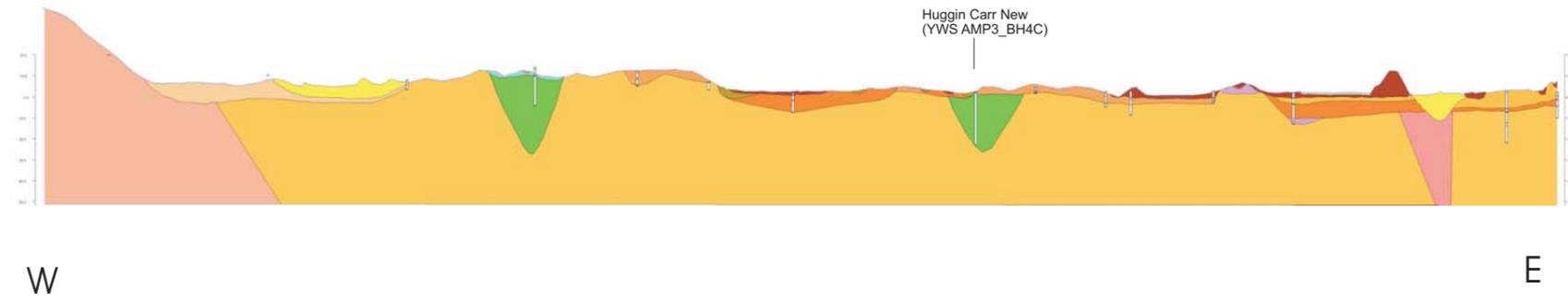
- Permeable
- Woolly permeable

Water Level (in selected EA observation wells)

- Unaturated
- Maximum Water Level (January 2001)
- Minimum Water Level (May 1997)

Location of cross section NS_1





Superficial Deposits



- Medio Gravel (1)
- Wey (2)
- Flint (3)
- Alkham (5)
- Blair Sand (5)
- River Terrace Deposits (5)
- Heal (7)
- Glauconitic Sand (8)
- Glauconitic Laminated Clay and Silts, with Sand (8)
- Glauconitic Lower Sand (10)
- Clayey Deposits (11)
- 'Older' River Gravel (12)
- Pre-glacial Channel Deposits (13)
- T8 (14)
- Channel Deposits (15)

Bedrock

- Meria Mudstone Group
- Sharnford Sandstone Group
- Flemish Limestone

Hydrogeology

- Permeable
- Weakly permeable

Water Level (in selected EA observation wells)

- Unstabilised
- Maximum Water Level (January 2001)
- Minimum Water Level (May 1997)

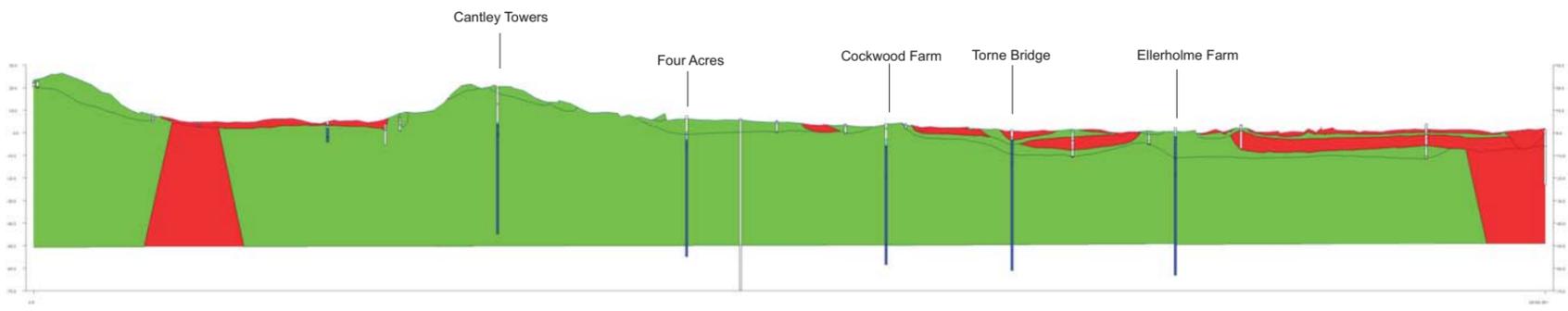
Location of cross section WE_6





W

E



W

E

Superficial Deposits

- Medio Gravel (1)
- Wey (2)
- Fine (3)
- Alluvium (4)
- Blown Sand (5)
- Fluvial Terrace Deposits (6)
- Heath (7)
- Glaucouslime Sand (8)
- Glaucouslime Laminated Clay and Sil. silt. Sand (9)
- Glaucouslime Loam Sand (10)
- Clayey Gravel (11)
- 'Older' River Gravel (12)
- Pre-Speonian Glacial Deposits (13)
- TS (14)
- Channel Deposits (15)

Bedrock

- Meria Mudstone Group
- Sharnford Sandstone Group
- Fensian (unstratified)

Hydrogeology

- Permeable
- Weakly permeable

Water Level (in selected EA observation wells)

- Unstratified
- Maximum Water Level (January 2001)
- Minimum Water Level (May 1997)

Location of cross section WE_3





Superficial Deposits

- Wash Gravel (1)
- Wash (2)
- Flint (3)
- Alluvium (4)
- Blown Sand (5)
- River Terrace Deposits (6)
- Heath (7)
- Glauconitic Sand (8)
- Glauconitic Laminated Clay and Sil. silt. Sand (9)
- Glauconitic Loam Sand (10)
- Clayey Sand (11)
- 'Older' River Gravel (12)
- Pre-Speonian Glauconitic Deposits (13)
- Till (14)
- Channel Deposits (15)

Bedrock

- Meria Mudstone Group
- Downland Sandstone Group
- Permian Sandstone

Hydrogeology

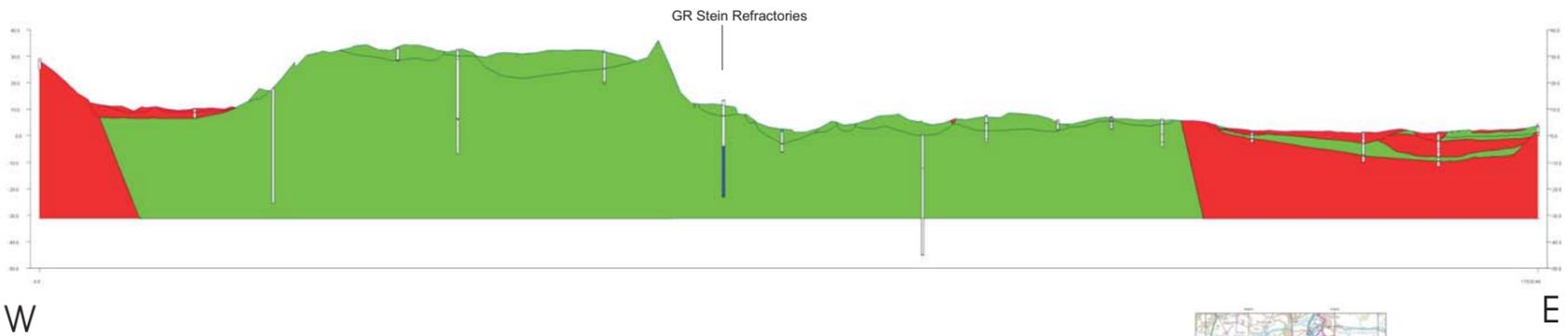
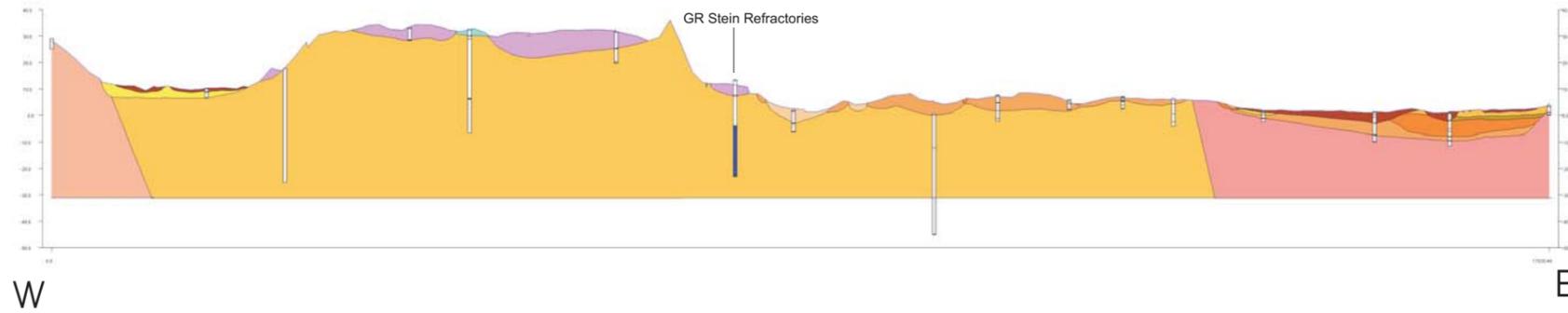
- Permeable
- Weakly permeable

Water Level (in selected EA observation wells)

- Unstabilised
- Maximum Water Level (January 2001)
- Minimum Water Level (May 1997)

Location of cross section WE_2





Superficial Deposits

- Wash Gravel (1)
- Wey (2)
- Flint (3)
- Alluvium (4)
- Blown Sand (5)
- River Terrace Deposits (6)
- Heath (7)
- Glauconitic Sand (8)
- Glauconitic Laminated Clay and Sil. with Sand (9)
- Glauconitic Lower Sand (10)
- Glauconitic Deposits (11)
- 'Older' River Gravel (12)
- Pre-Speersham Glauconitic Deposits (13)
- TB (14)
- Channel Deposits (15)

Bedrock

- Meria Mudstone Group
- Sharnford Sandstone Group
- Fensian (unroofed)

Hydrogeology

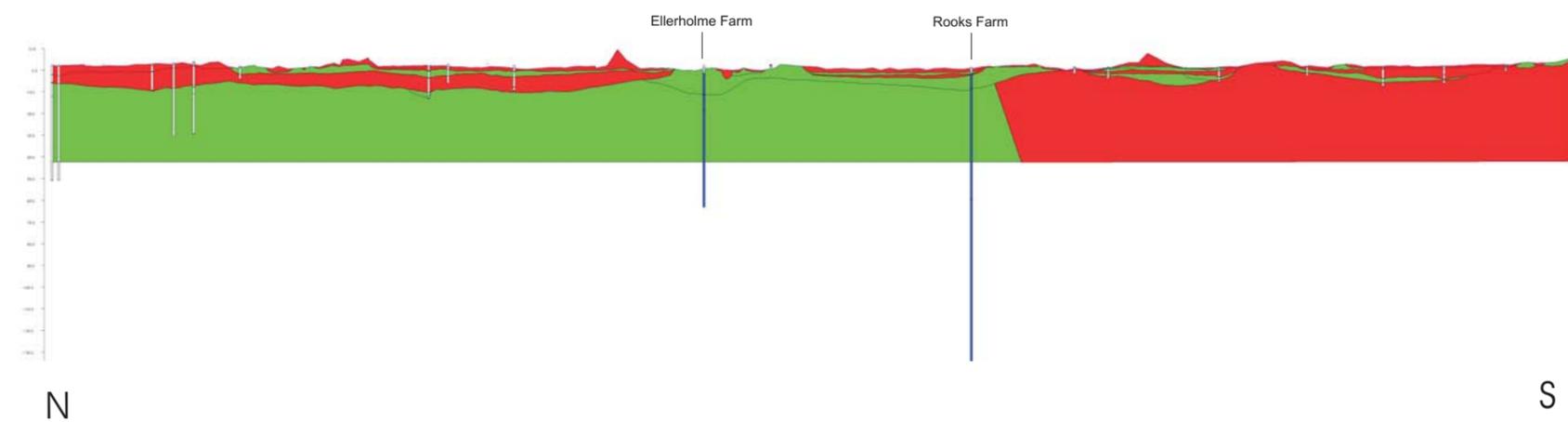
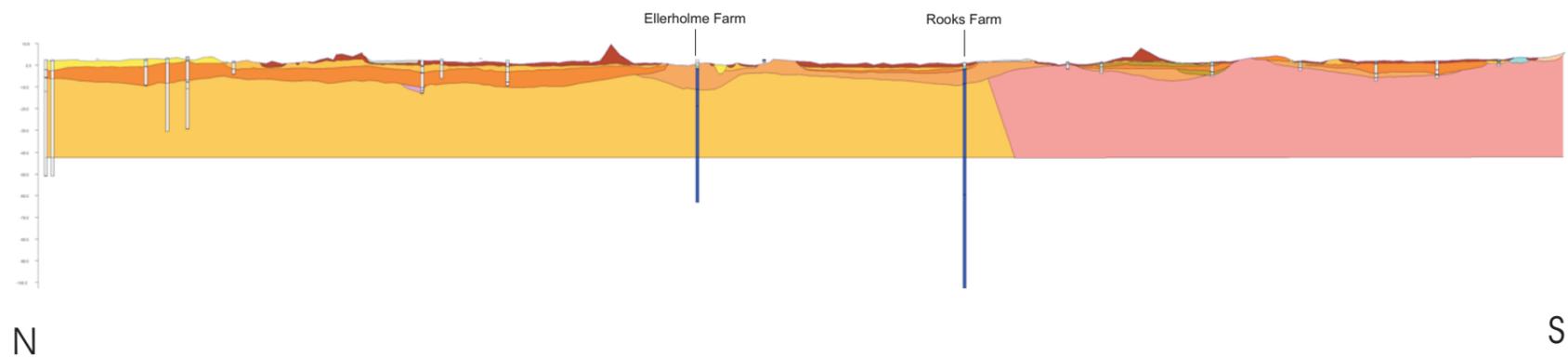
- Permeable
- Mostly impermeable

Water Level (in selected EA observation wells)

- Unroofed
- Maximum Water Level (January 2001)
- Minimum Water Level (May 1997)

Location of cross section WE_5





Superficial Deposits

- Muds (1)
- Silt (2)
- Fine (3)
- Alluvium (4)
- Blown Sand (5)
- River Terrace Deposits (6)
- Head (7)
- Glauconitic Sand (8)
- Glauconitic Laminated Clay and Silty, silty Sand (9)
- Glauconitic Lower Sand (10)
- Glauconitic Deposits (11)
- Older River Gravel (12)
- Pre-Speersham Glauconitic Deposits (13)
- T8 (14)
- Channel Deposits (15)

Bedrock

- Mersa Mudstone Group
- Sharnford Sandstone Group
- Permian (unlabelled)

Hydrogeology

- Permeable
- Weakly permeable

Water Level (in selected EA observation wells)

- Unlabelled
- Maximum Water Level (January 2001)
- Minimum Water Level (May 1997)

Location of cross section NS_2

