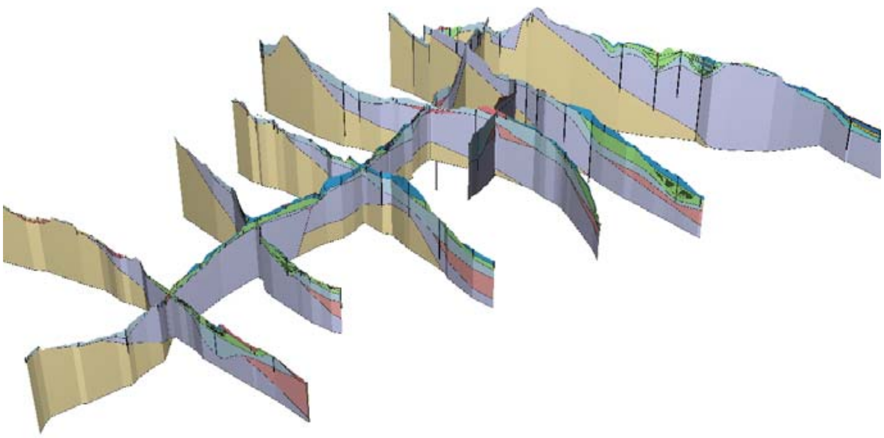
Superficial Geology and Hydrogeological Domains between Durham and Darlington Phase 1 (Durham South)

Report prepared for the Environment Agency by the British Geological Survey

Commercial Report CR/07/002N



BRITISH GEOLOGICAL SURVEY

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Front cover

Geological fence diagram for Durham South area.

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Foreword

This report is the published product of a commissioned study by the British Geological Survey (BGS) Geology and Landscape North and Geology and Landscape South Programmes on behalf of the Environment Agency North East Region.

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1 Introduction

The North East Region's Groundwater Modelling Strategy has identified the need for the development of a conceptual model for the Magnesian Limestone aquifer. In line with the Environment Agency R&D Technical Report W214 (Environment Agency Framework for Groundwater Resources Conceptual and Numerical Modelling), a scoping study was produced, that identified areas of uncertainty and work required for the development of the conceptual model.

The purpose of this project is to give the Environment Agency (EA) a regional understanding of the geology and hydrogeology of the Magnesian Limestone and overlying superficial deposits in the North East Region, using information presently held by the British Geological Survey (BGS). This report contributes to the conceptual model and understanding of the Magnesian Limestone aquifer.

There is uncertainty in the amount of recharge that the Magnesian Limestone receives from rainfall. The project is designed to gain a greater understanding of the geology of the superficial deposits and their hydrogeological properties. These are the key factors for the calculation of recharge to the Magnesian Limestone aquifer from rainfall. This element of the conceptual model is essential in understanding the potential water resource available within this aquifer.

1.1 SCOPE

The scope of the BGS project is to provide an interpretation of the geology of the superficial deposits overlying the Permian strata of the Durham area and to derive hydrogeological domains within them. It is important to note that the hydrogeological domains were derived from a computer analysis of interpreted boreholes within the project area. This was a separate exercise from the production of the geological cross-sections.

The geological sequence of interest comprises the Carboniferous Coal Measures, Namurian Stainmore Group and the basal Permian Sands, which lie beneath the Permian Magnesian Limestone and Marls. This phase of the study set out to interpret the regional geology of the superficial deposits lying above the bedrock sequence and develop hydrogeological domains within them, similar to those produce for the Manchester urban study (Crofts *et al*, 2006). These hydrogeological domains will be used by the EA to develop a recharge model for the Magnesian Limestone aquifer and will be integrated into current projects.

This study area has been split into the following 3 phases for management purposes and to meet deadlines of current projects: 1. Durham South (of which this report summarises the results); 2. Durham North; 3. Permian bedrock desk study, including 6 geological cross-sections.

Figures for the report are included in Appendix 1 and paper copies of the cross-sections in Appendix 4. Digital images of cross-sections, both as raw jpeg images and Corel draw diagrams are supplied separately on the accompanying project delivery CD.

2 Geological Summary

2.1 BACKGROUND

The first stage when constructing cross-sections using GSI3D software (© Insight GmbH) is to set up a generalised vertical section (GVS). To do this a review of existing literature was undertaken. Much of this literature has been summarised in Stone, Millward & Young (In prep.) for the forthcoming BGS British Regional Geology publication for Northern England. The lithostratigraphic summary from this report was used to define the GVS for the Durham superficial deposits study.

Correlation of geological units based on lithostratigraphy was chosen in preference to lithology because it allows a better representation of the glacial geological history and clearly shows packages of sediments that were deposited in specific glacial environments. Two glacigenic subgroups that contain deposits from the two main ice masses that impinged on the study area contain lithostratigraphic units that equate to each other in terms of time and process of deposition (see Table 1). Equivalent units were placed adjacent to each other in the GVS column. This summary and comparison of glacigenic subgroups has helped to condense a large amount of diverse and previously poorly constrained data for this area and the resulting geological cross-sections provide the best and clearest summary to date of the regional superficial geology.

	North Pennine Glacigenic Subgroup	**North Sea Coast Glacigenic Subgroup**
Late Devensian	Ebchester Sand and Gravel Formation	Fulwell Hill Sand and Gravel (not present in study area)
	Un-named Morainic deposits	Elwick Moraine Member
	Butterby Till Member	Horden Till Member
	Tyne and Wear Glaciolacustrine Formation	Peterlee Sand Formation
	Wear Till Formation	Blackhall Till Formation
Pre-Late Devensian	Maiden's Hall Sand and Gravel Formation	

Table 1 Comparison of glacigenic subgroups

2.2 BEDROCK

The bedrock underlying the Darlington, Durham and Sunderland area comprises Permian rocks in the east, which unconformably overly Carboniferous rocks to the west. The bedrock is simplified for schematic representation in the superficial deposits cross-sections into Permian Marls, Magnesian Limestone, Permian Yellow Sands (not differentiated in the Durham south cross-sections, but possibly present) and Carboniferous Coal Measures. The Permian Marls include the undivided Edlington Formation and Hartlepool Anhydrite (or gypsum) Formation at the top of the sequence; these consist of calcareous and gypsiferous mudstones with gypsum beds. The Magnesian Limestone includes the Raisby and Ford formations, which are indivisible in most boreholes and comprise dolomitic limestones and dolostones that form the main aquifer bodies in the area. The Permian Yellow Sands (Yellow Sands Formation) are weakly cemented, aeolian sandstones, distributed in ridges that represent buried sand dunes beneath the Magnesian Limestone. The Carboniferous Coal Measures are dominantly interbedded sandstones and mudstones with coal seams and thin limestone bands. They include Westphalian Coal Measures and parts of the Stainmore Group of Namurian age. More complete details and geological cross-sections of the Permian and Carboniferous sequence will be included in the bedrock-modelling phase of this study (Phase 3).

2.3 SUPERFICIAL DEPOSITS

The superficial deposits consist of glacial and associated glaciolacustrine and glaciofluvial sediments of Late Devensian age overlain by younger Flandrian deposits. The Late Devensian deposits have been divided using the lithostratigraphic nomenclature outlined in Stone, Millward & Young (In Prep.). The sequence of superficial deposits is shown in Table 2. The existing digital 1:50 000 geological superficial geology map is shown in Figure 1 and geological cross-sections referred to in the text are provided in Appendix 4. Digital versions of the cross-sections are included on the accompanying CD.

The Late Devensian deposits rest predominantly on bedrock. The bedrock surface represents a pre-Devensian erosion surface, into which several buried channels, mostly of east-west orientation, up to 80 m deep, were cut and later filled during the early stages of the Late Devensian glaciation. During the glaciation, ice streamed down the North Sea coast from the Tweed basin and other sources to the north (North Sea Ice Stream). In addition, a number of glaciers flowed across the area from the west, bringing ice from the Southern Uplands and Lake District across the Tyne and Stainmore Gaps respectively (North Pennine Ice Sheet). Local ice centres were also present, but probably cold-based and non-erosive, over the higher ground in the North Pennines and Cheviots (Stone, Millward & Young, In Prep.).

Superficial deposits of Late Devensian age in the study area demonstrate the interaction of the two main ice masses, the offshore (North Sea) and onshore (North Pennine) ice. Consequently, the Late Devensian deposits are classified into two Glacigenic Subgroups. Sediments sourced from the North Sea ice are classified under the **North Sea Coast Glacigenic Subgroup**, and those sourced from the North Pennine ice are in the **North Pennine Glacigenic Subgroup**. The boundary between the two subgroups occurs at the western-most edge of North Sea ice encroachment, which is marked by the presence of the Elwick Moraine Member between Sheraton and Elwick, and in the area around Darlington. The North Pennine Glacigenic Subgroup occurs predominantly to the west of this ice limit, with the North Sea Coast Glacigenic Subgroup predominantly on the eastern (coastal) side. The approximate margin of the North Sea ice is shown in Figure 2.

The two glacigenic subgroups contain a similar, ‘tripartite’ sequence of sediments, broadly consisting of lower and upper tills separated by an intervening glaciolacustrine, or in some places glaciofluvial, unit. This ‘tripartite’ sediment sequence has been interpreted as evidence for a period of ice advance in the Late Devensian, which deposited the basal tills, followed by a partial retreat of the onshore ice mass, during which a separation or period of buoyancy of the North Pennine ice and North Sea ice occurred. During this time a large glacial lake system, Glacial Lake Wear, developed as rivers carrying water from the retreating North Pennine ice mass in the west were dammed up against the North Sea ice that remained along the coastal region (Figure 2). At this same time subglacial channels were cut in tunnel valleys beneath the two main ice sheets and filled with glaciofluvial, glaciolacustrine and deformation tills where ice partially readvanced or resettled after a period of buoyancy. The channels tend to be parallel to the direction of the ice flow in a northeast-southwest or northwest-southeast orientation. The upper till units were deposited during a later ice re-advance over the area following deposition of these glaciolacustrine, glaciofluvial and deformation till sediments in the buried channels (Stone, Millward & Young, In Prep.).

Table 2 Stratigraphy of superficial deposits

Age	Generic Name	Litostratigraphic Name*	Thickness	Description	Glacigenic Subgroup
Recent	Made ground	Made ground (18)	0-10 m	Anthropogenic deposits.	
Flandrian	Marine deposits	Marine deposits (17)	0-5 m	Sand and gravel.	
	River Terrace Deposits	River Terrace Deposits (16)	0-10 m	Sand and sand and gravel terraces	
	Alluvium	Alluvium (15)	0-10 m	Interbedded sand, sand and gravel and silty clay in active river channels.	
	Peat	Peat (14)	>1 m	Peat.	
	Lacustrine deposits	Lacustrine deposits (13)	0-20 m	Soft to firm lacustrine clay, silt and sand. Some peat horizons.	
	Tidal flat deposits	Tidal flat deposits (12)	0-5 m	Sandy, silty clay.	
	Raised marine deposits	Raised marine deposits (11)	0-2 m	Thin and patchy clay and sand deposited on a marine terrace cut into superficial deposits.	
Late Devensian	Glaciofluvial sand and gravel	Ebchester Sand and Gravel Formation (10)	0-20 m	Glaciofluvial sand and gravel lying in isolated mounds or forming terraces on valley sides.	North Pennine
	Ice marginal diamictons and rafted till	un-named moraine (9)	0-5 m	Clay with boulders and gravel.	North Pennine
		Elwick Moraine Member (8)	0-5 m	Moundy deposits of sand and gravel containing shell fragments, sand, contorted silts, clays and pebbly clay diamictons. Locally comprises mostly till in push moraines.	North Sea Coast
	Upper deformation tills	Horden Till Formation (7)	min 2-10 m	Brown or red-brown clay with gravel. Stiff, contains a relatively high proportion of clasts of Upper Magneisan Limestone.	North Sea Coast
		Butterby Till Member (6)	min 2-20 m	Silty to sandy clay, stiff, reddish brown to brown, with sparse to abundant gravel. (Includes Pelaw Clay Member of Smith (1994)).	North Pennine
	Glaciofluvial and Glaciolacustrine Deposits	Peterlee Sand Formation (5)	min 0-15 m	Glaciofluvial sand, silt and clay, commonly coarsening upwards to gravel but within buried valleys locally comprised of up to 30m laminated clay.	North Sea Coast
		Tyne and Wear Glaciolacustrine Formation (4)	up to 50 m	Lacustrine clay and sandy/silty clay with lenses of sand, sand and gravel, and thin interbedded tills. In some areas sand and gravel dominates.	North Pennine
	Lower lodgement tills	Blackhall Till Formation (3)	up to 35 m	Silty clay with sand, gravel and cobbles. Grey to brown.	North Sea Coast
		Wear Till Formation (2)	up to 60 m	Silty or sandy clay with gravel, cobbles and/or boulders. Firm to stiff, extremely consolidated, stony, brown/blue with lenses of clay, silty clay, sand and sand and gravel.	North Pennine
	Basal sand and gravel	Maiden's Hall Sand and Gravel Formation (1)	up to 10 m	Sand or sand and gravel filling buried valleys in the bedrock.	North Pennine

Numbers in table refer to description of units within text and cross-section diagrams for clarity

2.3.1 Rockhead and Buried Channels

Rockhead elevation decreases to the east, resulting in a corresponding increase in thickness of superficial deposits eastwards towards the coast. In the west of the area, outcrops of bedrock are common and the superficial deposits are thin and patchy. In the area between Durham and Sunderland the Magnesian Limestone escarpment forms a distinctive north-south trending topographic ‘high’ with very little cover of superficial deposits. There is an extensive topographic depression in the area south of Hartlepool, towards the eastern ends of the E-W trending section lines, where soft bedrock (Edlington Formation) is present and rockhead lies below sea level.

A number of channels have been cut into the bedrock surface at least two stages in the glacial history of the area. Early (Pre-Devensian) channels generally trend east-west and later (possibly Devensian) channels trend generally northwest-southeast or northeast-southwest. These channels are up to 80 m deep and are filled with a complex sequence of clay, sand and gravel and diamictons of the Tyne and Wear Glaciolacustrine Formation (see section 2.2.3), underlain by the lower till. Notable channels are seen in cross-sections DS_3 and DS_4, to the west of Darlington, and DS_8, to the West of Hartlepool.

2.3.2 Late Devensian deposits: Lower tills

The lower till units rest directly on bedrock, or locally on isolated pockets of sand and gravel that occupy hollows in the bedrock surface. This basal sand and gravel unit is the **Maiden’s Hall Sand and Gravel Formation** (1) that fills a 10 m bedrock depression beneath the lower till at the point where section DS_1 crosses section DS_6, to the west of Sedgefield. The lower tills are extremely consolidated lodgement tills, which formed beneath flowing glacial ice, and contain many clasts of varying sizes in a matrix of clay, silt and clay.

In the area to the west of the North Sea ice limit, the lowest till unit is called the **Wear Till Formation** (2) (North Pennine Glacigenic Subgroup). It consists of blue to brown silty or sandy clay with gravel, cobbles and sporadic boulders. Clasts comprise mainly Carboniferous sandstone and mudstone with some coal, together with Whin Sill dolerite and erratics of igneous rocks from the Lake District and southern Scotland. Magnesian Limestone clasts are abundant where the Wear Till Formation overlies it. It also contains some lenses of clay, silty clay, sand and sand and gravel. The Wear Till Formation generally thickens eastwards up to a maximum of 60 m.

Along the Durham coast to the east of the North Sea Ice limit, the basal till is the **Blackhall Till Formation** (3), found to the eastern end of section DS_8. This is a stiff, grey to brown silt or clay with sand, gravel, cobbles and shell fragments. Clasts of Carboniferous sandstone, mudstone, limestone and coal are present along with rocks from the Southern Uplands and some local Permian lithologies from south of the Tyne.

2.3.3 Late Devensian deposits: Glaciofluvial and glaciolacustrine sediments

Sandwiched between the lower and upper till units is a complex sequence of glaciolacustrine sediments. These may be up to 50 m thick in buried valleys and up to 30 m thick in other areas. The sediments, termed the **Tyne and Wear Glaciolacustrine Formation** (4), consist largely of brownish-grey clay and silty clay or sandy clay, which is frequently laminated. Isolated lenses or pockets of sand or sand and gravel may be present within the clay. In buried valleys, such as those in section DS_8 near White Hurworth Farm [GR 4401 5345], the unit consists largely of sand and gravel, sand and sandy silt and frequently contains several lenses of pebbly clay and gravelly diamictons, which are interpreted as sub-glacial deformation tills (Merritt, J.W Pers. Com). This complex sequence was deposited in several lake basins during periods of ice retreat or ice buoyancy in the Late Devensian glaciation.

To the east of the North Sea ice limit, the middle unit of the ‘tripartite’ sequence is the **Peterlee Sand Formation** (5). This is a predominantly glaciofluvial deposit, which is sandy and may be cross-bedded; in some areas the unit may be gravelly. It also contains lenses of diamictons that are thought to have a similar origin to those in the Tyne and Wear Glaciolacustrine Formation.

The Peterlee Sand Formation is found in the Durham South area at the eastern end of section DS_8.

2.3.4 Late Devensian deposits: Upper tills

The upper till units overly the glaciofluvial and glaciolacustrine sediments in many areas, and sometimes rest directly on the lower till. These upper tills contain fewer clasts than the lower tills, are less consolidated and in many areas consist largely of clay. This has lead to a variety of interpretations, including the suggestion that they may be weathered surfaces of the underlying till or some other deposit. In this project the definitions from Stone, Millward & Young (In Prep.) have been used. They interpreted the units as deformation tills formed by ice moving over soft, deformable beds and typically containing very dispersed clasts. In places these upper tills and till lenses within the Tyne and Wear Glaciolacustrine Formation can be seen to overlie deformed glaciolacustrine deposits, for example, in sections at Maiden's Hall opencast quarry, north of Morpeth (Merritt, J W. Pers. Com.).

The upper till in the east of the area is the **Horden Till Formation** (7) (North Sea Coast Glacigenic Subgroup), a brown to red-brown clay with gravel, usually 2-10 m thick. Compared with the lower till in the area, the Horden Till Formation contains a relatively higher proportion of clasts derived from the upper parts of the Permian Limestone, the overlying sedimentary rocks, and Cheviot area derived volcanic rocks.

To the west, the upper till of the North Pennine Glacigenic Subgroup is the **Butterby Till Member** (6). It is less compact and stony than the underlying Wear Till Formation, but contains a similar suite of clasts. The unit previously described as the Pelaw Clay, which overlies most of the glaciolacustrine sediments in the Tyne-Wear area (Smith, 1994 and BGS 1:50 000 sheet 21 Sunderland) has been included in the Butterby Till Member. The maximum thickness of the Butterby Till Member is 20 m but it is most commonly between 2 and 15 m thick.

2.3.5 Late Devensian deposits: Late glacial ice marginal and glaciofluvial sediments

Moundy deposits of sand and gravel and diamictons (unsorted gravel and cobbles in a silty clay matrix) occur in the area between Easington and Elwick and to the eastern side of Darlington. These have been interpreted as ice-marginal deposits and grouped as the **Elwick Moraine Member** (8). A few moundy diamicton deposits are widely dispersed to the west of the main belt of the Elwick Moraine Member and have been also been classified as moraine, but have no lithostratigraphic name assigned (9).

Sand and gravel in mounds or terraces along valley sides form the **Ebchester Sand and Gravel Formation** (10). These are the product of glaciofluvial reworking of deposits left by retreating ice during the final deglaciation of the area.

2.3.6 Post-Glacial deposits

Raised Marine Deposits (11) occur in the region around Hartlepool. A raised marine terrace is present, cut into the superficial deposits to the west and south of Hartlepool docks. Patchy marine deposits are present on the terrace, and a raised storm beach can be found at the landward edge of the terrace at West Hartlepool, but this is not encountered in the cross-sections of the superficial deposits.

Tidal Flat Deposits (12) are present in Hartlepool but are not depicted in cross-section DS_8 as they are replaced by Made Ground in the region of Hartlepool Docks.

Lacustrine Deposits (13) consisting of clay and silty clay have formed throughout the Flandrian in lakes present in isolated hollows and poorly drained areas of the post-glacial superficial surface. DS_1 crosses an area of lacustrine deposits between Ricknall Grange and Bradbury.

Thin, patchy **Peat** (14) units may be contained within alluvial or lacustrine deposits.

The most extensive deposits of **Alluvium** (15) are found in the areas associated with the main drainage courses, especially the River Tees (section DS_3). Small patches of alluvium are found in minor tributary streams throughout the area. The alluvium consists of up to 3 m of sand, gravel and/or clay or silty clay.

River Terrace Deposits (16) occur in the valley of the River Tees (Sections DS_3 and DS_1). They form a sequence of sand and gravel benches along the valley at various elevations above the current river height.

Marine Deposits (17) are not present in the Durham South project area.

Made Ground (18) has been included in the cross-sections where it is present in the borehole log. Other types of artificial ground have not been encountered. Made Ground, especially in the first 1-2 m below the ground surface, is likely to be extensive throughout all built-up areas in the region. Older boreholes used to generate the cross-sections will not describe the extent of Made Ground where significant urban development has occurred since it was drilled.

3 Borehole Coding

Lithological interpretations of boreholes were derived from paper records held within the National Geoscience Data Centre at the British Geological Survey and additional digital records provided by the Environment Agency. Where possible, Environment Agency borehole records were matched with those in the records of the British Geological Survey and the Environment Agency name used in the borehole file. Where no match existed, geological data from the Environment Agency boreholes was entered manually into the project borehole files.

Approximately 690 boreholes were coded for the southern project area (Figure 3). Other interpreted boreholes within the BGS system were also included, giving a total of about 1,300 available for consultation in cross-section construction or borehole queries to calculate thicknesses of main aquitard or aquifer units within the superficial deposits (Figure 4).

3.1 CODING METHODOLOGY

Boreholes were coded according to the description of the down-hole lithology recorded on the paper records of the borehole. The quality of the original description varied according to the age of the record and the purpose for which the borehole was drilled (e.g. site investigation, water abstraction or coal exploration). In addition to lithological interpretation, the appropriate stratigraphic code was applied where the coder was confident of the interpretation. The stratigraphic codes used for the project were derived from the BGS Stratigraphic Lexicon (http://www.bgs.ac.uk/lexicon/lexicon.html).

Sites of all confidential and non-confidential boreholes can be obtained from the BGS website at http://www.bgs.ac.uk/geoindex/home.html

The lithological codes for the superficial deposits were derived from the BGS Superficial Deposits Coding Scheme (Cooper *et al*, 2005). The scheme uses six letters to denote the primary lithology of a deposit and is shown below in Table 3.

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

Table 3 Superficial deposits lithological coding scheme component codes

Where more than one lithological unit is present (for example a sandy clay), the letters can be combined in descending order of importance to reflect the full lithology of the material (for example CS for sandy clay). The coded lithological and stratigraphic information was added to the BGS Borehole Geology database to be retrieved subsequently for correlation.

The location of all non-confidential boreholes (and Environment Agency boreholes) used to create the cross-sections is shown in Figure 5.

3.2 BOREHOLE ELEVATION

Each borehole was referenced to an elevation with respect to Ordnance Datum. The presence of this information on a borehole log was variable. If the elevation was recorded on the borehole log it was used in the database. If the elevation was missing, it was either derived manually from Ordnance Survey contours and spot heights or automatically from the NextMap digital terrain model. Mismatches between DTM and borehole start heights may be due to change in ground conditions since the borehole drill date such as excavations or made ground and inherent errors in the DTM.

4 Cross-Section construction

The locations of the regional cross-sections are shown in Figure 1. In total, 8 cross-sections were constructed and correlated, six east-west and two north-south. This approximates to 148 km of section lines.

4.1 METHODOLOGY

The cross-sections for this study were created using GSI3D (Geological Surveying and Investigation in 3-D) subsurface modelling software (© Insight GmbH). Coded borehole data, digital elevation models, scanned and georegistered map images and digital geological maps were imported and used to define the distribution and geometry of the superficial deposits along the lines of section. The bedrock geology was represented schematically and is subject to a more detailed study in Phase 3 of this work.

A BGS DTM derived from Ordnance Survey Landform Profile data was used. Coded boreholes were imported into GSI3D from the BGS Borehole Geology database in their correct spatial positions. From the complete database of coded boreholes, the highest quality logs were selected for inclusion in the cross sections. The selection process was based a number of key criteria, including depth (preferably boreholes reaching bedrock) and quality of description.

Each borehole added to the line of section defined a control point for subsequent geological correlation. Approximately 690 boreholes were coded in the study area, of these 485 are non-confidential. The deepest boreholes used were up to 240 m deep, but many of these cannot be identified as they are held confidentially. The deep holes both on and off the lines of section were used to roughly constrain the geological stratigraphy and thickness of each unit. Lists of the non-confidential boreholes used in each cross-section with their depths, along with co-ordinates of synthetic points where no boreholes are present, are included in Appendix 1. An Excel spreadsheet of this borehole information is provided separately on a project CD.

In addition to the BGS held borehole data, EA boreholes were imported and included in the cross-sections where possible. A large number of these boreholes, however, do not lie on or close to the pre-defined section lines and have not been included.

4.2 CORRELATION

Coded boreholes (including lithology and lithostratigraphy) were displayed on screen in GSI3D. These descriptions were used as data-rich anchor points to begin to build the correlation. The geological units correlated along the sections are shown in Table 2.

Existing 1:50 000 scale 2-D digital geological map data (Figure 5) was used to aid correlation and define the limits and relationships of different geological units. Figure 6 shows the cross-sections displayed within GSI3D in 3-D.

The cross-sections intersect data poor and data rich areas. Data rich areas, where the borehole density is high, results in high confidence of the lithological correlations. In data poor areas, lines of correlation were projected from data rich areas, or interpreted from an understanding of the local geology. Geological confidence in these areas is lower. Many of the data poor result from the presence of underground bores that are unsuitable for inclusion in the project. The underground boreholes were, therefore, not coded for this phase of the study.

5 Hydrogeology and Hydrogeological Domains

For the purposes of this phase of the project, hydrogeological domains within the superficial deposits were identified, at a regional scale from the cross-sections. The domains applied to areas where superficial deposits in the project area are underlain by Permian bedrock comprising the Permian Yellow Sands Formation, Ford and Raisby Formations (Magnesian Limestone), Edlington Fomration (Permian Marls), Seaham Formation and the Roxby Formation. In addition, areas underlain by Carboniferous limestone inliers were included.

A methodology was developed to derive the hydrogeological domains via a combination of computer queries to analyse lithological borehole data and limited 3-D modelling of units defined as minor aquifers. A summary of the hydrogeology of the project area is given below along with a description of the methodology used to derive the hydrogeological domains.

5.1 OVERVIEW

An early attempt to zone the superficial deposits of the area of the Skerne valley, to the south of the Butterknowle Fault, was made by Cairney and Hamill (1977 & 1979). This identified four zones, which have been described below:

a) Relatively thin cover of glacial deposits to the west of the River Skerne.

b) The zone adjacent to and underlying the River Skerne, where the cover is always in excess of 6 m in thickness and comprises stiff grey clay with interbedded silt and sand.

c) To the east of the River Skerne, where the superficial deposits are in excess of 30 m in thickness and acts as an aquitard.

d) An infilled proglacial lake between Bradbury and Preston-le-Skerne, characterised by higher permeability deposits.

This study was primarily derived from engineering properties and is not as extensive as the work that forms the subject of this report.

The hydrogeological domains that form the focus of this model are designed to provide the basis for modelling groundwater recharge to the Magnesian Limestone. This section describes the hydrogeological information that has informed the designation of the hydrogeological domains. The model is based on the initial understanding that the Magnesian Limestone is a major aquifer, which to the east is capped by Permian Marl that causes increasing confinement of the groundwater in the Magnesian Limestone.

5.2 HYDROGEOLOGY OF THE MAGNESIAN LIMESTONE.

A detailed study of the hydrogeology of the Magnesian Limestone is beyond the remit of this project. However it is considered that the following account provides a useful summary of the main concepts that have informed the domain modelling. The hydrogeology is influenced by both the lithology and the structure. Groundwater flow is predominantly within fractures with some intergranular storage, (Brewerton *et al*, 1997). Characteristically, the Magnesian Limestone is heavily fractured and in the area to the east of Durham cavernous; as a consequence the hydraulic conductivity (and transmissivity) of the limestone is variable.

There is very little published information available with respect to the analysis of core samples, or field-testing; the data that is available confirms the variability in hydrogeological properties, with transmissivities ranging between 2200 m^2/day and 11 m^2/day, (Allen *et al*, 1997). The highest transmissivity values are associated with fault zones and areas of outcrop that have undergone collapse brecciation due to dissolution of gypsum in the underlying horizons (Dearman & Coffey, 1981). Allen *et al*, (1997) reported that in areas where the Middle Magnesian Limestone (Ford Formation) or brecciated Upper Magnesian Limestone (Seaham Formation – not present in the southern area) represents greater than half of the saturated thickness hydraulic conductivities may be greater than 12 m/day.

Gypsum is present in the Edlington (up to 30 to 40 m of gypsum at the base) and Roxby (approximately 10 m of gypsum towards the base) formations, particularly in the vicinity of Darlington, extending south towards Doncaster (Lamont-Black *et al*, 2005; Paukštys *et al*, 1999). The Edlington Formation acts as a leaky aquitard, separating lower (Yellow Sands, Raisby and Ford formations) and upper (Seaham Formation) aquifers (Lamont-Black *et al*, 2005). Allen *et al*, (1997) report that the hydraulic conductivity of the Lower Magnesian Limestone aquifer (Raisby Formation) is less than 5 m/day and that there is a variation in hydraulic conductivity with depth, suspected to reflect the presence of more massive and sometimes calcitic beds at the base of the formation.

Recharge areas predominate along the western outcrop of the aquifer; however some recharge also occurs through the superficial deposits, where flow paths associated with surface water sources have developed (Cairney & Hamill, 1977; Hamill, 1980). The regional hydraulic gradient is to the east and southeast (Lamont-Black *et al*, 2005). Lamont-Black *et al* (2005) report that recharge is carried down dip (2-3 degrees), such that an upward head is generated across the gypsum at the base of the Edlington Formation, which drives gypsum dissolution. Groundwater levels determined in nested piezometers installed in boreholes to the southeast of Darlington (Lamont-Black *et al*, 2005) indicate that groundwater levels in the superficial deposits are higher than those in the solid rock beneath, which is attributed to the low permeability of the superficial deposits and indicates the potential for some recharge. Greater seasonality of groundwater levels was observed in piezometers installed in the solid geology. Various authors, including Brewerton *et al*, (1997) report that groundwater levels have steadily risen due to changes in pumping regimes and in particular the cessation of pumping in areas of former coal mining. This particularly affects the south-easterly dipping Carboniferous strata exposed to the west of the Magnesian Limestone and dipping beneath it.

5.3 HYDROGEOLOGICAL DOMAIN MAPPING

Domain mapping, as a tool for use in the context of assessing 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, with variable structure and are important for determining the amount of water that will recharge the deeper groundwater system. Clearly, this needs to be considered in the context of the head distribution and topography, as defined in the conceptual model and referred to above. Notwithstanding this, the principle of domain mapping is the recognition of sequences of lithologies that are characterised by similar hydrogeological properties.

Domains are used to reduce the complexity of the superficial deposits for the purposes of understanding the recharge processes better. The lithostratigraphical units are grouped according to how the superficial sequence will affect groundwater flow between the limestone aquifers and the ground surface.

The domains that form the subject of this report have been scheduled from an assessment of the permeability of the superficial deposits (as described and coded within borehole records) and their distribution on the sections. Many of the units are thin, which reduces their hydrological effectiveness. Accordingly, it is necessary to apply thickness criteria in the scheduling of the domains. Thus, following consultation with the Environment Agency, the domains were further subdivided to reflect the variability in the thickness of the low permeability strata, essentially the tills and glaciolacustrine deposits. The schedule of hydrogeological domains that resulted from this assessment is shown in Table 4.

The poorest representation in the domains is that of the Tyne and Wear Glaciolacustrine Formation (named the Middle Sands in Smith & Francis (1967)). This is because the deposits are generally not laterally continuous, often forming isolated mounds, as described above. Accordingly, it is not possible to capture them at this scale of modelling. Locally they are likely to be water-bearing and where they occupy buried channels there is a potential for them to form groundwater flow paths. For this reason the buried channels have been presented as an additional domain.

Once the domains had been scheduled, the mechanism of their derivation comprised the calculation of total continuous aquifer and aquitard thicknesses for the grid of boreholes using the programming function within Map Info (Section 5.5), correlation with the sections and limited use of 3-D modelling within GSI3D (Section 5.5).

Table 4 Hydrogeological domains for the Durham South Model

Hydrogeological Domain	Characteristics	Notes on Litho-stratigraphical units
1	> 30 m aquitard over bedrock aquifer	Aquitards: till (Weardale and Butterby) and/ or glaciolacustrine deposits
2	10 – 30 m aquitard over bedrock aquifer	Aquitards: till (Weardale and Butterby) and/ or glaciolacustrine deposits
3	10 –30 m aquitard over > 5m of minor aquifer over bedrock aquifer	Aquitards: till (Weardale and Butterby) and/ or glaciolacustrine deposits Minor Aquifer: Maiden's Hall Sand and Gravel
4	>5m minor aquifer over 10 – 30 m aquitard, over bedrock aquifer	Minor aquifers: Terrace deposits, Ebchester Sand and Gravel, Alluvium Aquitards: as defined above
5	5-10 m aquitard over bedrock aquifer	Aquitards: as defined above
6	5 – 10 m aquitard over > 5m minor aquifer over bedrock aquifer	Aquitards: as defined above Minor aquifer: Maiden's Hall Sand and Gravel
7	> 5 m minor aquifer over 5 – 10 m of aquitard over bedrock aquifer	Minor aquifers: Terrace deposits, Ebchester Sand and Gravel, Alluvium Aquitards: as defined above
8	> 5 m minor aquifer over > 30 m aquitard over bedrock aquifer	Minor aquifers: Terrace deposits, Ebchester Sand and Gravel, Alluvium
9	>5 m of minor aquifer over <5 m aquitard over bedrock aquifer	Minor aquifers: Terrace deposits, Ebchester Sand and Gravel, Alluvium
10	<5 m of aquifer or aquitard over bedrock aquifer	
11	Channel deposits	Geographic area of probable Pre-Devensian and Devensian buried channels defined at regional scale

5.4 CALCULATION OF HYDROGEOLOGICAL DOMAINS STAGE 1

The hydrogeological domains were derived in three stages. During the first stage, all interpreted and coded boreholes available within the project area were classified as an aquifer (permeable) or aquitard (weakly permeable) based on their lithology. Boreholes used included those coded for the project and other coded borehole data within the BGS Borehole Geology database. Every lithological combination within boreholes extracted for use in the project was selected and assigned an aquifer or aquitard classification. In general, sand or gravel dominated units are classified as aquifer and clay or silt dominated units are classified as aquitard.

A series of database queries were designed to extract the attributed borehole data and calculate the total net thickness of superficial deposits classified as aquifer or aquitard within each borehole. The total thickness calculation sums the thickness of each separate aquifer or aquitard unit. In addition, the greatest continuous thickness of superficial deposits classified as aquifer or aquitard was calculated. In the latter case, the resulting calculation shows areas where there is thick continuous aquifer or aquitard, not separated by other units. The methodology for producing the borehole data extraction and query is described below:

1. The models represent a mathematical interpolation of BGS' legacy borehole and map datasets including new data supplied for this project by the EA. No third party data relating to Quaternary deposits has been used. A mathematical model does not take into account any conceptual modelling of the form of the superficial deposits.
2. The 'Natural Neighbour' modelling used with this data provides a smoothed, average-fit surface. Alternative modelling techniques will generate alternative models (see below).
3. The borehole data used to make the models is subject to a small degree of error; new borehole data lodged with BGS Offices in recent months may not have been incorporated within the models.
4. The map data used to make the models is based upon DigmapGB50 Version 3.14.
5. The models provide indicative values of thickness and elevation and not definitive values.
6. Some borehole logs do not record any geological description within the superficial deposits. In these cases, an aquifer or aquitard classification cannot be applied. The borehole queries would regard these borehole entries as "null" values. Where null values form greater than 20% of the geological record the entire log was excluded from the calculation. This prevents incorrect values representing 0 m thickness of aquifer or aquitard being produced in the final thickness maps.

5.4.1 Gridding details

1. Grids are created using Vertical Mapper and MapInfo V8. Interpolation between data points is via Natural Neighbour analysis i.e. each expected grid value is calculated by area weighting the Voronoi neighbourhood of the nearest surrounding data points.
2. The grids are generated with a cell spacing of 25 m by 25 m, and data is aggregated by a 25 m radius (i.e. points located a cell spacing from their neighbours are averaged).
3. Grids are smoothed (Hermitian smoothing) with local minima and maxima honoured but extrapolation beyond these values is limited.
4. Grids are nulled where DigmapGB50 indicates no superficial material to be present.
5. Gridding of data is iterative. Initially only boreholes proving the whole superficial thickness are processed; boreholes that terminate within the deposits are subsequently

added where interpolation indicates they will affect the model (this provides a 'minimum thickness model and is useful in areas of low borehole density).

It is important to understand that this phase of the hydrogeological domains production was calculated from a series of database queries of the classified borehole lithological data only. The use of additional quantitative permeability data, although potentially valuable was beyond the scope of a regional hydrogeological domains study. The thematic maps that were produced during this first phase of hydrogeological domains calculation are shown in Appendix 3.

5.5 CALCULATION OF HYDROGEOLOGICAL DOMAINS STAGE 2

The second phase of the production of hydrogeological domains involved 3-D modelling of the thickness and distribution of units classified as minor aquifer in Table 4. The regional cross-sections have shown that, in general, a major aquitard unit in the superficial deposits is represented by glacial Till or Glaciolacustrine deposits. In some areas, these deposits are either underlain or overlain by units classified as minor aquifers in Table 4. The underlying minor aquifer is represented by the Maiden's Hall Sand and Gravel. The overlying minor aquifer is represented by a combination of Alluvium, Alluvial Terrace deposits and the Ebchester Sand and Gravel.

For the calculation of the hydrogeological domains, the estimated surface and subsurface distribution of each minor aquifer unit was defined from the regional cross-sections and "helper" sections within GSI3D. Helper sections provide a means of using additional borehole data and interpreted thicknesses constrained by correlation lines on the cross-sections, to model each geological unit. In total, 51 helper sections were used to define the distribution and thickness of all minor aquifers within the project area.

The thicknesses calculated from this process were exported digitally as ASCII grids with a 25 m cell size and converted to ESRI grids for use in the GIS calculation of the hydrogeological domains. The BGS Landform Profile DTM derived from OS data used as a top, capping surface for the calculation had a 50 m cell size.

5.6 CALCULATION OF HYDROGEOLOGICAL DOMAINS STAGE 3

The third and final stage of producing the hydrogeological domains involved combining the results from stages 1 and 2 and applying a series of GIS spatial queries to combine and query the digital grids. The grids and contours defined in Section 5.5 (from borehole analysis) were queried against the grids and contours defined in Section 5.6 (from limited 3-D modelling of those deposits identified as potential minor aquifers). In all cases, the domains were applied to areas where superficial deposits are underlain by Permian bedrock comprising the Permian Yellow Sands Formation, Ford and Raisby Formations (Magnesian Limestone), Edlington Fomration (Permian Marls), Seaham Formation, Roxby Formation and Carboniferous Limestone inliers. The hydrogeological properties of bedrock units were not considered in the definition of the hydrogeological domains.

In addition, the extent of Domain 11 was digitised based on regional analysis of the cross-sections of the probable location of infilled Pre-Devensian and Devensian buried valleys. Their exact geometry and location is not defined, but Domain 11 is included to highlight the potential area affected by these buried valleys where deposits may be more sandy and variable. The hydrogeological domains are presented in Figure 7.

6 Limitations

6.1 BOREHOLE DATA

- Approximately 690 boreholes were coded for the southern project area. Other interpreted boreholes within the BGS system were also included giving a total of about 1,300. A large number of the boreholes were either of poor quality, very shallow, or inadequately logged. Also many underground boreholes exist in this area and are of no use in the superficial geological study. The borehole distribution was uneven, leaving some areas with poor data coverage. As a result, some parts of the interpretation are fairly well constrained and others are less certain.
- Many of the shallow boreholes do not encounter bedrock. Rockhead is constrained by those boreholes that did encounter bedrock, and by reference to a BGS rockhead elevation model.

6.2 GEOLOGICAL INTERPRETATION

- The superficial geology of the study area is complex, and there have been very few detailed studies defining the relationships of the geological units. This project provides a 2-D interpretation of the geology along section lines. Extrapolation between cross-sections will not provide a 3-D geological interpretation. Further detailed borehole analysis and GSI3D modelling would be required if a full 3-D hydrogeological study is intended. A key example is the large number of buried channels described in the literature for the study area. A small number of these are represented in the Durham south cross-sections. A full 3-D geological study would be needed to produce an accurate representation of this complicated network of channels and their lithological variability.
- Boreholes that penetrate the buried valleys exhibit many geological variations. Time limitations on the project allowed only limited subdivision of the buried channel deposits. Some till lenses and sand lenses were identified but not correlated. Further study would allow a more comprehensive interpretation of these complex deposits which may be extensive lateral conduits of groundwater.
- Cross-section interpretations are based on lithostratigraphy. The geological maps used to aid interpretation are based on lithology and depositional environment. Consequently, the two cannot be directly compared. Undifferentiated glacial sand and gravel deposits shown on the maps are a key example of this. In the cross-section they may be classified as the Ebchester Sand and Gravel Formation or as part of the Tyne and Wear Glaciolacustrine Formation.
- Bedrock is depicted schematically in the cross-sections and divided into representative geological categories to represent the bedrock geology present beneath superficial deposits. No detail in relation to structural dip or exact borehole correlations is intended for this part of the study. Faults are not modelled, but are schematically represented as steep geological boundaries where contrasting units are juxtaposed.

6.3 CROSS-SECTION CONSTRUCTION

- Cross-section interpretation was based on BGS borehole data, EA borehole data, BGS DiGMap50 digital geological maps (Superficial Deposits and Bedrock), BGS rockhead model, published BGS geological maps, published literature and unpublished BGS reports. An Ordnance Survey LandFormProfile 1:50 000 Digital Terrain Model (DTM) was used.

- The interpreted cross-section lines closely follow the original sections defined in the project outline. However, some deviation has been necessary due a lack of borehole data along these proposed lines. The cross-sections were created by selecting the best quality boreholes within a buffer zone of 200 m – 300 m of the proposed lines, and by including as many EA boreholes that were within a reasonable distance of the line as possible.
- Correlation lines were drawn based on our own lithostratigraphic interpretation of the borehole data.
- The geological model is defined by cross-section only. No borehole analysis was carried out beyond the cross-sections, other than their lithological interpretation used in the derivation of hydrogeological domains.

6.4 UNCERTAINTY

Factors contributing to the uncertainty of the geological cross-sections include:

- Borehole data quality
- Borehole distribution (parts of cross-section had limited amounts of data)
- Geological complexity
- Poorly defined pre-existing lithostratigraphy for the area

Factors contributing to the uncertainty of the production of the second stage of the hydrogeological domains include:

- The hydrogeological domains were identified from those relationships within the superficial deposits identified from the regional cross-sections only and where a thick aquitard was overlain or underlain by a minor aquifer. This is appropriate for the scope of the project and should only be used in conjunction with other regional studies. Other, more detailed hydrogeological domains with more complex spatial relationships may exist (such as interbedded sand units within Till or Glaciolacustrine deposits) but it was beyond the scope and methodology of this phase of the project to apply them to the hydrogeological domains. Such domains can only be derived efficiently and effectively by using a 3-D geological modelling approach.

  For example, in the area shown in Figure 8, an area of "thick aquifer" has been identified from the borehole queries with a distinctive NW-SE trend. However, as this does not assess the spatial relationships of the geological units, it is not possible to determine where this aquifer lies within the sequence of superficial deposits. The 3-D spatial relationships would be important to determine to fully understand potential vertical and lateral hydrogeological flow paths.
- The helper sections that were used to constrain the thickness and distribution of the overlying and underlying aquifers are generally poorly constrained away from the cross-sections. Where possible, additional boreholes were used, but a detailed analysis of all boreholes was not possible within the resources of the project.
- The spatial relationships derived from the GIS queries within the hydrogeological domains are based on the assumption that in all cases, the Maiden's Hall Sand and Gravel underlies the area of continuous aquitard and that the Alluvium, Alluvial Terraces and the Ebchester Sand and Gravel overlie it. The presence and nature of other potential stratigraphical relationships cannot be identified using the methodology described here. The production of the 3-D distribution of the top and base elevation and thickness of each geological unit interpreted from a 3-D geological model would be required.

- In defining the distribution of the superficial deposits classified as minor aquifers, only the larger areas shown on the geological map were selected for inclusion. Small or thin areas that were beyond the resolution of the regional study were not included. This process was based on an assessment of the areas most likely to be significant in the application of the hydrogeological domains.

6.5 RECOMMENDATIONS

6.5.1 Geological

- We recommend a full 3-D geological modelling study to fully understand the spatial relationships and associated 3-D hydrogeological properties within the superficial deposits. 3-D modelling may be appropriate at a more detailed scale in specific areas or sites of interest.

6.5.2 Hydrogeological

- It is important to note that the borehole queries used for the first phase of the production of the hydrogeological domains do not assess the spatial relationships of aquifer or aquitard units within the borehole, only thickness. Consequently, it is not possible to assess from this query whether an aquifer overlies an aquitard, an aquitard overlies an aquifer or whether the two are interbedded. It would only be possible to assess the spatial relationships fully in 3-D by building an attributed 3-D geological model.
- Where “null” values occur in the borehole queries (Section 5.5) and have been excluded, 3-D modelling and cross-section construction would allow the geologist to assess these null values in relation to surrounding boreholes. Consequently, the modeller would be able to assess the probable stratigraphy and resulting hydrogeological properties as part of the 3-D modelling process.
- Although beyond the scope of this project, layers to show groundwater contours (as discussed with the client) would be of benefit to the model.
- Dissolution features (as discussed with the client) would be a potentially useful addition to the hydrogeological model, but was beyond the scope of this project. For example Smith & Francis, (1967) make reference to a swallow hole at NZ 2952 2912. It would be possible to generate layers to show dissolution features by adding data to the BGS karst database.
- Consider potential recharge associated with quarry locations.

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Appendix 1 Figures

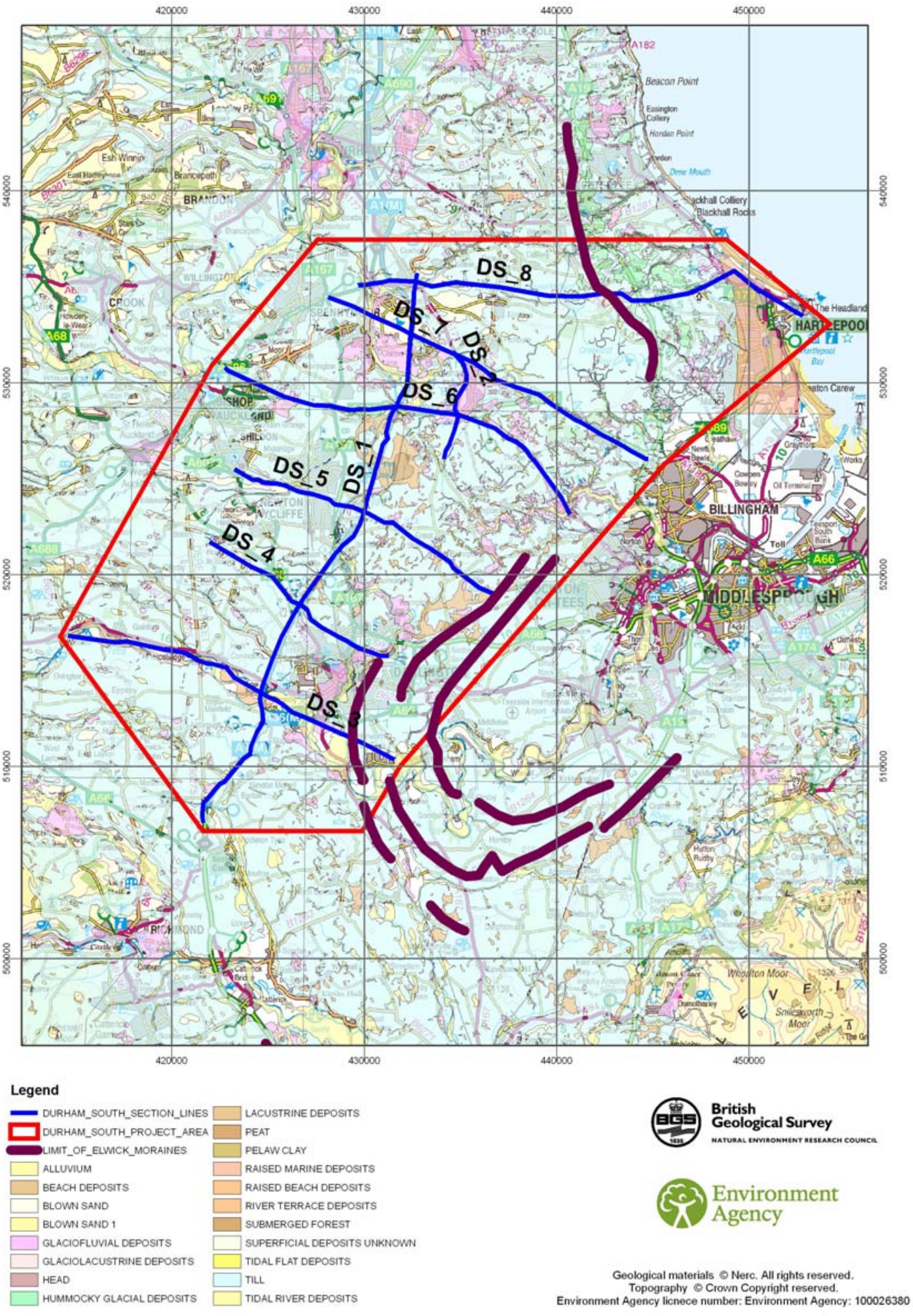


Figure 1 Existing Superficial Deposits map (DiGMapGB 50) of the Durham South area

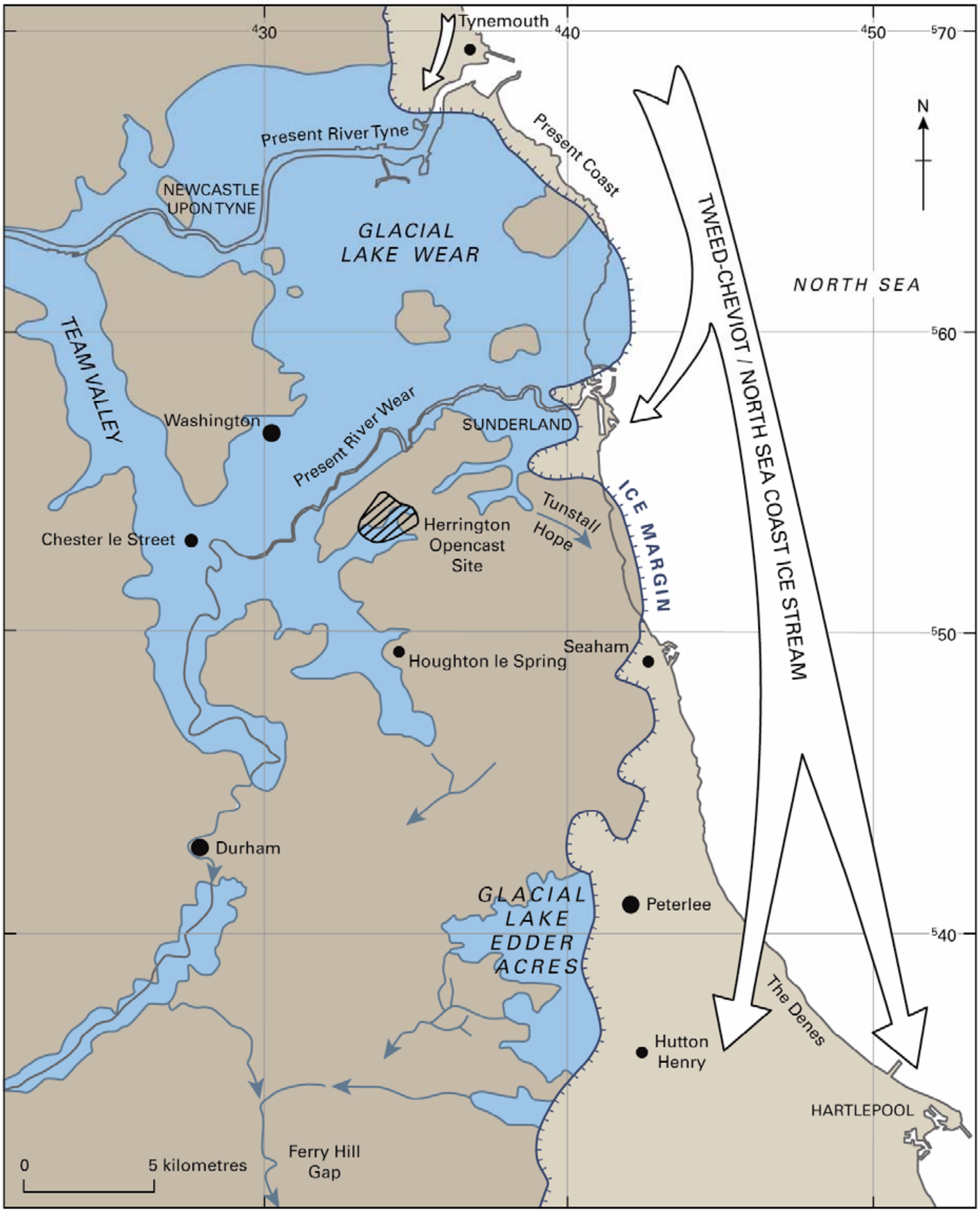


Figure 2 Glacial Lake development in the Late Devensian (Stone, Millward & Young, In Prep.)

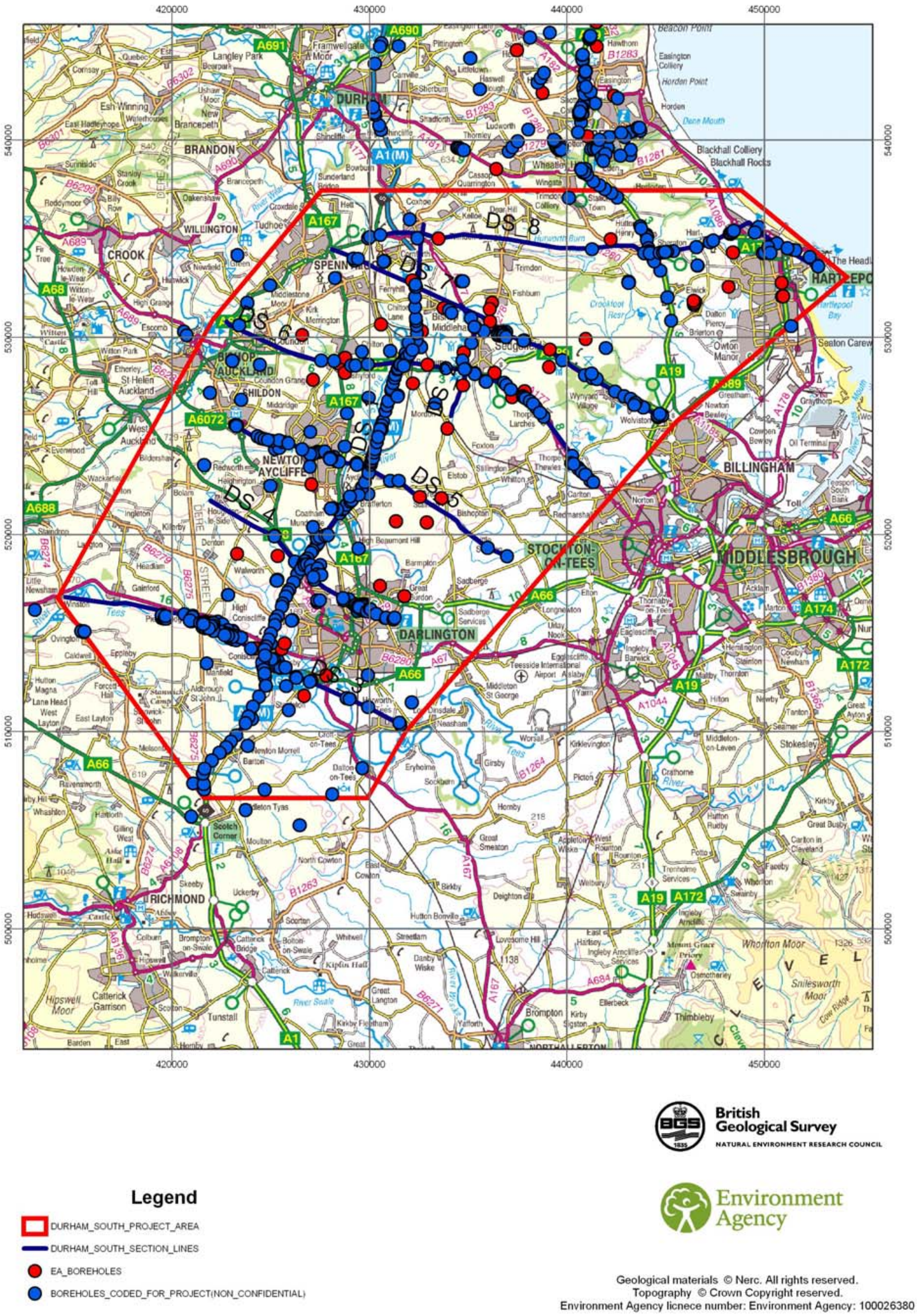


Figure 3 All boreholes coded for project or provided (from EA) in Durham South region (partially on Durham North region)

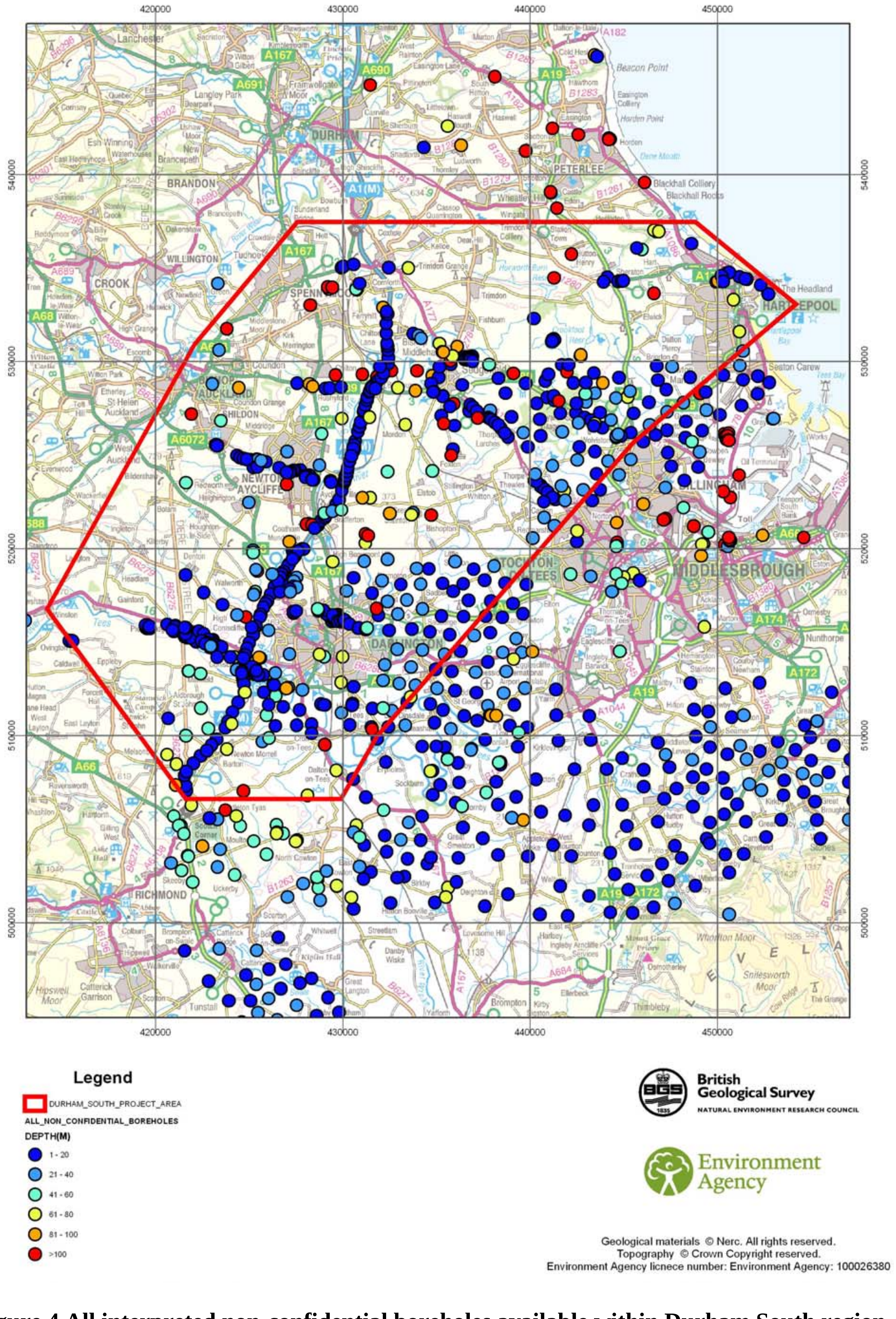


Figure 4 All interpreted non-confidential boreholes available within Durham South region

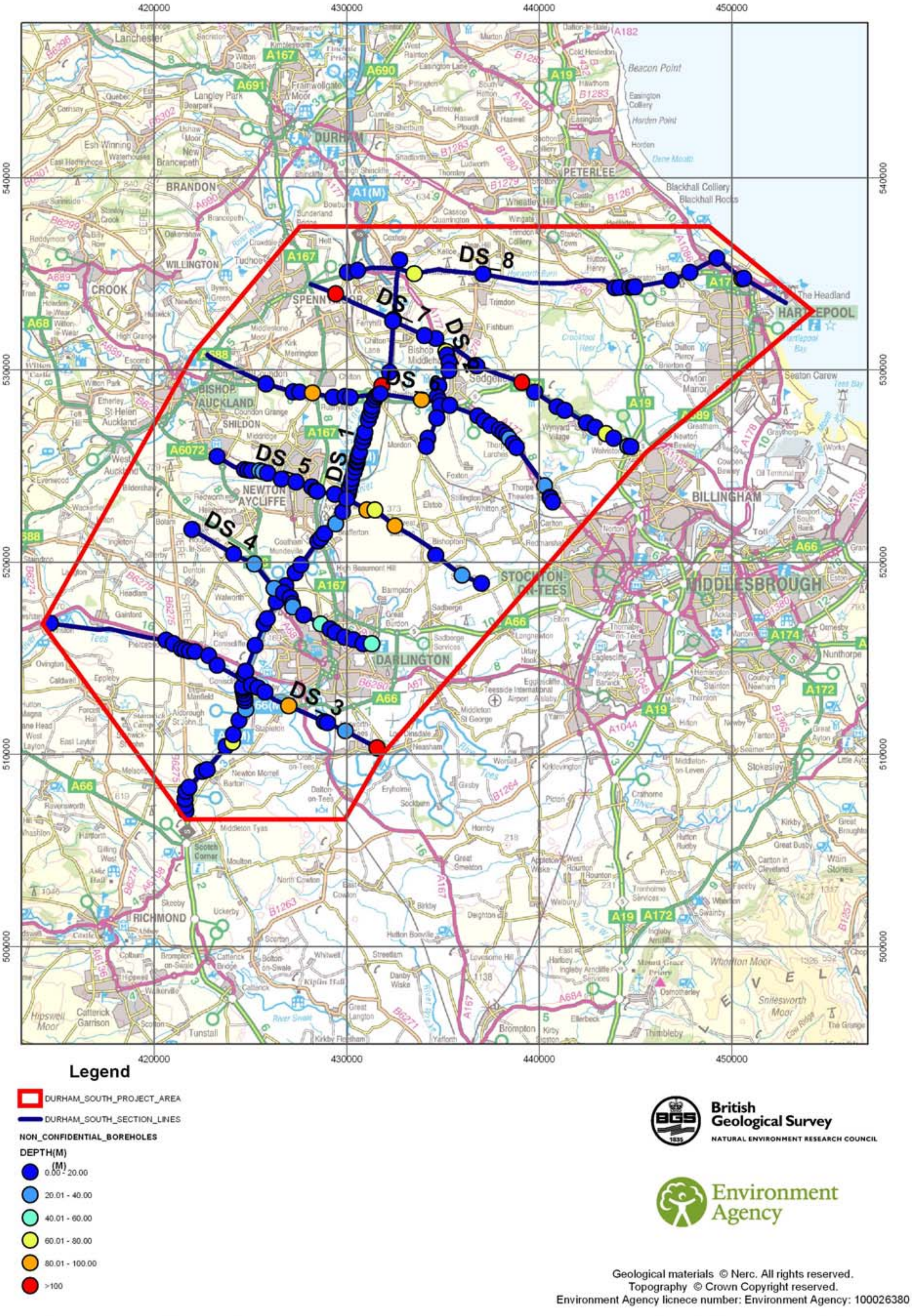
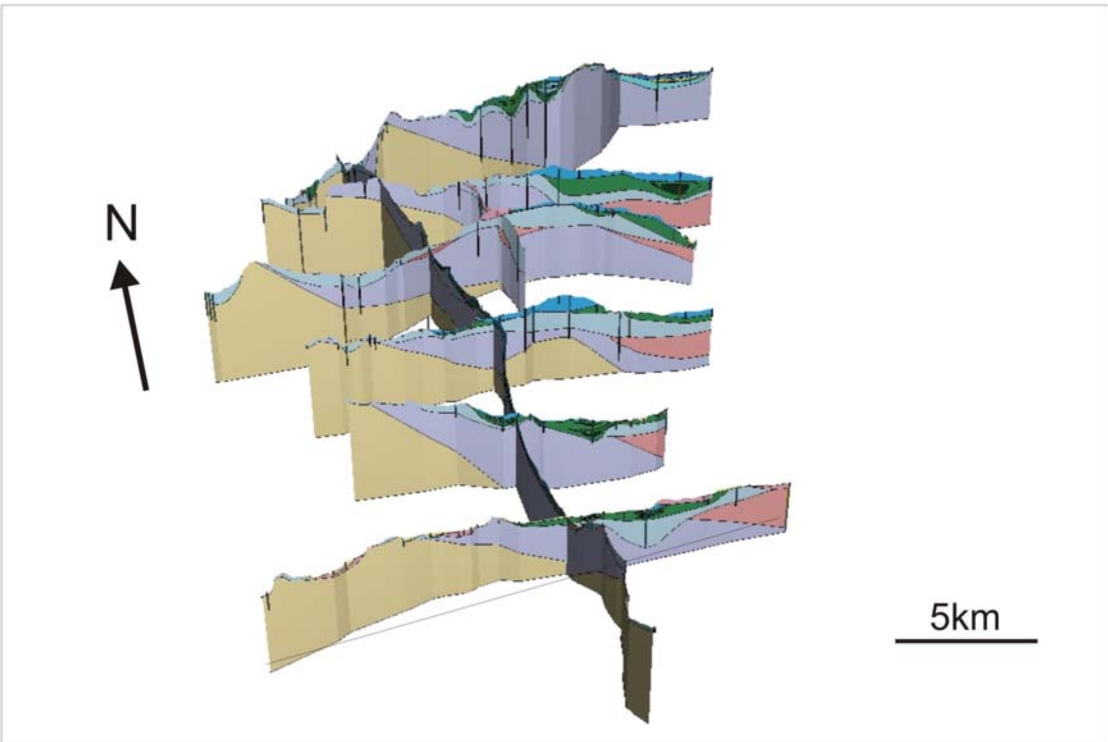
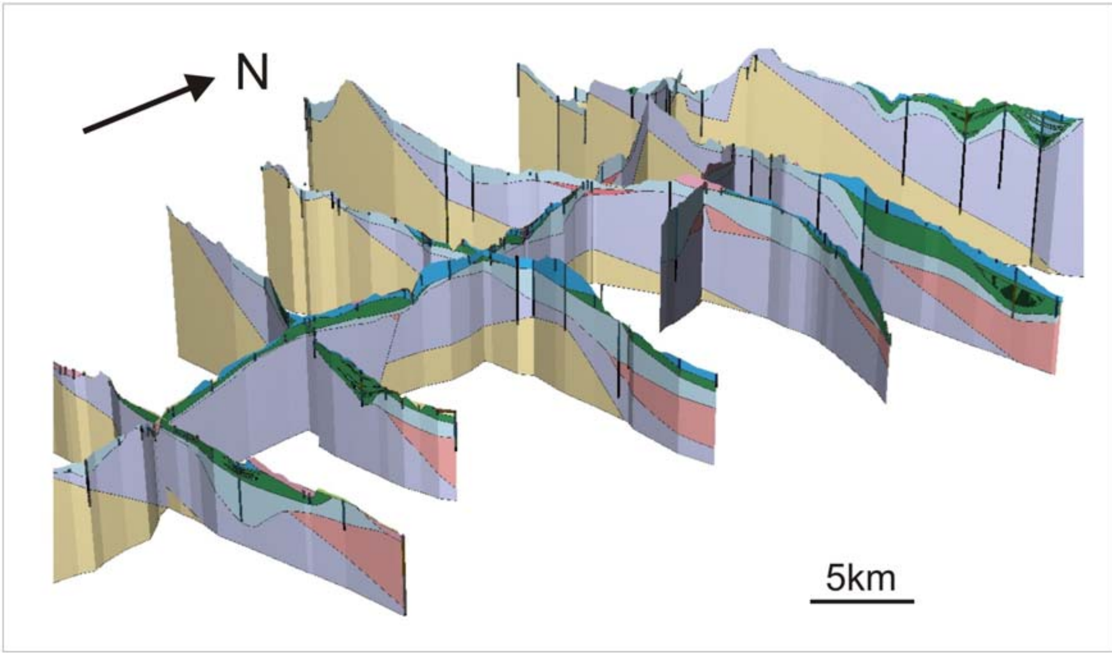


Figure 5 Location of cross-sections and non-confidential boreholes used in interpretation


N
5km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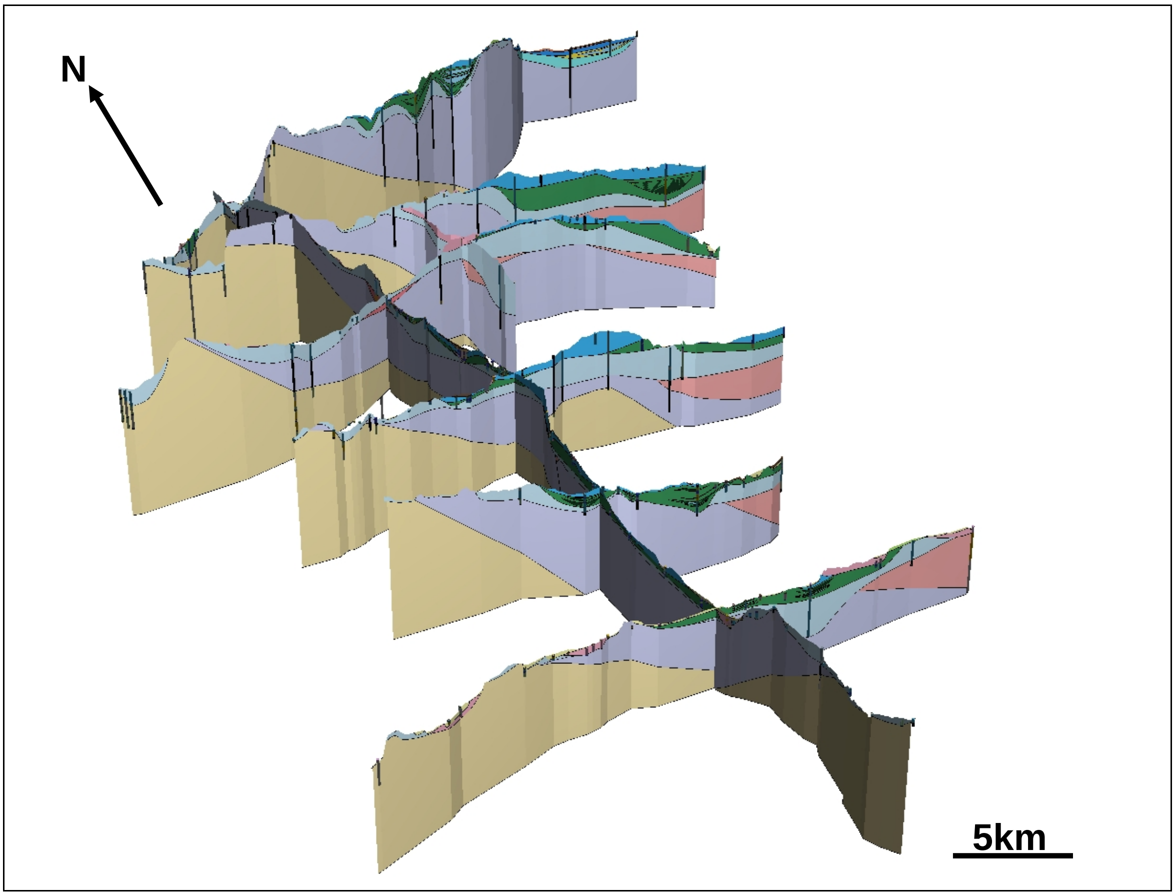


Figure 6 Durham South cross-sections in 3-D

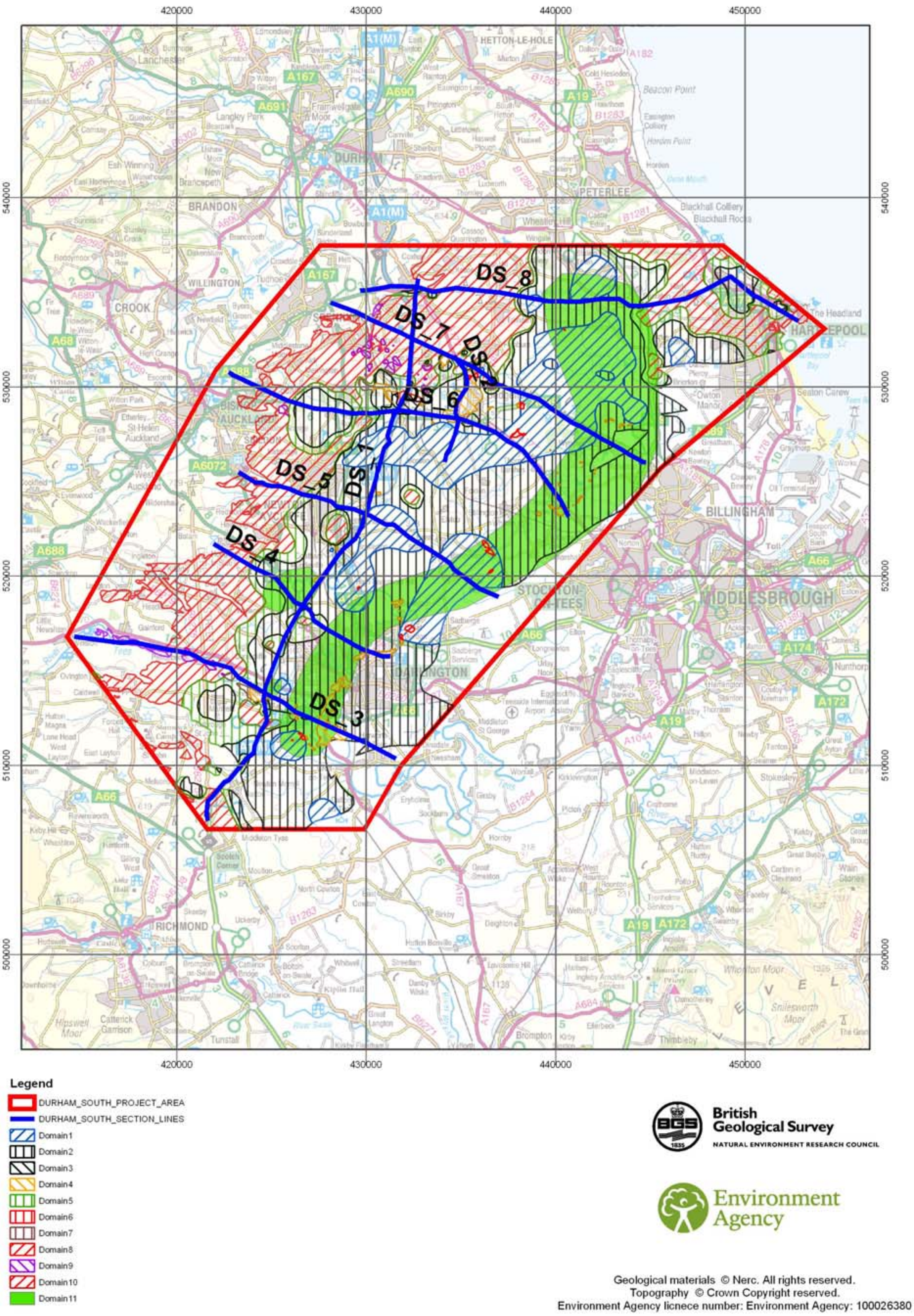


Figure 7 Hydrogeological domains Durham South

Blank areas within the project area denote superficial deposits underlain by bedrock units other than Permian bedrock and Carboniferous Limestone.

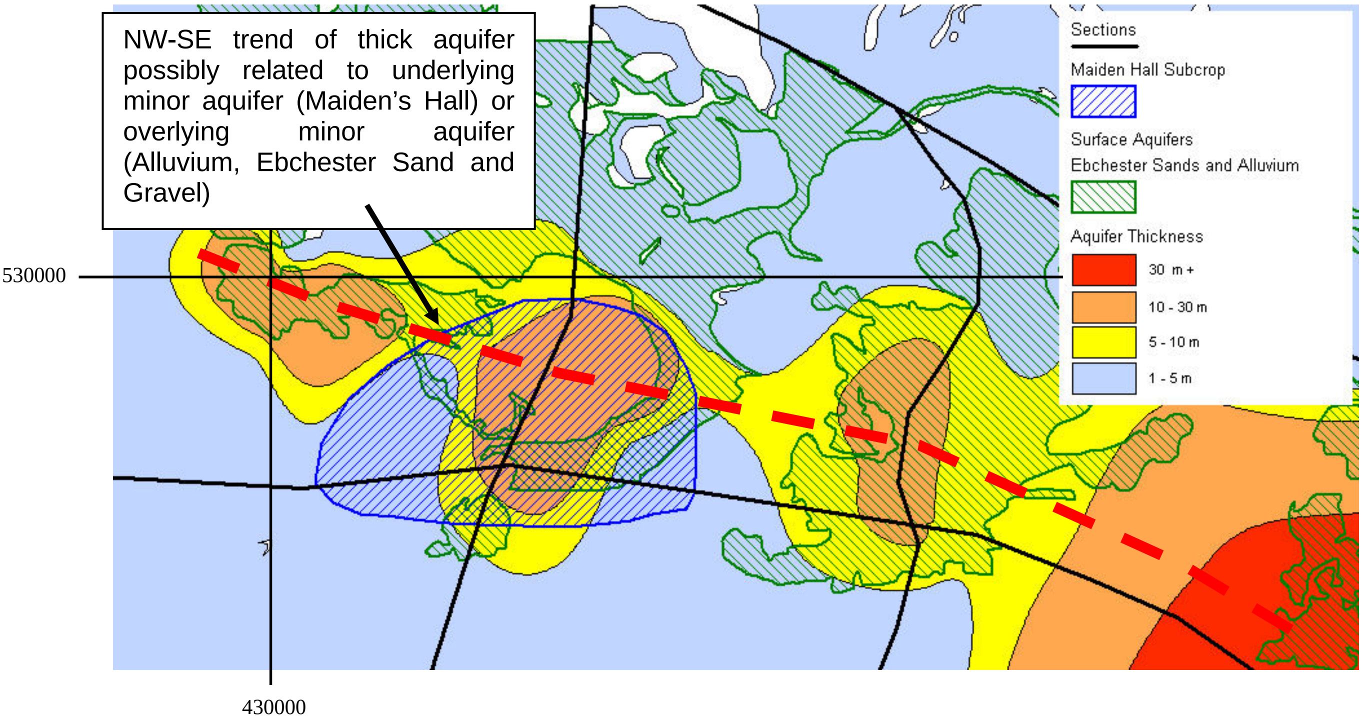


Figure 8 Sedgefield. Area of thick minor aquifer within superficial deposits but spatial relationships related to thickening uncertain

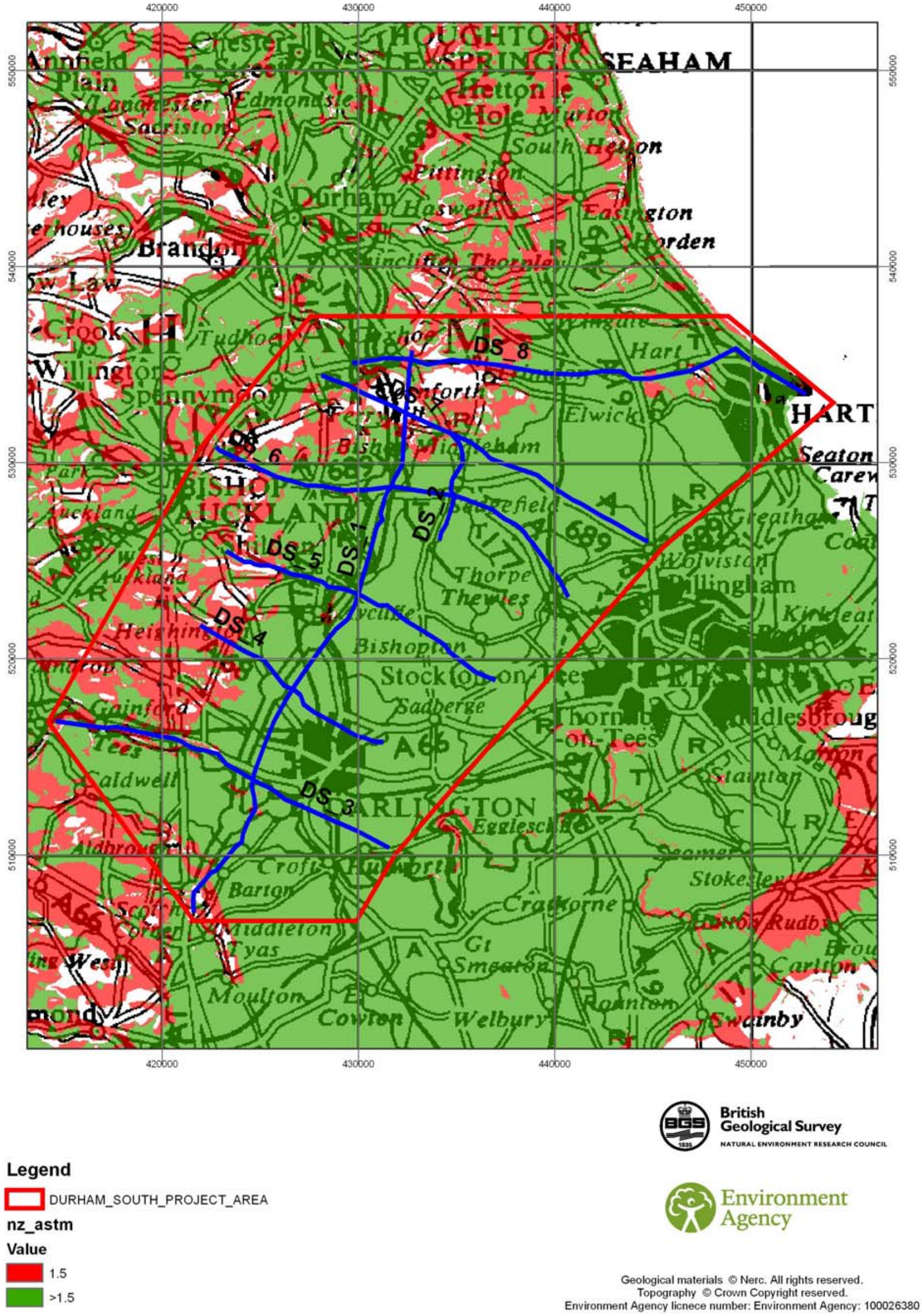


Figure 9 Superficial Deposits less than 1.5m thick. From BGS Superficial Deposits Thickness (ASTM) data

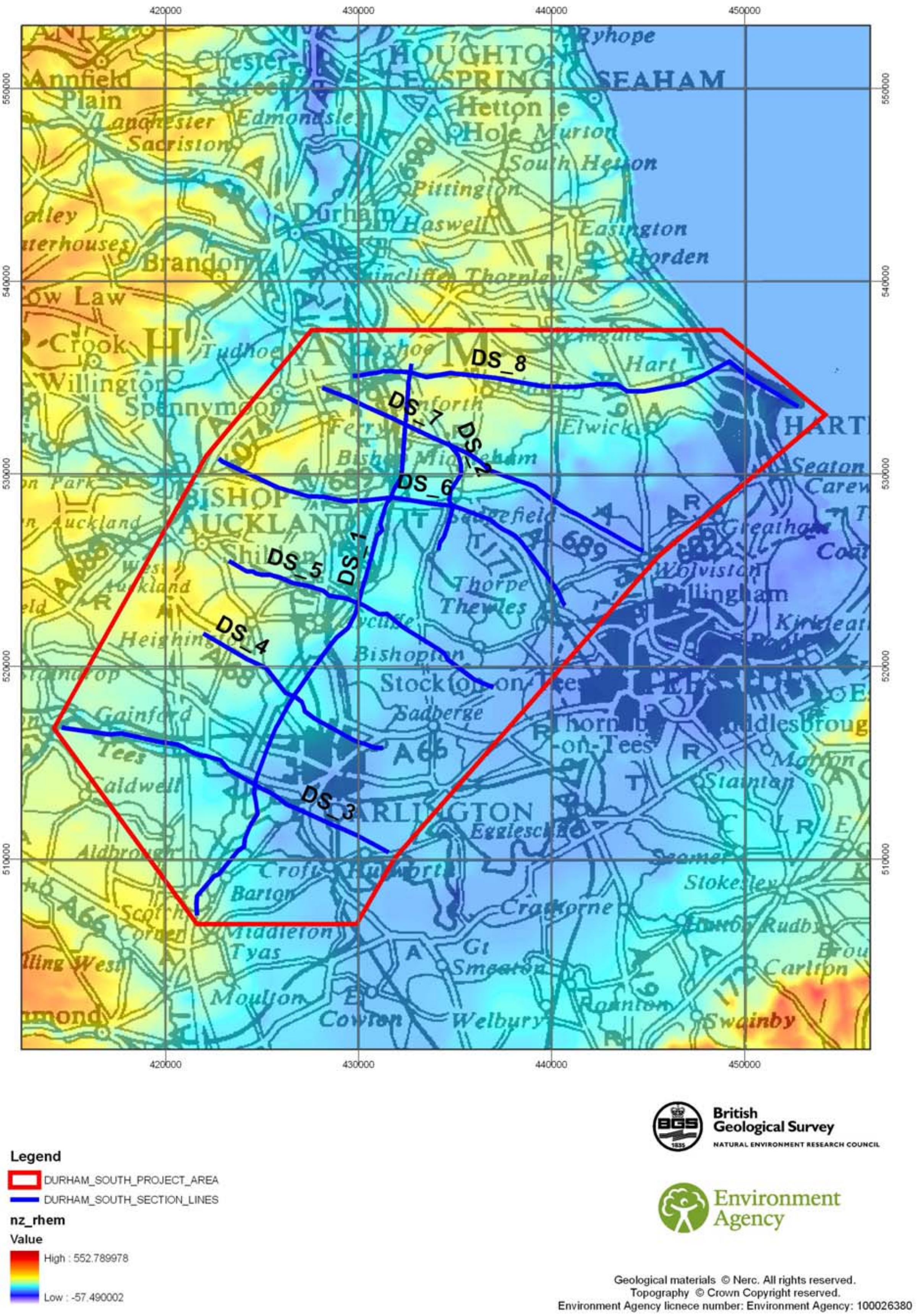


Figure 10 Rockhead elevation from BGS Rockhead Elevation data

Appendix 2 Non-confidential cross-section boreholes

Non-confidential boreholes used in the construction of cross-sections. NA = Not Applicable (used where a synthetic point has been used to constrain the orientiation of the section and has no depth).

DS_1

BOREHOLE NAME	EASTING	NORTHING	DEPTH (M)
NZ20NW59.	421617	507079	10.00
NZ20NW62.	421594	507336	9.50
Coordinate	421579	507676	NA
NZ20NW69.	421625	508106	3.20
Coordinate	421800	508291	NA
Coordinate	422490	509116	NA
NZ20NW8 H	422727	509213	11.07
NZ21SW14 G	423728	510426	5.08
NZ21SW3.	424049	510657	61.27
Coordinate	424102	511048	NA
NZ21SW13 U	424397	511785	9.22
NZ21SW2.	424742	512338	20.12
NZ21SW7 C	424694	512778	12.19
NZ21SW13 E	424670	512956	5.79
NZ21SW13 B	424640	513145	3.96
NZ21SW8 D	424587	513348	10.67
NZ21SW8 A	424596	513438	14.48
NZ21SW12 X	424567	513515	8.23
NZ21SW12 N	424678	514161	6.25
NZ21SW12 G	424733	514329	14.33
NZ21NE17 T	425231	515671	14.86
Coordinate	425684	516797	NA
NZ21NE17 B	425846	517075	11.28
NZ21NE10 C	426335	517964	10.67
NZ21NE16 C	426754	518645	15.24
NZ21NE16 A	426837	518780	10.06
NZ21NE9.	427305	519453	4.57
NZ21NE8.	427609	519873	10.67
NZ22SE9 B	428492	521091	13.11
NZ22SE11 B	428638	521263	15.24
NZ22SE11 M	428829	521493	16.15
NZ22SE13 A	429429	522003	26.52
NZ22SE12 E	429771	522639	12.19
NZ32SW1 40	430058	523548	3.35
NZ32SW1 41	430082	523642	3.35
NZ32SW1 42	430105	523721	11.28

NZ32SW1 44	430123	523876	16.76
NZ32SW1 49	430211	524153	13.87
NZ32SW1 52	430254	524345	15.70
NZ32SW1 57	430366	524693	6.40
NZ32SW1 60	430438	524958	6.10
NZ32NW6 62A	430507	525176	5.33
NZ32NW6 63A	430542	525304	18.14
NZ32NW6 63F	430562	525468	17.22
NZ32NW6 64C	430606	525538	10.06
NZ32NW6 65	430663	525753	6.10
NZ32NW6 67	430799	526251	6.10
NZ32NW6 70	430870	526521	7.32
NZ32NW6 73	430940	526782	7.01
NZ32NW6 82	431113	527407	8.53
NZ32NW6 85	431192	527673	7.62
NZ32NW6 88	431267	527934	6.71
NZ32NW6 90	431302	528115	13.41
NZ32NW6 96	431439	528448	11.89
NZ32NW6 98	431522	528627	13.26
NZ32NW6 103	431631	528702	16.76
NZ32NW2.	431809	529187	271.27
Coordinate	432210	529877	NA
Coordinate	432402	532638	NA
Coordinate	432737	535727	NA

DS_2			
BOREHOLE NAME	EASTING	NORTHING	DEPTH (M)
Coordinate	434598	531639	NA
Lizards Farm	435140	530970	65.00
Coordinate	435198	530780	NA
Coordinate	435303	530413	NA
Coordinate	435298	529985	NA
Coordinate	434766	529161	NA
Coordinate	434692	528615	NA
NZ32NW138.	434821	528368	12.19
Coordinate	434841	528155	NA
Coordinate	434670	527515	NA
Coordinate	434208	526449	NA
Coordinate	434126	526032	NA

DS_3			
BOREHOLE NAME	EASTING	NORTHING	DEPTH (M)
Coordinate	414591	516828	NA
NZ21NW12.	420610	515950	8.20
NZ21NW21 2	420988	515778	4.50

NZ21NW14902 3	421412	515520	11.58
NZ21NW14902 B4	421576	515452	10.08
NZ21NW14902 11	421816	515372	13.11
NZ21NW14902 9	422097	515362	5.49
NZ21NW73.	422830	515150	5.49
NZ21SW114.	423250	514640	3.96
NZ21SE241.	425041	513615	2.13
NZ21SE42.	425380	513470	13.30
NZ21SE14905 1	425729	513262	7.62
NZ21SE3 D	426972	512540	81.00
NZ21SE51 A	428829	511699	11.95
NZ21SE51 D	428978	511650	15.00
NZ21SE40.	429915	511235	39.62
NZ31SW9.	431554	510359	104.32

DS_4			
BOREHOLE NAME	EASTING	NORTHING	DEPTH (M)
Coordinate	421939	521718	NA
Coordinate	424123	520418	NA
NZ21NE4.	425191	519921	25.30
NZ21NE5.	426208	518635	32.31
NZ21NE15503 1	426714	518424	9.00
NZ21NE15503 6	427039	518167	12.00
NZ21NE15503 12	427160	517851	12.00
NZ21NE7.	427190	517685	24.38
Coordinate	427747	517276	NA
NZ21NE89.	428650	516780	49.53
NZ21NE37 21	429123	516524	7.61
NZ21NE148.	429390	516360	16.50
NZ21NE14531 2	429870	516110	11.00
NZ31NW16 26	430330	515972	6.71
NZ31NW16 31	430834	515773	6.71
NZ31NW14.	431270	515770	54.17

DS_5			
BOREHOLE NAME	EASTING	NORTHING	DEPTH (M)
NZ22NW271.	423250	525500	6.00
NZ22SW13430 5	424670	524830	3.05
NZ22SW13430 6	424850	524790	3.05
NZ22SE13430 7	425030	524760	3.05
NZ22SE23 G	425449	524755	24.99
NZ22SE28.	425636	524701	24.84
NZ22SE13430 17	425880	524640	2.44
NZ22SE13430 24	426590	524330	3.66
NZ22SE75 C	427346	524193	7.00

NZ22SE106.	428163	523934	20.00
NZ22SE13534 1	428390	523730	10.67
NZ22SE13534 2	428450	523680	10.82
NZ22SE5.	429359	523539	9.14
Coordinate	429980	523282	NA
Ricknall Lane (NRA 10)	431030	522720	97.54
Lea Hall (NRA J)	431460	522730	79.86
Hauxley Farm (NRA 17)	432499	521899	94.49
Coordinate	434604	520367	NA
NZ31NE11.	435970	519330	21.30
NZ31NE12.	436970	518910	18.00

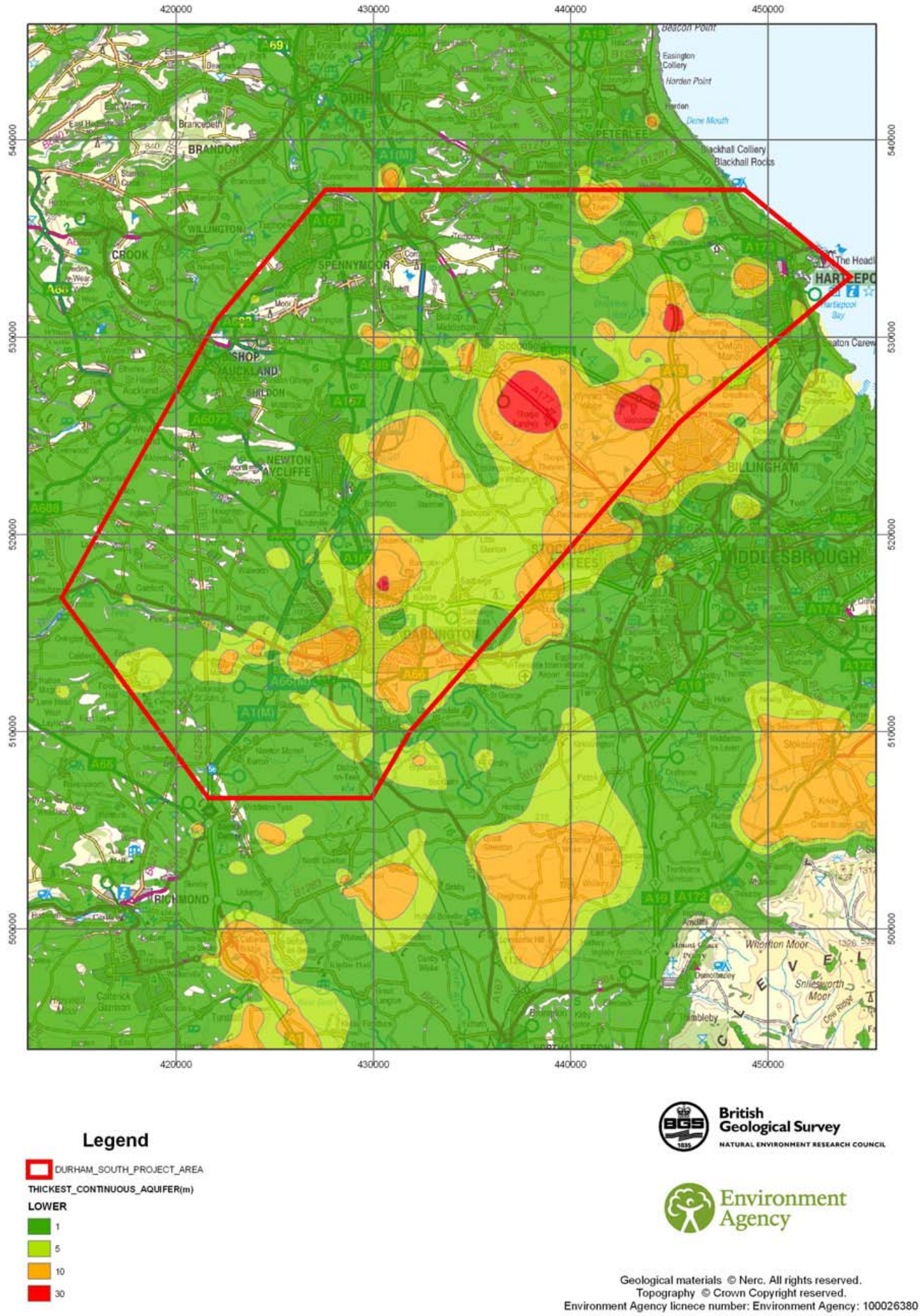
DS_6			
BOREHOLE NAME	EASTING	NORTHING	DEPTH (M)
Coordinate	425792	529293	NA
Coordinate	427214	528877	NA
NZ22NE15369 1	427549	528841	6.00
NZ22NE7.	428211	528804	84.58
NZ22NE40 4	429279	528585	4.27
NZ22NE40 7	429907	528629	4.88
Coordinate	430176	528596	NA
Coordinate	431741	528777	NA
NZ32NW94.	433870	528450	80.85
NZ32NE83.	435334	528182	12.19
Coordinate	436800	527621	NA
NZ32NE53 G	437145	527346	6.00
Coordinate	437449	527131	NA
NZ32NE54 A	437912	526904	6.50
NZ32NE54 C	438110	526763	6.00
NZ32NE54 E	438283	526618	7.00
NZ32NE44.	438437	526446	24.40
NZ32NE54 J	438626	526172	6.50
NZ32NE46.	438819	525974	18.00
NZ42SW32.	440258	523986	25.00
NZ42SW18 A	440553	523391	9.14
NZ42SW18 B	440572	523337	9.30
Coordinate	440686	523154	NA

DS_7			
BOREHOLE NAME	EASTING	NORTHING	DEPTH (M)
NZ23SE24.	429417	533977	146.91
NZ33SW175 157	432362	532564	7.01
Coordinate	434019	531794	NA
NZ33SE14917 3	436680	530250	6.40
NZ33SE14917 8	436760	530200	1.25

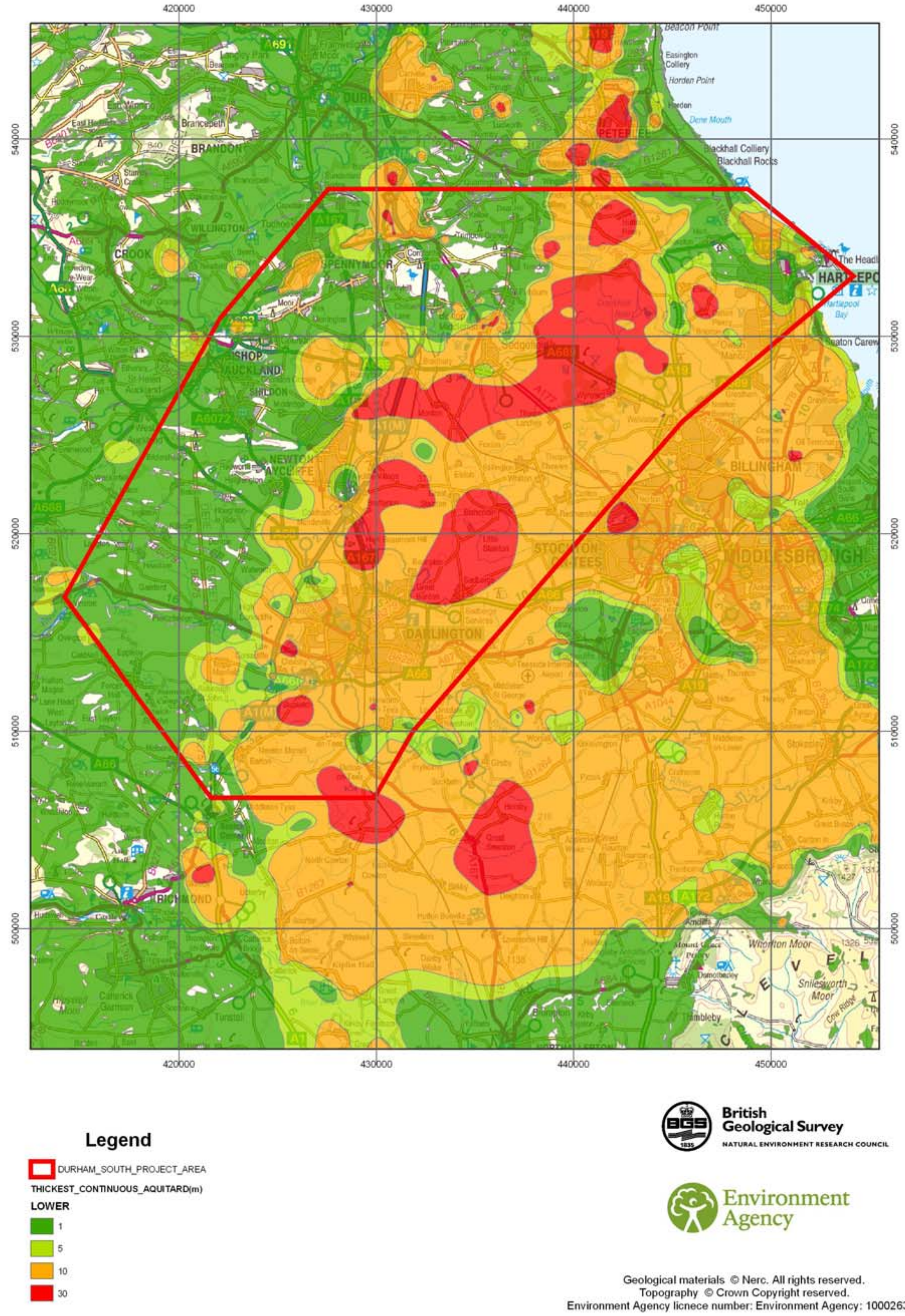
Waterloo OBH	439093	529366	188.98
NZ32NE35.	439750	528853	18.40
NZ42NW11 1	440913	528093	4.57
NZ42NW11 3	441299	527915	4.27
NZ42NW11 11	442432	527248	3.35
NZ42NW11 14	442901	527010	4.88
NZ42NW13.	443455	526695	73.87
NZ42NW11 20	443858	526448	2.44
NZ42NW38 73	444599	526043	30.50
Coordinate	444740	526019	NA

DS_8			
BOREHOLE NAME	EASTING	NORTHING	DEPTH (M)
NZ33NW234.	430026	535099	17.40
NZ33NW238.	430555	535198	15.00
Garmondsway	433491	535017	73.15
Coordinate	437047	534982	NA
NZ43SW29 L	443912	534279	10.97
Coordinate	444161	534286	NA
NZ43SW88.	444700	534290	2.80
NZ43SW90.	444870	534310	4.00
NZ43SW91.	444970	534330	4.00
Coordinate	446840	534666	NA
Coordinate	447796	535089	NA
Coordinate	449210	535837	NA
Hartlepool industrial Estate	450517	534760	92.00
NZ53SW273.	450620	534770	12.00

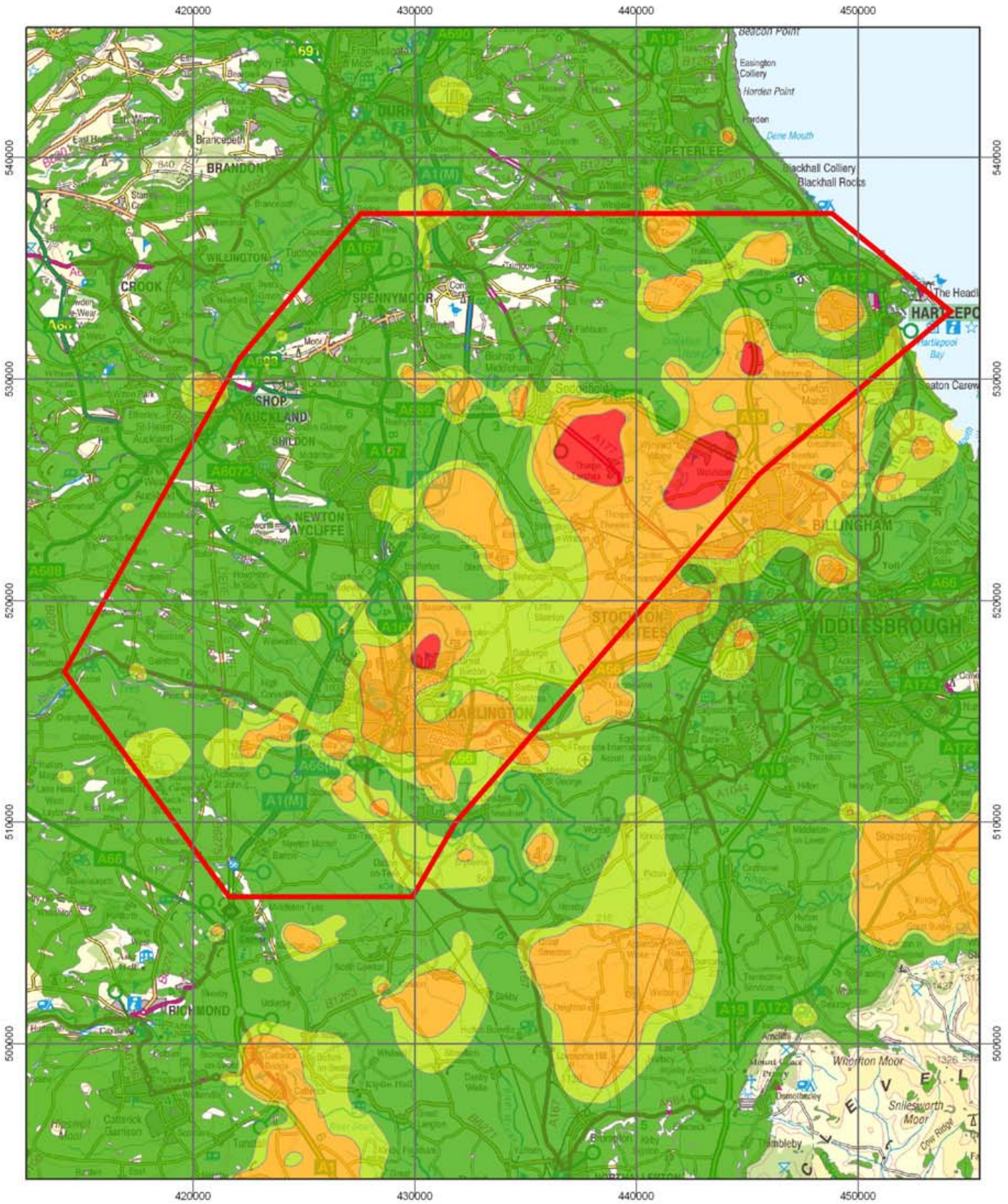
Appendix 3 Aquitard and Aquifer thickness maps



Thickest continuous aquifer (superficial deposits). All thicknesses metres (m). *Partial data for Durham North (Phase 2) included but may be subject to change.*



Thickest continuous aquitard (superficial deposits). All thicknesses metres (m). *Partial data for Durham North (Phase 2) included but may be subject to change.*



Legend

DURHAM_SOUTH_PROJECT_AREA

TOTAL_THICKNESS_AQUIFER(m)

LOWER

- 1
- 5
- 10
- 30

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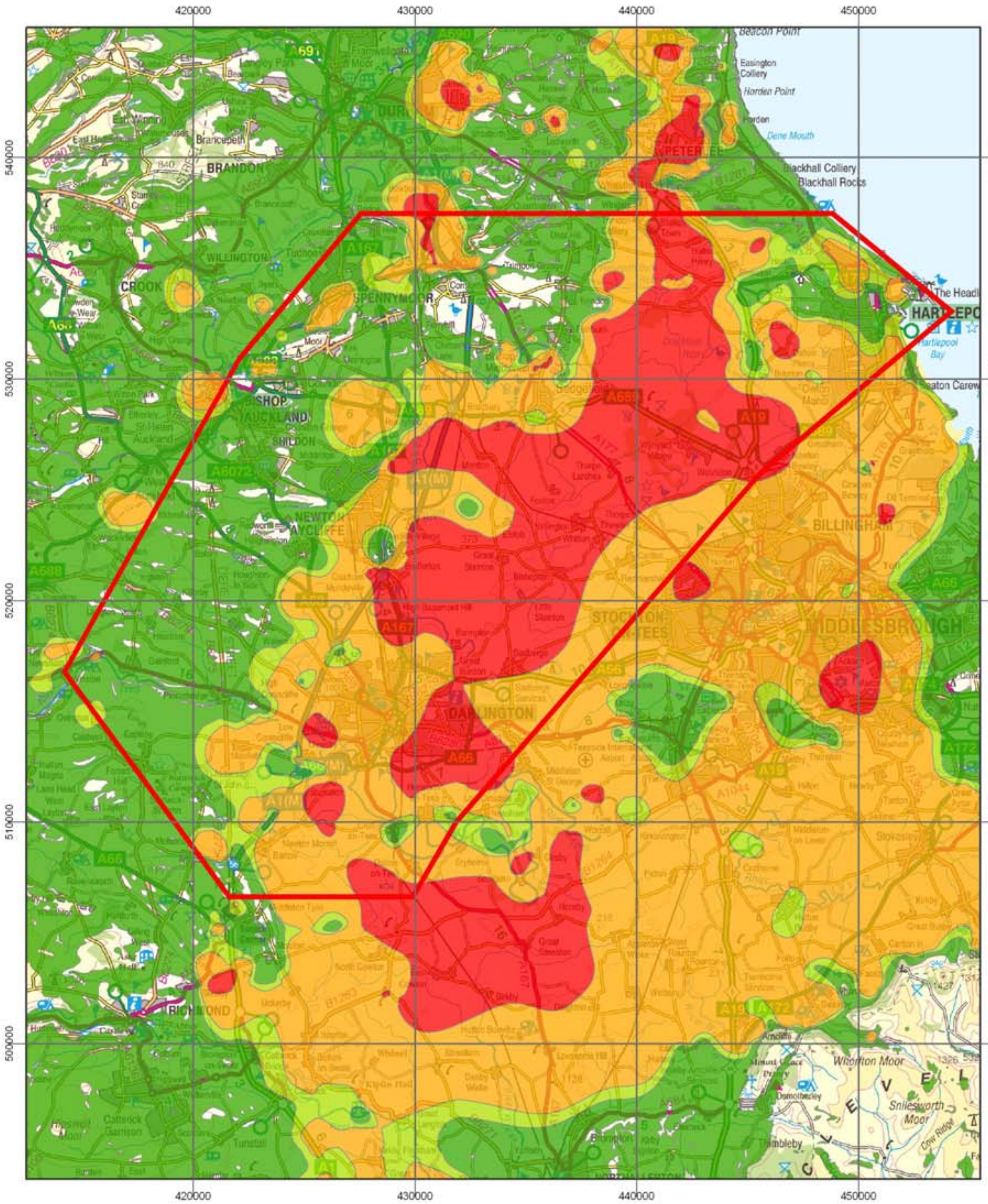
Total thickness of aquifer (superficial deposits). All thicknesses metres (m). *Partial data for Durham North (Phase 2) included but may be subject to change.*



Legend

DURHAM_SOUTH_PROJECT_AREA

TOTAL_THICKNESS_AQUITARD(m)

LOWER

1

5

10

30

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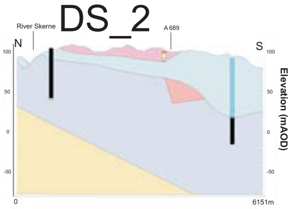
Total thickness of aquitard (superficial deposits). All thicknesses metres (m). *Partial data for Durham North (Phase 2) included but may be subject to change.*

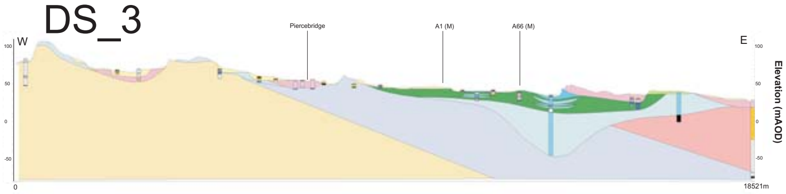
Appendix 4 Cross-Sections

DS_1

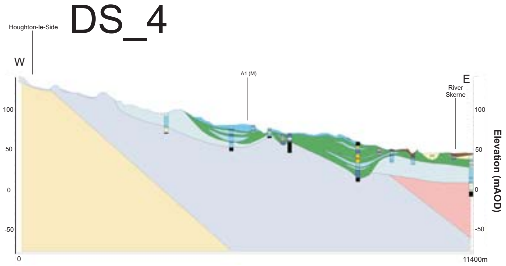
DS_2



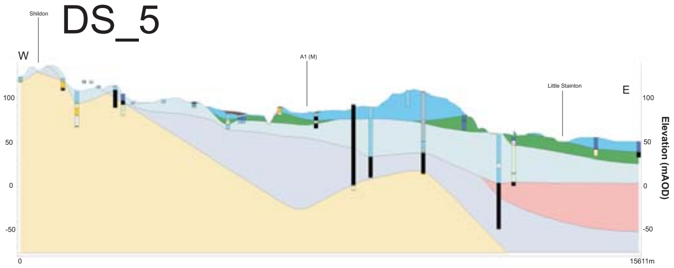
DS_3



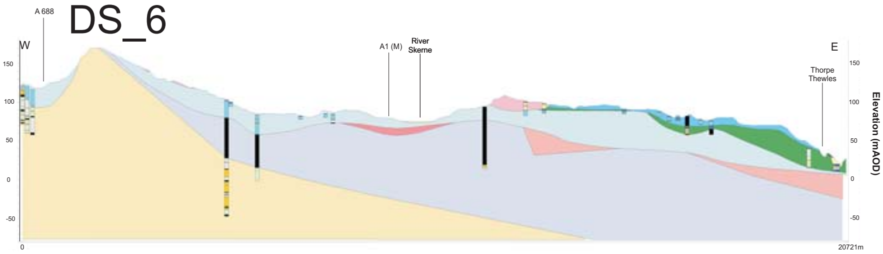
DS_4



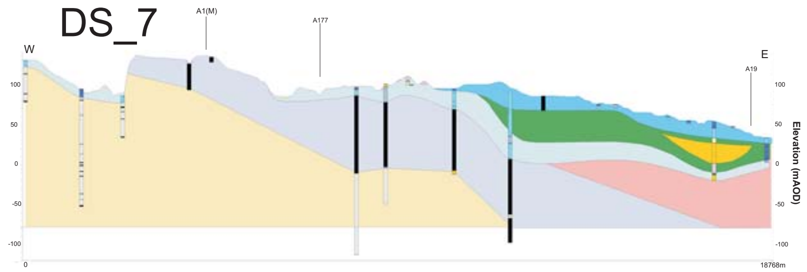
DS_5



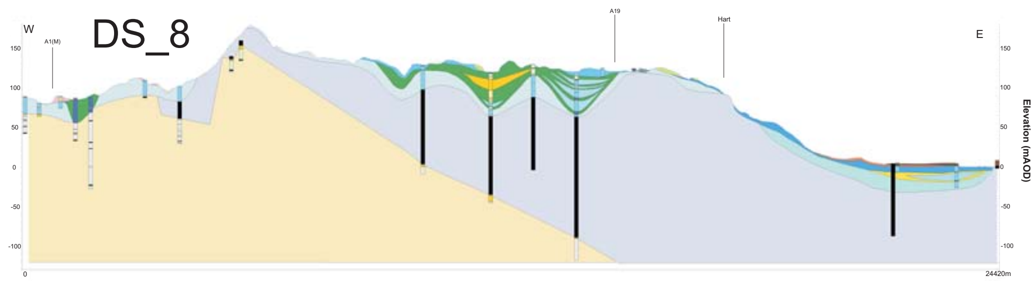
DS_6



DS_7



DS_8



Horizontal Scale 1:50 000
Vertical Exaggeration x 20

Superficial Deposits

- Made Ground (18)
- Marine (17)
- River Terrace Deposits (16)
- Alluvium (15)
- Peat (14)
- Lacustrine (13)
- Tidal Flat Deposits (12)
- Raised Marine Deposits (11)

North Pennine Glacigenic Subgroup

- Ebchester Sand and Gravel Formation (10)
- Moraine (9)
- Butterby Till Formation (6)
- Tyne and Wear Glaciolacustrine Formation(4) *including lenses of sand or sand and gravel*
- Wear Till Formation (2)
- Maiden's Hall sand and Gravel Formation (1)

North Sea Coast Glacigenic Subgroup

- Elwick Moraine Member (8)
- Horden Till Formation (7)
- Peterlee Sand Formation (5)
- Blackhall Till Formation (3)

Lithology of Superficial Deposits in Borehole Logs

- Soil or Made Ground
- Gravelly Clay
- Clay or Silt and Clay
- Silt and sandy Silt
- Sand
- Sand and Gravel
- Superficial Deposits Undifferentiated

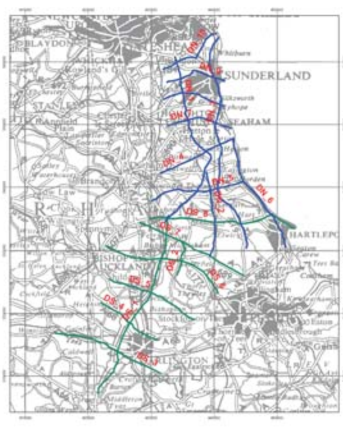
Bedrock

- Permian Marls
- Permian Limestone
- Carboniferous Coal Measures and Namurian Stainmore Formation

Bedrock correlations are shown schematically only
Permian Yellow Sands undifferentiated for Phase 1 Durham South

KEY

- Durham North Superficial Geology section lines (Phase 2)
- Durham South Superficial Geology section lines (Phase 1)



The cross-sections are compiled from borehole information that varies considerably in distribution, age, quality, depth and content. The geological information has been compiled from these boreholes and digital map data at a scale of 1: 50 000. Use of the cross-section interpretations at scales larger than 1:50 000 is not recommended. The varied distribution of the borehole data means that in some places the sections are well constrained and in others the geological lines are considerably extrapolated. The cross-sections are the best interpretation that the geologist has been able to make from the existing information and new boreholes may require this interpretation to be modified.

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Durham South Magnesian Limestone Study Phase 1
In confidence report CR/07/002