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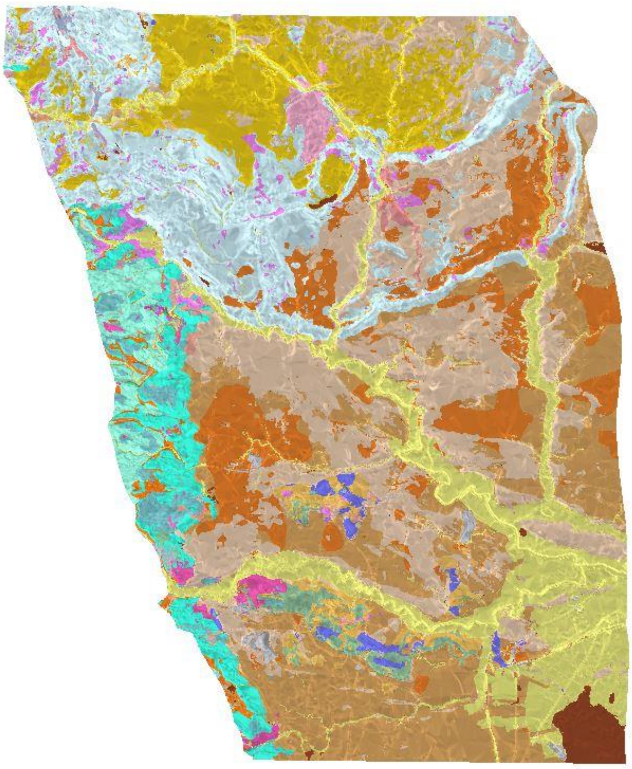
Environment Agency

A 3D geological model of the superficial deposits in the Selby area

Groundwater Programme

Commissioned Report CR/17/112



BRITISH GEOLOGICAL SURVEY

GROUNDWATER PROGRAMME

COMMISSIONED REPORT CR/17/112

A 3D geological model of the superficial deposits in the Selby area

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Keywords

3D model; superficial deposits; Selby; Vale of York

National Grid Reference

SW corner 437200,415000
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Front cover

3D view of the Selby superficial geology model

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Foreword

This report accompanies the Selby 3D geological model of the superficial deposits from Thorne, just north of Doncaster to Haxby, just north of York, the published products of a study by the British Geological Survey for the Environment Agency. The report authors wish to thank Harris Tarnanas at the Environment Agency for commissioning the work and providing additional borehole data to help constrain the geological model. The Selby model borders the existing Doncaster superficial geology model to the south (Price *et al*, 2006).

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Summary

The Selby 3D geological model, commissioned by the Environment Agency, covers an area of 1,300km^2 and shows the distribution and thickness of superficial deposits between Thorne, just north of Doncaster, to Haxby, just north of York. Surfaces derived from this model will be used by the Environment Agency to construct a numerical, spatially distributed model of recharge to the underlying regionally important Sherwood Sandstone Group aquifer and to update their existing numerical regional groundwater model. This report describes the geological units modelled, the 3D modelling methodology used and the limitations of the model.

1 Introduction

This report accompanies the Selby 3D geological model of the superficial deposits between Thorne and Haxby. This work was commissioned by the York office of the Environment Agency to address water resource issues in the region. The primary focus of the model is the superficial deposits, which are particularly complex in the northern half of the model area, where they are highly variable, both laterally and vertically.

The main output of the model is a series of grids that represent the tops, bases and thicknesses of the modelled units. These grids will be used by the Environment Agency to update their existing groundwater models, improve the representation of groundwater movement through the shallow subsurface and its connectivity with the Sherwood Sandstone Group aquifer. The Environment Agency are particularly interested in two geological scenarios: (1) areas where Sherwood Sandstone Group bedrock outcrops at the ground surface; and (2), where permeable superficial deposits connect the bedrock (Sherwood Sandstone Group) to the ground surface.

2 Location and topography

The Selby superficial geology model covers an area of 1,300 km^2 from Thorne to Haxby (Figure 1). The ground elevation of the model area is shown in Figure 2, where the Ordnance Survey Terrain 50 Digital Terrain Model (DTM) is colour ramped according to elevation (areas of highest elevation are coloured red and low areas are blue). In the north of the model area, the DTM shows a series of arc-shaped ridges forming morainic landforms developed in the Vale of York till. The southern-most of these, the Escrick Moraine, defines the widely accepted southern limit of the Vale of York lobe of the British-Irish Ice Sheet during the last glaciation (Ford et al., 2008; McMillan and Merritt, 2012). An alternative ice limit model presented by Gaunt (1976), Bateman *et al*. (2007) and Friend *et al*. (2016), the so-called 'Lindholme Advance', extends the Devensian limit further south in north Lincolnshire. The geological basis for this revised ice limit is somewhat tentative, with alternative interpretations of the data possible. Therefore, within this model the Escrick Moraine is used as the Devensian limit because it conforms to BGS's conceptual model of the Vale of York's glacial history and is the most widely accepted interpretation. In contrast, the topography in the southern half of the model area is much flatter and dominated by glacial lake deposits that are dissected by the tracts of modern river systems, including the Aire, Ouse and Derwent. The west of the model area is represented by higher-ground where Permian rocks are locally exposed and the superficial deposits are generally thin and patchy.

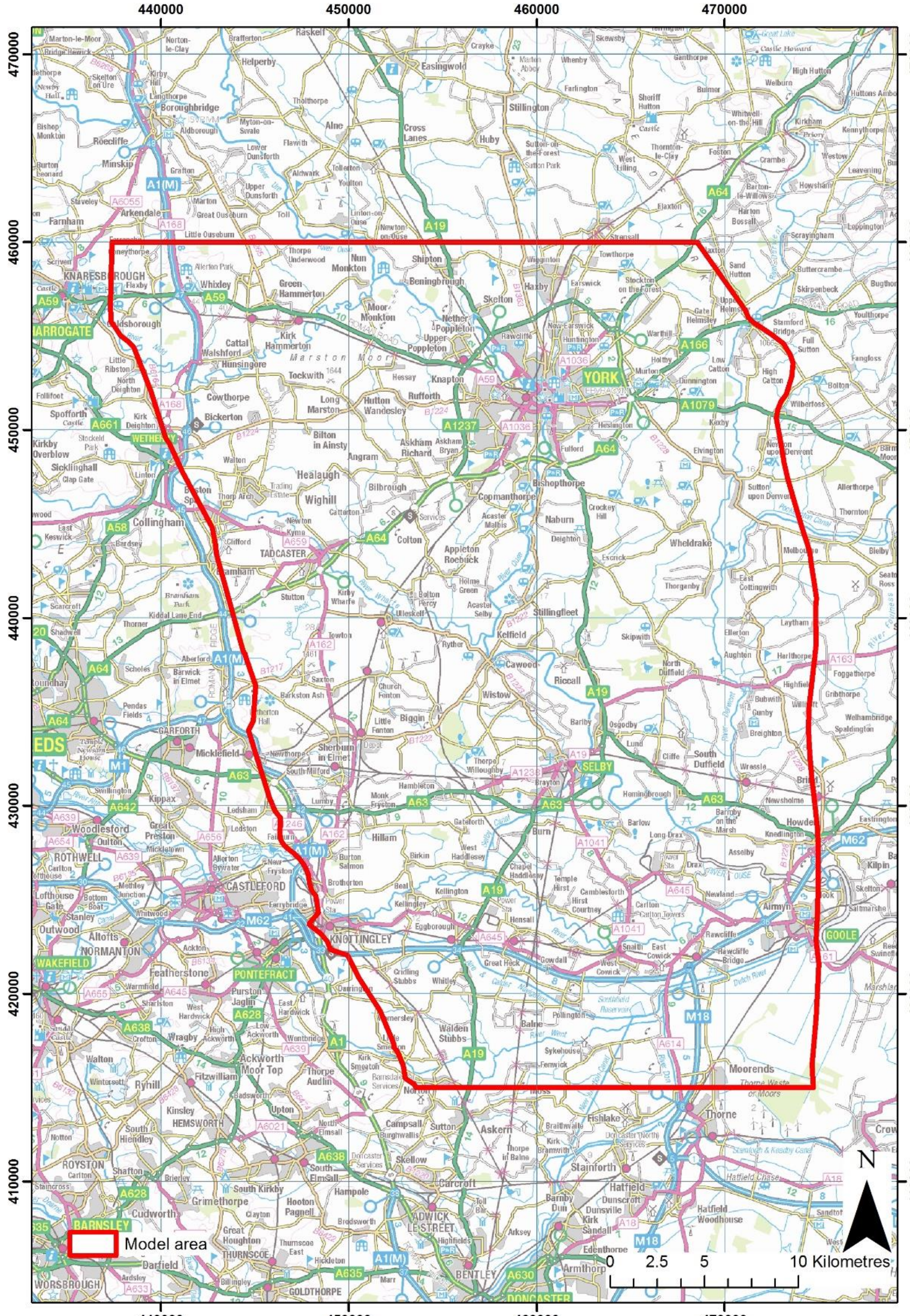

Figure 1 Location of the model area. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

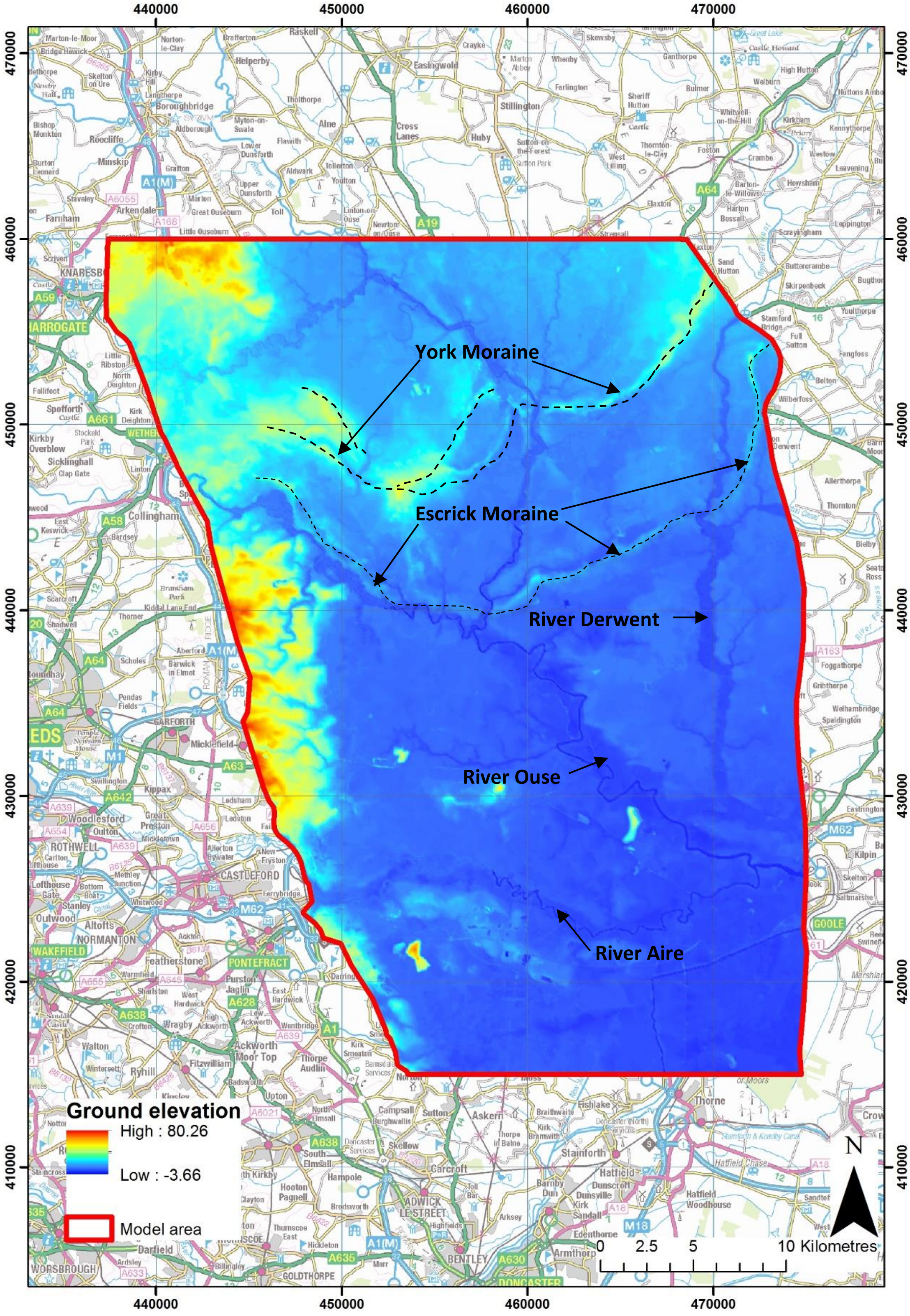

Figure 2 Ordnance Survey Terrain 50 Digital Terrain Model, colour ramped to show areas of highest elevation in red and low areas in blue. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

3 3D Modelling Methodology

3.1 DATA AND INFORMATION SOURCES

3.1.1 Geological map data

The Selby model uses digital geological map data from the corresponding 1:50 000 scale geological map sheets that cover the model area: 62 (Harrogate), 70 (Leeds), 71 (Selby), 78 (Wakefield) and 79 (Goole). No modern 1:50 000 scale map data is available for the York sheet in the north-east corner of the model area. Therefore, unpublished 1:10 000 scale geological map data was used for this part of the model (Figure 3). The current 1:50 000 scale mapping on the York sheet (63) is based on the 1882 edition of the geological map, whereas the 1:10 000 scale mapping uses survey data from the 2000s when the entire sheet was re-surveyed at 1:10 000 scale. This 1:10 000 scale mapping was therefore judged to be more suitable for use in the model than the existing published 1:50 000 scale mapping. It post-dates the published 1:50 000 scale mapping and is more accurate because the geological boundaries are based on modern topographic base maps and GPS was used to pinpoint the location of field observations.

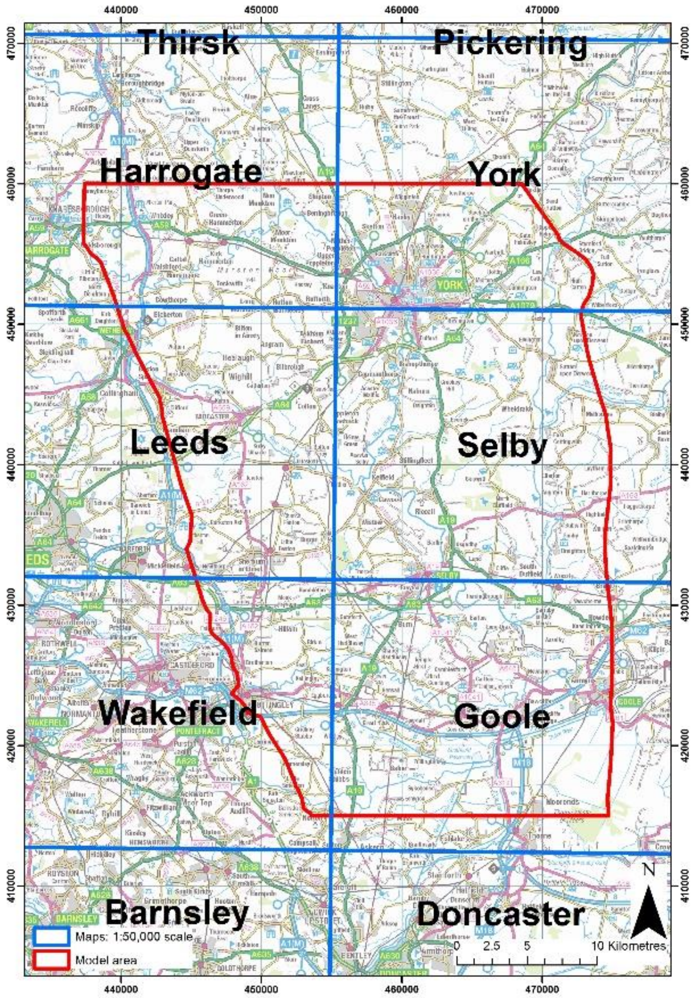

Figure 3 1:50 000 scale geological map sheets used to constrain the model. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

3.1.2 Digital Terrain Model

The model is capped by the Ordnance Survey *Terrain 50* Digital Terrain Model (DTM), which represents the ground surface. This was used at the full resolution 50 m horizontal cell size and

10 m vertical resolution for model construction and calculation. The delivered grids are subsampled to 200 m and aligned to the Environment Agency's regional groundwater model. These 200 m cell size grids are shown in the thickness maps.

3.1.3 Borehole records

The model considers a subset of borehole logs available in the project area. The downhole information in borehole records was 'coded' into corporate databases and extracted for use in the 3D modelling software. Boreholes were selected for coding based on the level of detail recorded in them, the drilled depth and proximity to other coded boreholes. Boreholes with the most detail in the superficial deposits that reach rockhead were preferentially selected for coding because they describe the full thickness of the superficial deposits and enable geological subdivisions and rockhead to be defined more accurately. Boreholes that show the greatest geological complexity were also targeted for coding. During borehole coding, some thin units were grouped for simplification. For example, a 10 cm-thick peat horizon in alluvium or a 20 cm-thick sand seam in the glaciolacustrine deposits are not always coded separately. It has been necessary to consider lower quality borehole logs in areas such as South Duffield, where all available boreholes are used regardless of the quality of the log because the borehole density is much lower. This will influence the level of confidence in the model in these areas, particularly if the mapping indicates more geological complexity.

A total of 2,083 borehole logs from the BGS Single Onshore Borehole Index were used to constrain the model, with an additional eight borehole records supplied by the client. Two of these are located outside the model area and were not used (Greenlands Farm and Marr). The remaining six boreholes are used in the cross-sections (Figure 4).

3.1.4 Previous studies

The Selby model incorporates an open framework of nine cross-sections commissioned by the Environment Agency in a previous study of the Vale of York (Ford *et al*, 2003). All cross-sections have been reinterpreted and some are re-routed in the Selby model to use new or additional borehole information. The Selby model covers the entire York-Haxby detailed geology model area (Burke and Price, 2013). Two reinterpreted and extended cross-sections from the York-Haxby model are incorporated into the Selby model. Cross-sections from the Doncaster model to the south are also used in the Selby model, but have not been interpreted. The Vale of York cross-sections, York-Haxby model extent and Doncaster cross-sections used are shown in Figure 4. Two cross-sections from a study at Heck-Pollington (Lee, *et al*, 2016) were used to inform cross-sections in the Selby model, but are not included in the final model.

3.2 BUILDING THE MODEL

The model comprises 22 Quaternary units, 6 schematic bedrock units and artificial ground (areas where the ground level has been artificially raised). Different techniques were used to model the Quaternary and bedrock units. These methodologies are described in turn below.

3.2.1 Modelling the Quaternary

The standard GSI3D modelling workflow was followed to model the Quaternary units and made ground in this project (Kessler *et al*, 2009). GSI3D software utilises a range of data such as boreholes, digital terrain model (DTM) and geological linework to enable the geologist to construct a series of interlocking cross-sections. Borehole data is represented in GSI3D by two proprietary files: a borehole identification file (.bid) that contains 'index'-level information including location and start-heights; and a borehole log file (.blg) that contains the borehole interpretation. Constructing cross-sections is intuitive and flexible, combining borehole and outcrop data with the geologist's experience to refine the interpretation.

Using both the information from the cross-sections and the distribution of each unit a calculation algorithm creates the triangulated surfaces for the top and base of each unit. In order to control the relative vertical ordering of the calculation, a generalised vertical section file (.gvs) is established. A proprietary legend file (.gleg) is created to control symbolisation of the cross-section and model. The modeller can view all the units in 3D and iteratively return to the cross-section to make amendments or add further cross-sections to refine the model. This process is a standard methodology within BGS for modelling Quaternary and simple bedrock horizons and is fully documented in Kessler *et al* (2009).

A total of 289 cross-sections were constructed to constrain the Quaternary units in the Selby model (Figure 4). Cross-sections from the existing Doncaster model to the south were used to match the depths of the modelled units without revising the Doncaster model. Boreholes from just outside the model area helped constrain the geology at the model margins.

Figure 4 Distribution map of all 2,083 BGS boreholes (pink dots) and six EA boreholes (light blue dots) used to inform the 289 cross-sections that constrain the Selby model. The Heck-Pollington study area is shown as red circles. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

Figure 5 is a 3D view of the cross-sections in the northern half of the model, looking from the south, with all units shown. The completed 'fence diagram' of cross-sections is the half way point to developing a full 3D model and gives the modeller a sense of the distribution and geometries of the modelled units.

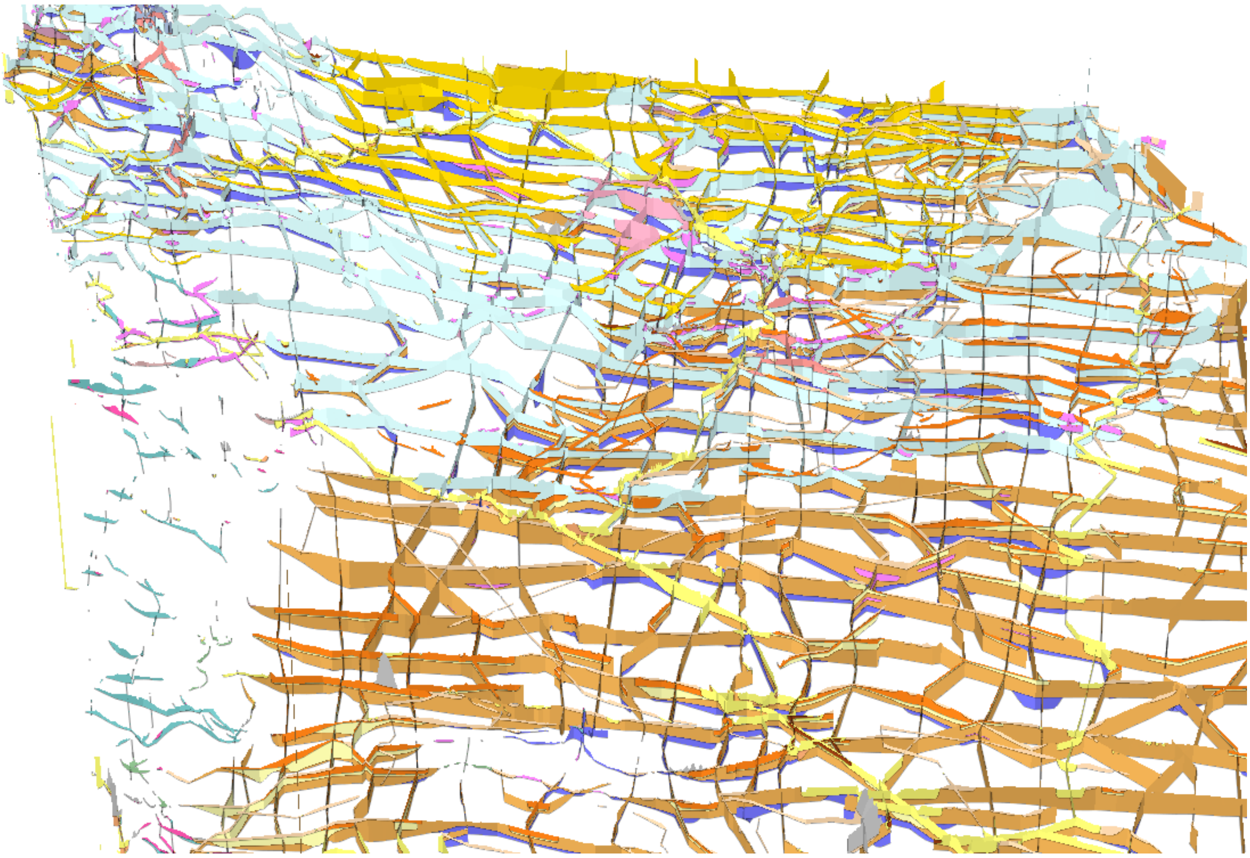

Figure 5 3D view of the cross-sections constructed to constrain the Quaternary geology in the northern part of the model

3.2.2 Modelling the bedrock

The bedrock was schematically modelled as a 'ribbon' using a more simplified and automated technique. This involved calculating a rockhead elevation surface (the combined bases of all modelled Quaternary units) and lowering its elevation by 5m. The corresponding 1:50 000 scale bedrock geological map was used to define the extents of the bedrock units in the model area and was used to segregate the lowered rockhead grid into segments. These segments define the base surface for each bedrock unit. No attempt has been made to model the bedrock in true 3D, nor to match the boreholes to the bedrock map. Thicknesses, dips and faults are not represented.

3.3 MODELLING DECISIONS AND ASSUMPTIONS MADE

The Selby model honours the corresponding geological map data. However, there are occasional mismatches between the geological maps and borehole logs. These mismatches were resolved by prioritising the borehole log over the geological map data and editing the modelled extents of the affected units. One such geological map/borehole mismatch occurs near Escrick in cross-section *EA_Selby_WE61_HB_NorthEast* (grid ref: 461980 442360). At this locality the geological map records Elvington Glaciolacustrine Formation at the ground surface, but borehole 123006 records only till to a depth of 12 m (Figure 6). In the cross-section the correlation of Elvington Glaciolacustrine Formation is broken to honour the borehole and till is modelled from the ground surface to rockhead.

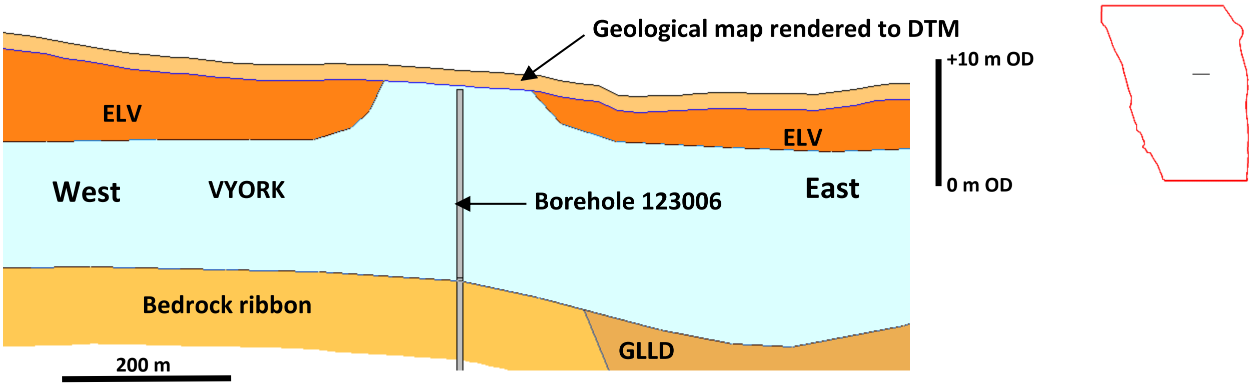

Figure 6 Cross-section *EA_Selby_WE61_HB_NorthEast*, where borehole 123006 records till from the ground surface to rockhead, but Elvington Glaciolacustrine Formation (ELV) is mapped. The correlation of ELV is broken and till is modelled to give precedence to the borehole evidence over the geological map. Vertical exaggeration x20.

Mismatches can also occur at the boundaries between 1:50 000 map sheets because of different survey dates and differences in the understanding of the geology at the time of survey. These can be spatial mismatches, such as offset geological boundaries, or differences in the attribution of the geology across a sheet boundary. One such sheet boundary mismatch in the model area occurs between the Wakefield and Goole sheets. This was resolved by matching the Goole sheet to the more recently surveyed Wakefield sheet, using borehole evidence for guidance (Figure 7). Several units in the model have similar DiGMap colours, which were changed in the model for easier identification (e.g. LABD).

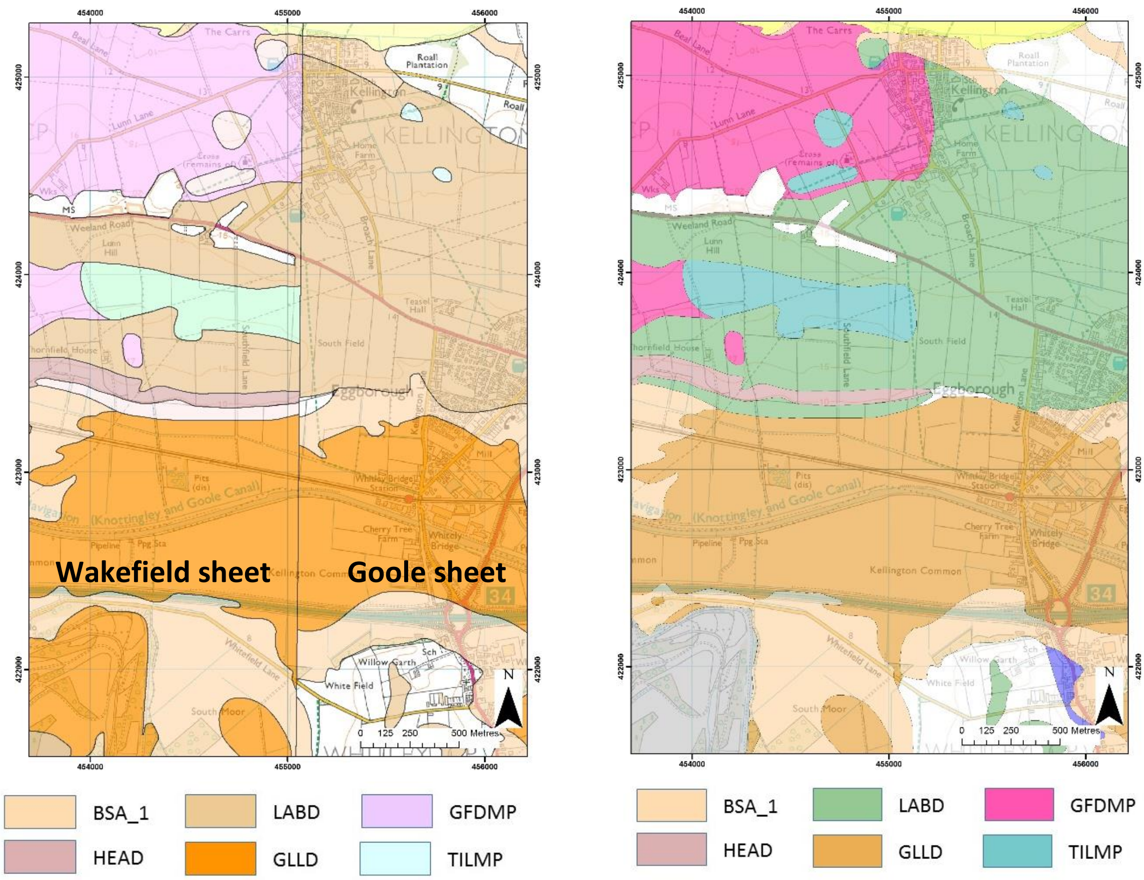

Figure 7 Mismatches between the Wakefield and Goole 1:50 000 scale map sheets in the Eggborough area were resolved in the model. Includes BGS DigMapGB-50 data © NERC. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

All polygons from the corresponding geological maps are included in the unit distributions. However, as set out in the proposal document, it has not been possible to model every polygon of every unit to give it a thickness/volume. This particularly affects the calculation of thin sinuous units, such as head and alluvium, and polygons that fall between the cross-sections. This is apparent when comparing the thickness grids to the modelled distribution later in this report.

Borehole start heights were honoured during cross-section correlation. Anomalous borehole start heights (those that sit 5 m or more above or below the Digital Terrain Model (DTM) were investigated and corrected where possible, or rendered to the DTM if no other start height information was available. These anomalies can reflect changes in the ground elevation where the boreholes pre-date a quarry or road embankment, or errors in the borehole data itself, such as incorrect feet to metres conversions. With boreholes being the primary source of depth information, incorrect borehole start heights can affect the thicknesses and bases of modelled units.

Some mapped geological units that share similar lithological and hydrogeological properties are grouped into single units in the model. For example, river alluvium and warp (accumulations of clay and silt on deliberately flooded ground) are modelled as *ALV*. Similarly, all cover sand units are modelled as *BSA_1* (Naburn Sand, Sutton Sand etc). These combined units are explained in more detail in Section 4.

Esker sand and gravel deposits are modelled as *GFDU_T_VYORK*. The Hunsingore Esker Member, mapped in the north-east corner of the model, is partly exposed at the ground surface and partly enclosed within the Vale of York till sheet. To represent this relationship in the 3D modelling software the unit *VYORK_T* is used to represent the upper part of the till where it encloses the esker (Figure 8). The Wakefield geological map shows where these esker deposits continue within the till sheet and was used to inform the extent of this esker in the model.

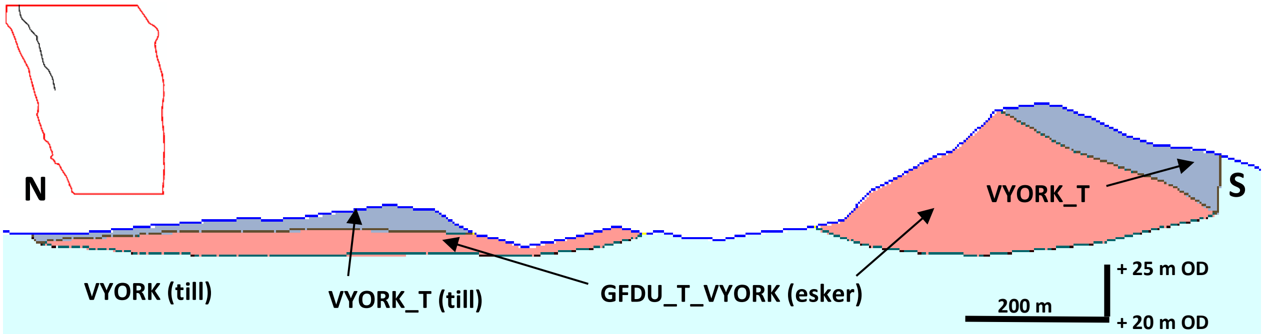

Figure 8 Cross-section *EA_Selby_NS5_LH_NorthWest* shows the Hunsingore Esker Member both at surface and enclosed within the Vale of York till. Vertical exaggeration x10.

Similarly, moraines are separated from the Vale of York till sheet in the geological maps based on their geomorphology. However, because their age and composition are consistent with the Vale of York Formation till sheet they are modelled as a single unit (*VYORK*).

Lenses are shown in the cross-sections where proven in boreholes, but are not calculated as volumes. A lens is a laterally discontinuous lithologically distinct unit enclosed within a parent unit. Five stratigraphic levels of lenses are represented in the cross-sections: a peat lens in the alluvium; two sand and gravel lenses; a laminated clay lens in the till (Figure 9), and a sand and gravel lens in the laminated clay of the Hemingbrough Formation. These lenses are not modelled as volumes.

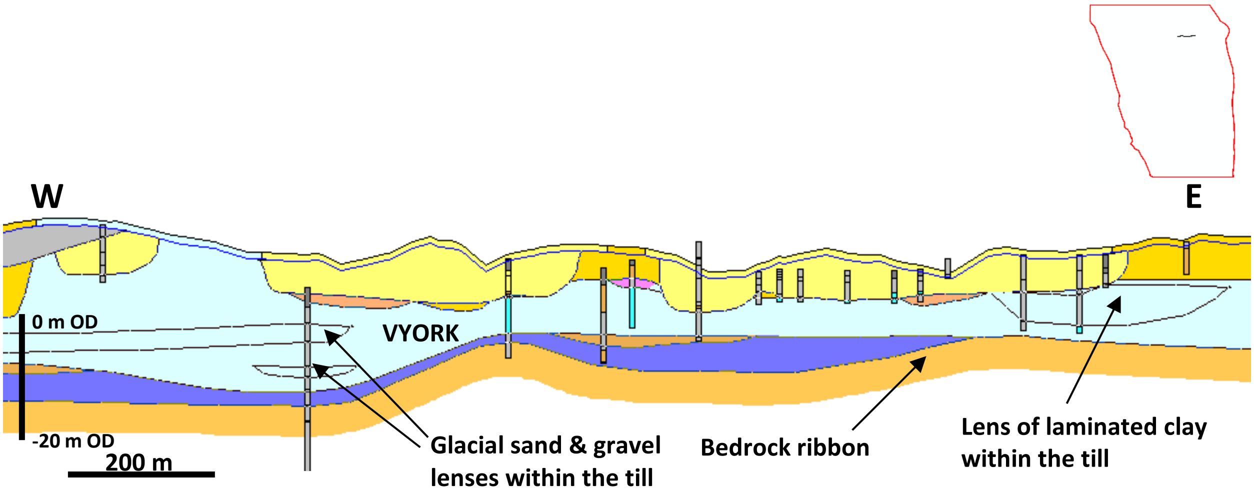

Figure 9 Cross-section *EA_Selby_WE68_HB*, showing lenses within the till. Two lenses of sand and gravel are modelled in the west of the section and a lens of laminated clay in the eastern part. These lenses are not coloured. Vertical exaggeration x10.

Glacial sand and gravel is modelled as *GFDU* where possible to limit the number of geological units. This includes patches of sand and gravel that were mapped as part of the Escrick and York moraine complexes, glaciofluvial terrace deposits and isolated patches of Devensian sand and gravel mapped in the Gateforth area.

A basal sand and gravel unit, modelled as *GFDUD*, includes areas where boreholes record Sherwood Sandstone Group, but describe it as sand. Using borehole descriptions alone it is often difficult to distinguish between a sand composed of bedrock that has weathered *in situ* and sand that was laid down by glacial processes (cf. Lee *et al*., 2016). GFDUD therefore represents a rockhead uncertainty layer. GFDUD is also used modelled in areas underlain by other bedrock units for consistency. GFDUD is matched to the geological unit *GLLD_BS* in the Doncaster model to the south.

A northern continuation of the Moss Channel, a major buried channel feature, is represented in the south-west corner of the Selby model using a map of subglacial channels in the Doncaster area shown in Figure 40 of the Doncaster memoir (Gaunt, 1994). Additional buried channels are inferred from sinuous outcrops or ‘ribbons’ of till which in other areas (e.g. East Anglia) are good indicators of similar buried channels where borehole coverage is limited or absent (Bricker *et al*, 2012). The infill of buried channels is modelled as *TILMP* but typically contain a variety of lithologies (e.g. till, sand, sand and gravel, silt and clay), reflecting their complex genesis.

Modelling all instances of artificial ground in the model area is beyond the scope of the project. However, there are areas where artificial ground forms artefacts in the Digital Terrain Model, which affects the modelled thickness of superficial deposits at the ground surface. For example, cross-section *EA_Selby_NS10_LH_South* runs close to junction 34 of the M62 motorway near Knottingley, where the natural ground level is around 6-8 m above sea level. However, a feature in the Digital Terrain Model at this location has a maximum ground elevation of 67 m (Figure 10). This corresponds with an area of mapped ‘made ground’ (built up ground) in the BGS DiGMapGB-50 artificial ground layer and an ash disposal area on the topographic map. The DiGMap artificial ground polygon was used to define the extent of this area of made ground, which prevents the over-thickening of the natural superficial deposits in the model and corresponding grids.

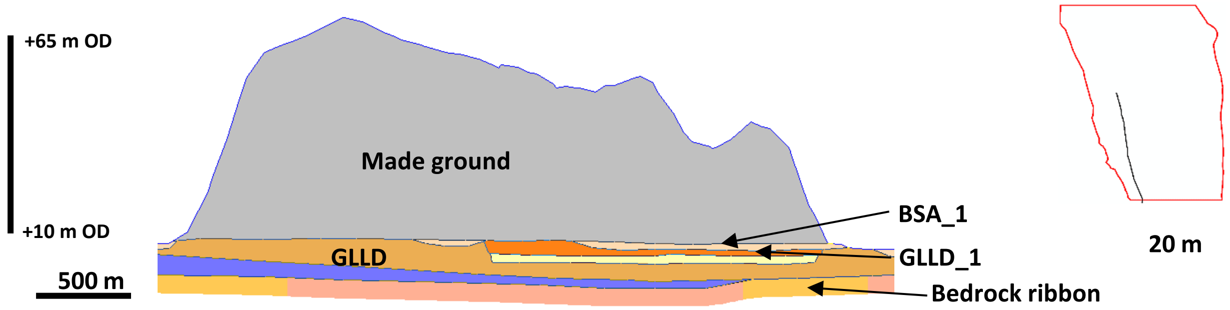

Figure 10 Made ground (grey) is modelled in cross-section *EA_Selby_NS10_LH_South*, where a spoil heap forms a feature in the Digital Terrain Model. Vertical exaggeration x10.

3.4 MODEL LIMITATIONS

It is has not been possible to model all thin ribbon-shaped units, such as alluvium, and polygons that fall between cross-sections as volumes. These units therefore have zero thickness in some areas.

The representation of the geology in the model is simplified, with units of similar lithologies grouped into single geological units. Such groupings include several named cover sands and alluvium/warp.

The level of geological complexity that can be represented is limited by the regional scale of the model. For example, some boreholes record thin (c. 20cm thick) horizons of sand and gravel/laminated clay that cannot be modelled at this scale.

The 3D modelling software used is also a limitation because the geological units have to follow a rigid stratigraphic hierarchy. This prevents the same unit being modelled at two different levels in the same cross-section, such as VYORK where eskers are modelled. This was addressed by adding the upper till unit VYORK_T to enable till to be modelled above and below the eskers, although in reality they are the same stratigraphic unit.

3.5 MODEL CALCULATION AND QA

In order for a geological model to be approved for publication or delivery to a client a series of standard QA checks is carried out. This includes visual examination of the modelled cross-sections to ensure that they match each other at cross-section intersections and fit the borehole and geological map data used and the Digital Terrain Model. The model calculation is checked to ensure that all units calculate to their full extent within the area of interest and the modelled geological surfaces are checked for artefacts such as spikes and thickness anomalies. Scientific checks are also carried out on the model to ensure the units follow the correct stratigraphic order and that their geometries make geological sense. Any issues found in the QA checking process are recorded and addressed before delivery/publication of the model.

The calculation of the model is improved by the addition of ‘helper’ sections. These are typically needed along linear features, such as alluvium, and through polygons that fall between cross-sections. However, it is beyond the scope of this project to add a helper sections every small polygon in the model area. Priority is given to alluvium and more laterally persistent units, such as cover sand.

No attempt has been made to establish model uncertainty up to the point of the model delivery.

3.6 DATA DELIVERY

The 3D modelling software calculates the top and base of each unit in the model from the top down, using the Ordnance Survey 50 m Digital Terrain Model as a capping surface. These surfaces are Triangular Irregular Networks (TINs), which are generated by triangulating between the digitised nodes along the cross-sections and the nodes along the edges of the unit distributions.

For delivery these TINs are converted to 200m cell size ASCII grids aligned to the Environment Agency's existing groundwater model grid. A 3D pdf and shape files representing the distribution of the modelled geological units are also supplied for visualisation purposes.

4 Geology of the model area

4.1 BEDROCK GEOLOGY

The bedrock geology of the model area comprises rocks of Permian to Triassic age (Table 1). The oldest rocks are late Permian and belong to the Zechstein Group, which outcrop on the high ground in the west of the model area (Figure 11). These bedrock units are described from oldest to youngest as follows: The Cadeby Formation (formerly named Lower Magnesian Limestone) consists of dolomite and dolomitic limestone. The Edlington Formation (formerly named Middle Permian Marl) consists of red calcareous mudstone with gypsum. The Brotherton Formation (formerly named Upper Magnesian Limestone) comprises dolomitic limestone and is folded and brecciated where gypsum layers have dissolved. The Roxby Formation (formerly named Upper Permian Marl) is composed of red calcareous mudstone with gypsum (Cooper & Gibson, 2003).

The most widespread bedrock unit in the model area is the Triassic Sherwood Sandstone Group (the principal groundwater aquifer in the region), which consists of fine to coarse grained red-brown fluvial and aeolian sandstones. These are often cross-bedded and can contain channels, pebble beds and mudstone layers. The Sherwood Sandstone Group reaches up to 435 m thick in the Selby district (Cooper *et al*, 2008).

Mercia Mudstone Group is mapped in the far east of the model area where it overlies the Sherwood Sandstone Group. The basal part of the Mercia Mudstone Group consists of grey pyritic and micaceous mudstones with limestone and sandstone beds. Beds and secondary veins of gypsum are common in the lower part of the Mercia Mudstone Group. The rest of the succession is composed of red-brown calcareous and gypsiferous mudstone (Ford *et al*, 2008).

Bedrock is represented in the model as a 'ribbon' for illustrative purposes only. Although numerous geological faults and other structures such as regional dips are mapped in the area they are not represented in the model.

Table 1 List of bedrock units in the relative stratigraphic order used in the model

<table>
<tr><th>Unit name</th><th colspan="2">Full name</th><th>Description</th></tr>
<tr><td>MMG-MDST</td><td colspan="2">Mercia Mudstone Group</td><td>Red-brown and green mudstone and siltstone with interbedded gypsum in the upper part of the sequence</td></tr>
<tr><td>SSG-SDST</td><td colspan="2">Sherwood Sandstone Group</td><td>Red-brown fine to coarse grained sandstone</td></tr>
<tr><td>ROX-CAMDST</td><td>Roxby Formation</td><td rowspan="4">Zechstein Group</td><td>Red calcareous mudstone with gypsum</td></tr>
<tr><td>BTH-DOLMST</td><td>Brotherton Formation</td><td>Dolomitic limestone</td></tr>
<tr><td>EDT-CAMDST</td><td>Edlington Formation</td><td>Red calcareous mudstone with gypsum</td></tr>
<tr><td>CDF-DOLO</td><td>Cadeby Formation</td><td>Dolomite and dolomitic limestone</td></tr>
</table>

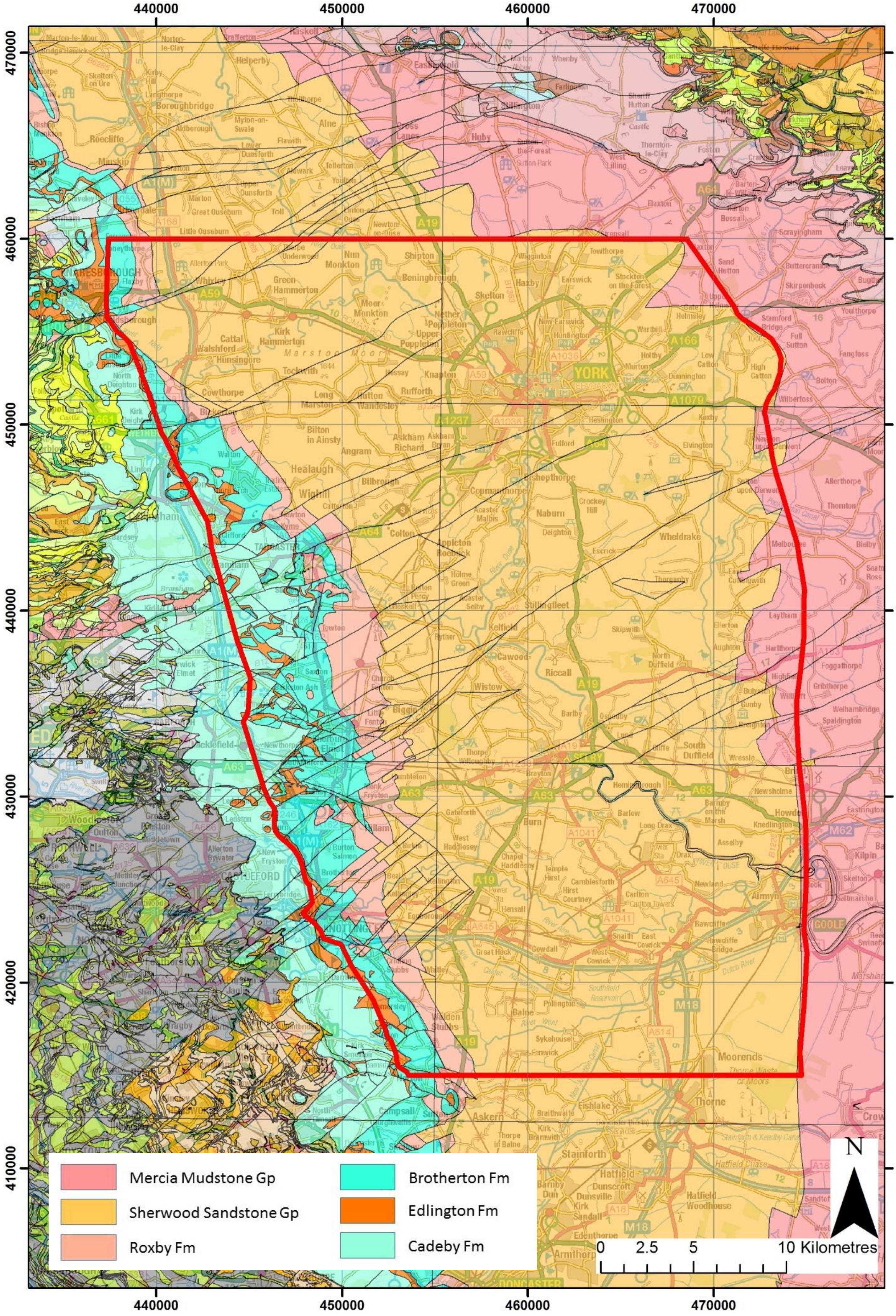

Figure 11 1:50 000 scale bedrock geology map of the model area. Model area outlined in red. © Crown copyright and database rights (2017). Ordnance Survey [100021290 EUL]. Includes BGS DigMapGB-50 data © NERC.

4.2 QUATERNARY GEOLOGY

4.2.1 Quaternary geological setting

The Quaternary succession of the model area is dominated by Late Pleistocene and Holocene sediments. The Late Pleistocene succession is primarily composed of glacial deposits that were laid down during the last major period of glaciation to affect the UK. Although there is significant debate surrounding the number of glaciations that occurred during the last cold stage (118 ka to 11.7 ka; Marine Isotope Stage 5-2), in Yorkshire the glacial geology corresponds to the Late Devensian (Dimlington Stadial) glaciation (c.30-15 ka) (McMillan and Merritt, 2012).

The model area can be divided into two broad ‘domains’ separated by the Escrick Moraine (Figure 12). The southern domain is characterised by its relatively flat, low-lying topography, which is dominated by sediments of the Hemingbrough Glaciolacustrine Formation (Ford *et al*., 2008). This formation is composed of laminated clay, silt and sand deposited in an extensive proglacial lake system called Glacial Lake Humber that developed in front of the Vale of York ice lobe (part of the Last British-Irish Ice Sheet). First recognised by Kendall (1893), Glacial Lake Humber extended from the north of York to the south of Doncaster and formed when the Humber estuary was blocked by ice (Bateman *et al*, 2007; Murton *et al*, 2009; Fairburn *et al*, 2016).

The northern domain is geologically more complex and dominated by highly deformed sediments associated with the Vale of York till sheet, deposited by the Vale of York ice lobe (Bateman *et al*, 2015). Ice advanced southwards forming the Escrick Moraine and then retreated north to form the York Moraine during a major ice marginal still-stand. The action of ice pushing into and overriding the pre-existing sediments caused widespread deformation of the underlying sediments (a process called glacitectonics). This process created the highly irregular morainic topography that dominates the landscape. The main geological unit in the northern domain is till of the Vale of York Formation. This widespread till sheet underlies the vast majority of the northern half of the model. Lenses of glacial sand and gravel and laminated clay within the till have been identified in boreholes and modelled in the cross-sections.

The Vale of York till sheet is overlain by laminated clay and silt associated with two separate glaciolacustrine systems. The Elvington Glaciolacustrine Formation occurs between the Escrick and York moraines and formed in a moraine-dammed proglacial lake that established when the ice margin had retreated northwards to York (Ford *et al*, 2008). Alne Glaciolacustrine Formation is mapped to the north of York and is thought to have been deposited in a later proglacial lake that was established as the ice margin retreated further north again (Ford *et al*, 2008).

Remnants (outliers) of an older till sheet associated with an earlier (Middle Pleistocene) ice advance are found on higher ground in the west of the model area. Mapped as Harrogate Till Formation and TILMP with associated gravels, these deposits are relatively thin and have a patchy distribution pattern. These deposits could stratigraphically be associated with the various northwest-southeast trending buried channels outlined previously, although this relationship has not been proven.

Widespread cover sand deposits of the Breighton Sand Formation overlie the glacial sediments in the model area. These are primarily composed of sand with minor components of gravel, clay and peat. These cover sand deposits were laid down by a combination of fluvial and aeolian processes (Ford *et al*, 2008). The Sutton Sand Formation is another cover sand that is mapped in the southern half of the model area. This is a true aeolian sand, but for the purposes of the model is included with the Breighton Sand Formation.

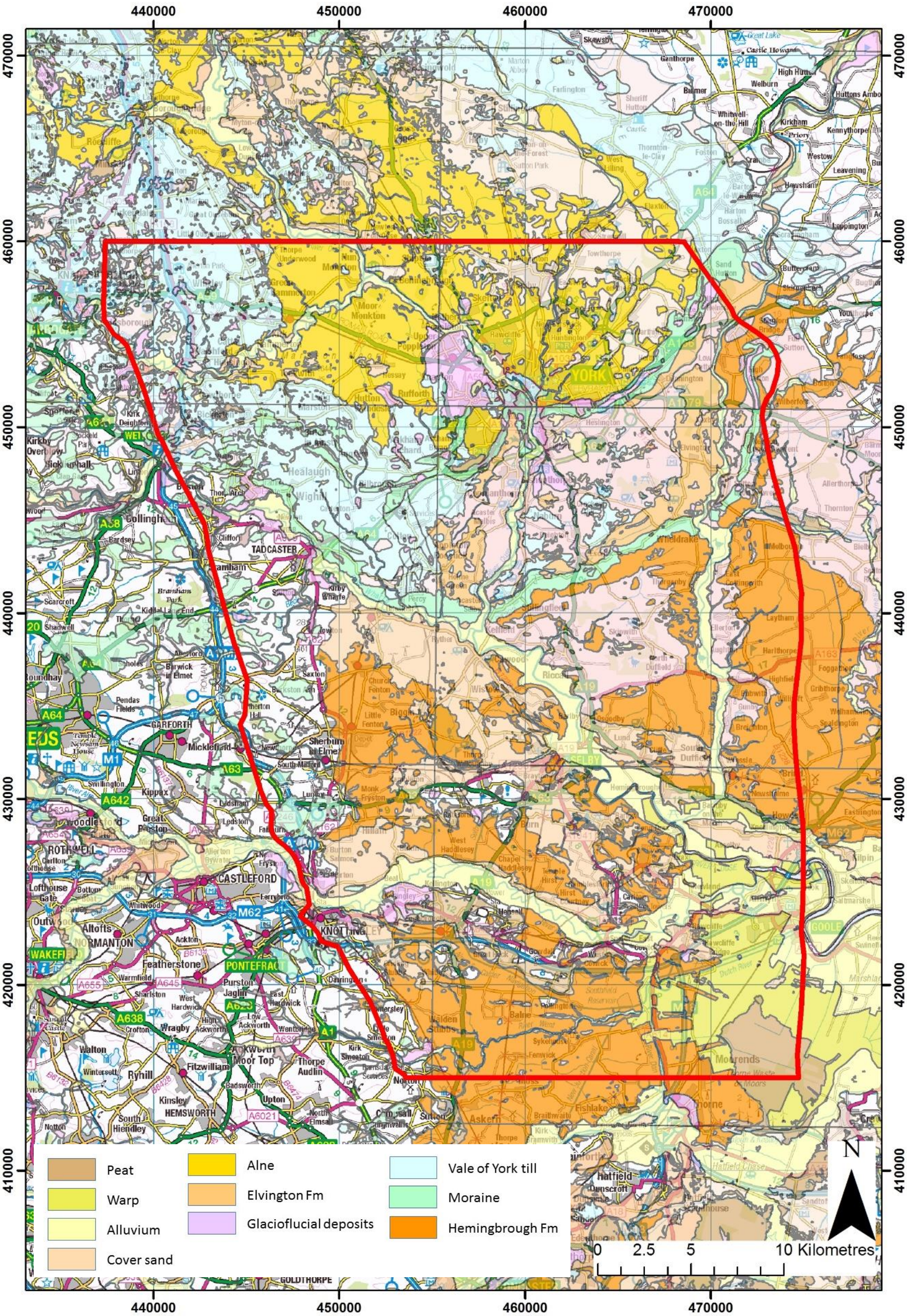

Figure 12 1:50 000 scale Quaternary geology map of the model area. Major geological units are labelled, model area outlined in red. © Crown copyright and database rights (2017). Ordnance Survey [100021290 EUL]. Includes BGS DigMapGB-50 data © NERC.

The model area is drained by several rivers and associated floodplains where alluvium has been mapped. All alluvium is modelled as a single unit, which includes ‘warp’, a veneer of clay and silt that has accumulated on deliberately flooded land to improve the soil. A lens of peat identified within the alluvium is represented in the cross-sections. Also present above the floodplains on the valley flanks are river terrace deposits. These are modelled to match the geological mapping and beneath alluvium where proven in boreholes. These river terrace deposits formed after the first (Middle Pleistocene) glaciation of the region but prior to the Late Devensian glaciation and record relic drainage patterns (Gaunt, 1994; Lee et al., 2016).

The model also reveals the extent of geological units where they are concealed beneath others. Alne Glaciolacustrine Formation, for example, has a wider distribution pattern than shown on the geological map because it extends beneath sand and gravel deposits. Similarly, the Hemingbrough Glaciolacustrine Formation is modelled much further north than its mapped surface distribution, being proven beneath the Vale of York till sheet in boreholes.

The geometric relationships between the modelled units are shown in four representative cross-sections below, two in the northern half of the model are and two in the southern half. The northern cross-sections (Figures 13 and 14) demonstrate the geological complexity in this part of the model, particularly in the York Moraine area. The York Moraine is composed of till (*VYORK*) and thick accumulations of glaciofluvial deposits (*GFDU*). Lithological variability in the till itself is modelled where lenses of laminated clay (*GLLD_Lens*) and sand and gravel (*GFDU_Lens*) are identified in boreholes. The Vale of York till sheet (*VYORK*) is both overlain and underlain by glaciolacustrine sediments. The Alne (*ALNE*) and Elvington (*ELV*) Glaciolacustrine formations mantle the till sheet and the Hemingbrough Formation underlies the till sheet. The Hemingbrough Glaciolacustrine Formation is subdivided where possible into a basal laminated clay unit (*GLLD*), an intervening running sand (*GLLD_S*) and an upper laminated clay unit (*GLLD_1*). Only GLLD is modelled where the units cannot be subdivided.

Two cross-sections from the south of the model area are shown in Figures 15 and 16. Here the topography is much flatter and Hemingbrough Glaciolacustrine Formation deposits dominate. As in the north of the model, the Hemingbrough Glaciolacustrine Formation is subdivided into GLLD, GLLD_S and GLLD_1 where possible and only GLLD is modelled elsewhere. A prominent bedrock ‘high’ near Thorpe Willoughby is capped by pre-Devensian glacial deposits (*TILMP* and *GFDMP*). Another noticeable feature in the Digital Terrain Model is formed by a spoil heap at Thorne Colliery, which is modelled as made ground (*MGR*) in Figure 16.

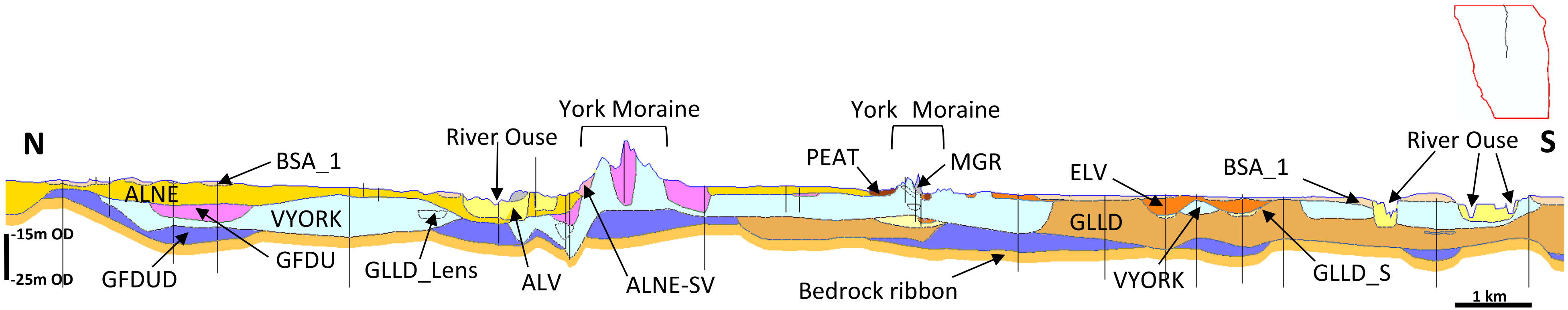

Figure 13 Cross-section *EA_Selby_NS_15_LH_NorthEast*, which runs north-south through the centre of the northern half of the model. This cross-section shows glaciolacustrine deposits above and below the Vale of York till sheet (Alne Glaciolacustrine Formation in gold, Elvington in dark orange, Hemingbrough in pale orange) and lenses of laminated clay within the till. The Vale of York till sheet terminates in the south of the cross-section. Boreholes are shown as black vertical lines. Lenses are not coloured. Key as per Table 1. Vertical exaggeration x30.

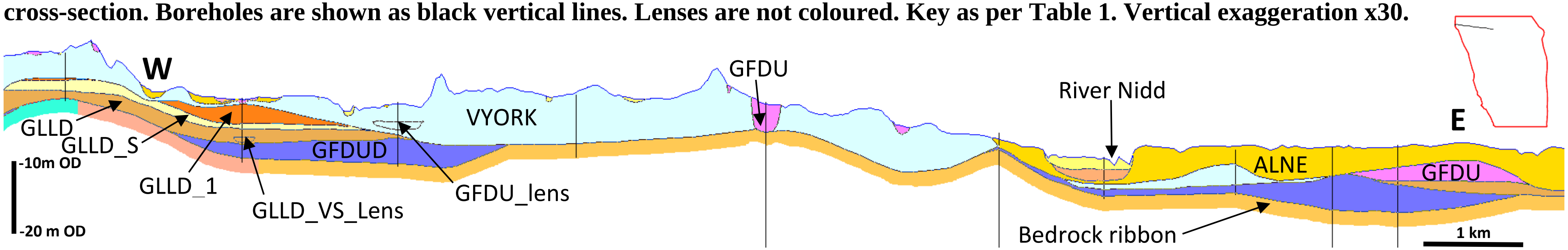

Figure 14 Cross-section *EA_Selby_WE5_LH_NorthWest*, which runs west to east through the north-west of the model area. This part of the model is dominated by Vale of York till, which includes lenses of sand and gravel. The Vale of York Formation till is underlain by Hemingbrough Glaciolacustrine Formation in the west of this section, with the three sub-units modelled using borehole evidence. A lens of sand and gravel is modelled in the basal laminated clay unit. Alne Glaciolscustrine Formation dominates in the eastern part of the section and occupies a 'hole' in the till sheet. Boreholes are shown as black vertical lines. Lenses are not coloured. Key as per Table 1. Vertical exaggeration x30.

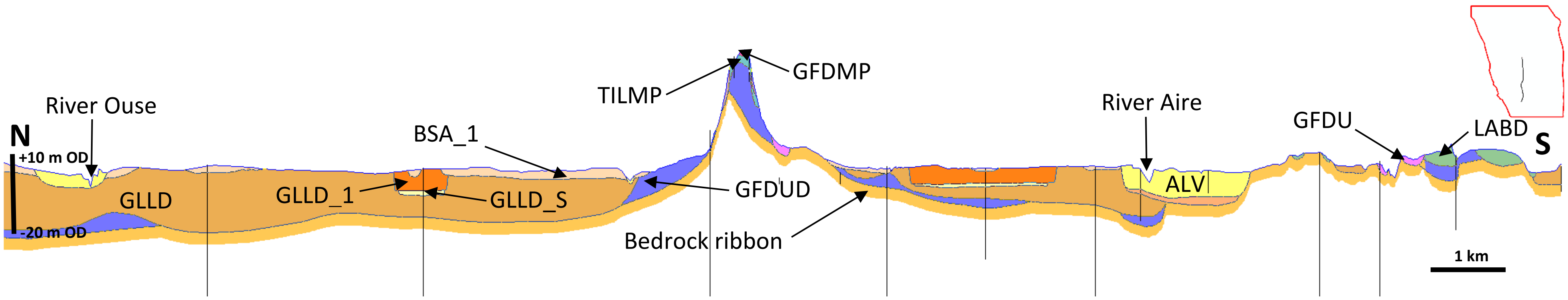

Figure 15 ***Cross-section EA_Selby_NS15_LH_South*****, which runs through the centre of the southern half of the model. This half of the model is dominated by the Hemingbrough Glaciolacustrine Formation laminated clay succession, which is subdivided into the upper and lower laminated clay units (*****GLLD_1*** **and** ***GLLD*****) and intervening sand (*****GLLD_S*****) where borehole evidence allows. The topographic high near Thorpe Willoughby is capped by Pleistocene till (*****TILMP*****) and associated glacial sand & gravel (*****GFDMP*****) with bedrock exposed on the flanks (white space and GFDUD where the Sherwood Sandstone Group bedrock is weathered to sand). Boreholes are shown as black vertical lines. Key as per Table 1. Vertical exaggeration x30.**

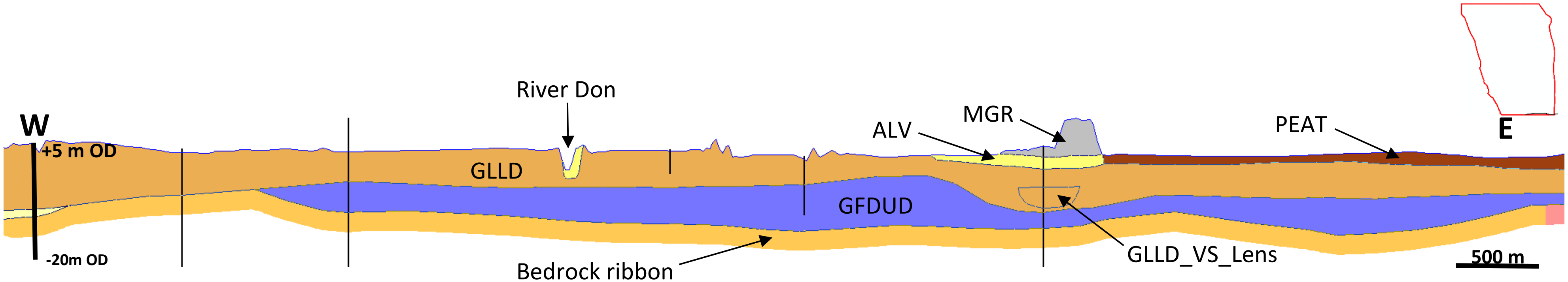

Figure 16 Cross-section ***EA_Selby_WE26_HB*****, which runs west to east in the south-east corner of the model. This part of the model is dominated by Hemingbrough Glaciolacustrine Formation laminated clay and silt. Only** ***GLLD*** **is modelled in this cross-section because of insufficient borehole evidence to separate out the component units. Overlying the glaciolacustrine sediments are peat associated with Thorne Waste Moors and alluvium of the River Don floodplain. A spoil heap associated with the disused Thorne Colliery (modelled as** ***MGR*****) forms a prominent feature in the Digital Terrain Model. Boreholes are shown as black vertical lines. Lenses are not coloured. Key as per Table 1. Vertical exaggeration x30.**

Figure 17 shows a 3D view of the calculated model with all units shown, looking from the south-east. This demonstrates the relationship between the topography and geology, with Permian rocks outcropping on the high ground in the west, moraines in the till sheet forming ridges and Hemingbrough Glaciolacustrine Formation occupying the flat ground in the southern half of the model. The grouping of similar lithological units can be seen in this view, such as warp and alluvium in the south-east corner and Vale of York till/moraines.

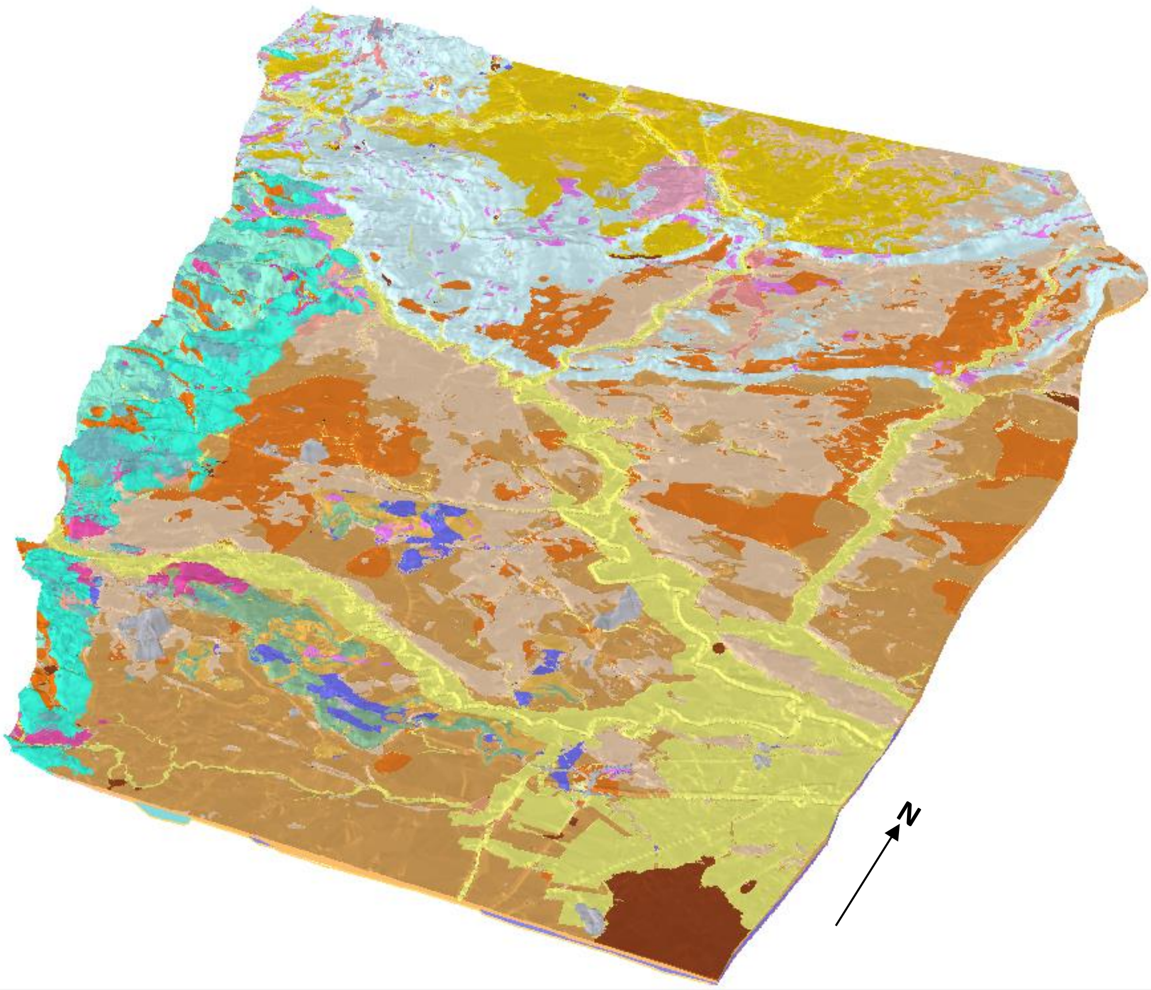

Figure 17 3D view of the calculated model with all units shown. Vertical exaggeration x20. (Key as per Tables 1 and 2).

Table 2 List of superficial units in the relative stratigraphic order used in the model. Simplified lithological descriptions relate to 'bulk' composition however units vary and may include a range of sediment at a local scale.

Unit name	Full name	Description (simplified lithology)
MGR	Made ground	Modelled where artificial ground forms obvious features in the DTM and where boreholes record significant thicknesses of made ground
Peat	Peat	Peat deposits
ALV	Alluvium (undifferentiated)	Silt, clay, sand and peat. Includes warp
RTD_1	River terrace deposits	Includes mapped river terrace deposits and sub-alluvial gravel. Composed of sand and gravel. Includes a single polygon of mapped alluvial fan deposits on the York sheet
BSA_1	Cover sand	Mapped as named units overlying the glaciolacustrine clays, but not subdivided in the model. Consists of clayey/silty sand, can be laminated and/or have a gravelly base
HEAD	Head	Accumulates at the base of slopes and in valley bottoms through the down-slope movement of material. Variable composition
ALNE-SV	Alne Glaciolacustrine Formation (sand and gravel).	Sand and gravel facies of the Alne Glaciolacustrine Formation. Overlies the laminated clay/silt/sand
ALNE	Alne Glaciolacustrine Formation	Laminated clay/silt/sand of the Alne Glaciolacustrine Formation
ELV	Elvington Glaciolacustrine Formation	Laminated clay/silt/sand of the Elvington Glaciolacustrine Formation
GFDU	Glaciofluvial deposits (undifferentiated)	Composed of sand and gravel. Includes sand and gravel of the Vale of York Formation, mapped GFDU and sand and gravel beneath Alne and Elvington Glaciolacustrine formations
VYORK_T	Vale of York Formation upper till.	Composed of bouldery, cobbly, gravelly, sandy clay. Modelled only where eskers are partially enclosed within the Vale of York till
GFDU_T_VYORK	Vale of York Formation glaciofluvial sand and gravel. Modelled only	Used to represent esker sand and gravel deposits. Modelled only where eskers are partially enclosed within the Vale of York till
VYORK	Vale of York Formation till (includes mapped moraines)	Vale of York till sheet, composed of bouldery, cobbly, gravelly, sandy clay
GFDU_B_VYORK	Sand and gravel unit at the base of the Vale of York Formation	Composed of sand and gravelly sand. Modelled where sand and gravel/cobbles occur at the base of the Vale of York Formation
LABD	Lacustrine beach deposits	Marginal facies of the Hemingbrough Glaciolacustrine Formation. Composed of sand and gravel
GLLD_1	Upper laminated clay of the Hemingbrough Glaciolacustrine Formation	Laminated clay and silt with minor sand
GLLD_S	Sand unit of the Hemingbrough Glaciolacustrine Formation	Intervening running sand unit in the Hemingbrough Formation, often contains coal fragments
GLLD	Lower laminated clay unit of the Hemingbrough Glaciolacustrine Formation	Laminated clay and silt with minor sand
Lower_Till	Till unit beneath the Hemingbrough Glaciolacustrine Formation	Bouldery, cobbly, gravelly, sandy clay of uncertain age
GFDMP	Older glacial sand and gravel (probably Anglian)	Glacial sand and gravel

TILMP	Harrogate Till Formation (Anglian)	Bouldery, cobbly, gravelly, sandy clay. Also used for the Moss Channel
GFDMP0	Older glacial sand and gravel (probably Anglian) that underlies the Harrogate Till Formation	Glacial sand and gravel. Also used for the Moss Channel
GFDUD	Basal sand and gravel unit/completely weathered Sherwood Sandstone Group bedrock	Glacial sand and gravel. Includes weathered Sherwood Sandstone Group bedrock where boreholes describe it as sand
GFDU_Lens	Lens of glaciofluvial sand and gravel within Vale of York Formation till	Glacial sand and gravel. Not calculated as a volume
GFDU_Lens2	Second lens of glaciofluvial sand and gravel within Vale of York Formation till	Glacial sand and gravel, used where boreholes record two lenses. Not calculated as a volume
GLLD_lens	Lens of glaciolacustrine clay within Vale of York Formation till	Laminated clay and silt with minor sand. Not calculated as a volume
Peat_lens	Lens of peat within alluvium	Composed of peat. Not calculated as a volume

4.3 SUPERFICIAL DEPOSITS DISTRIBUTION MAPS AND THICKNESS GRIDS

This section shows the distributions and thicknesses of the modelled units. Each thickness grid has cell size of 200 m and is superimposed on the unit distribution to show the calculation. The geological units extend slightly outside the modelled area to improve the calculation at the model edges but the calculation itself and derived thickness grids are restricted to the model boundary.

4.3.1 Basal sand and gravel/weathered Sherwood Sandstone Group

The basal Quaternary unit in the model is *GFDUD*, which corresponds with *GLLD_BS* used in the Doncaster model. GFDUD is used to model basal sand and gravel across the model area and weathered Sherwood Sandstone Group where described as sand in boreholes. Weathered Sherwood Sandstone Group is included because it can be difficult to separate from glacial sand and gravel in borehole descriptions (Lee *et al.*, 2016). GFDUD has a relatively wide but patchy distribution throughout the model area and reaches a maximum thickness of 28.8 m. ‘Bullseyes’ where this unit suddenly thickens occur where boreholes record a deep weathering profile to the Sherwood Sandstone Group. For example, borehole 122131 is used in an alluvium helper section along the River Ouse, just south of Selby (Figure 18). This borehole records 29 m of sand and Sherwood Sandstone Group sand and corresponds with a ‘bullseye’ in the GFDUD thickness grid (Figure 19). These depth differences relate to the description of Sherwood Sandstone Group in the borehole. This may reflect spatial variability in weathering of the Sherwood Sandstone Group or variability in the quality of borehole descriptions.

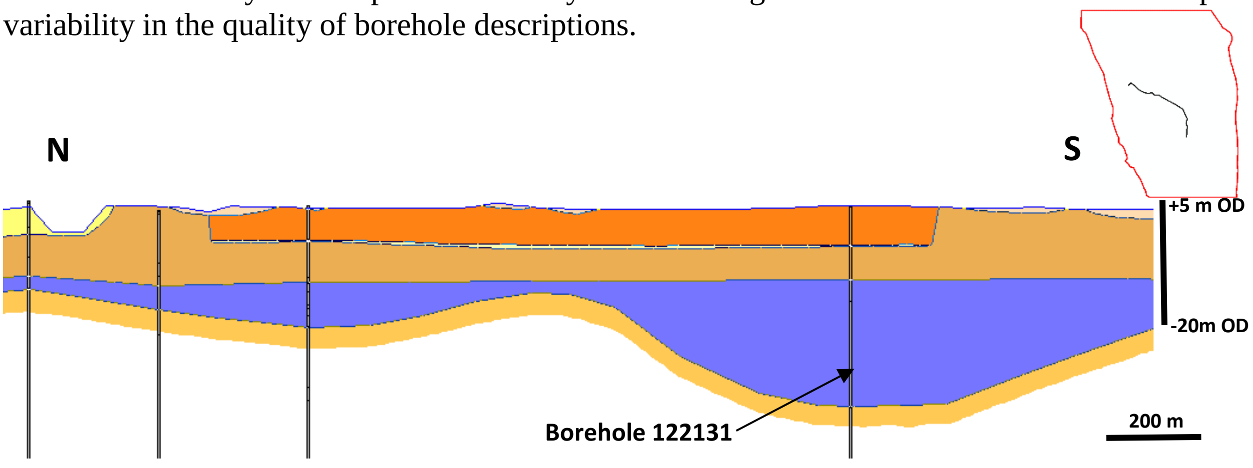

Figure 18 Cross-section *EA_Selby_ALV_H7_HB*, which runs through a borehole recording 29 m of sand and Sherwood Sandstone Group sand (vertical exaggeration x10).

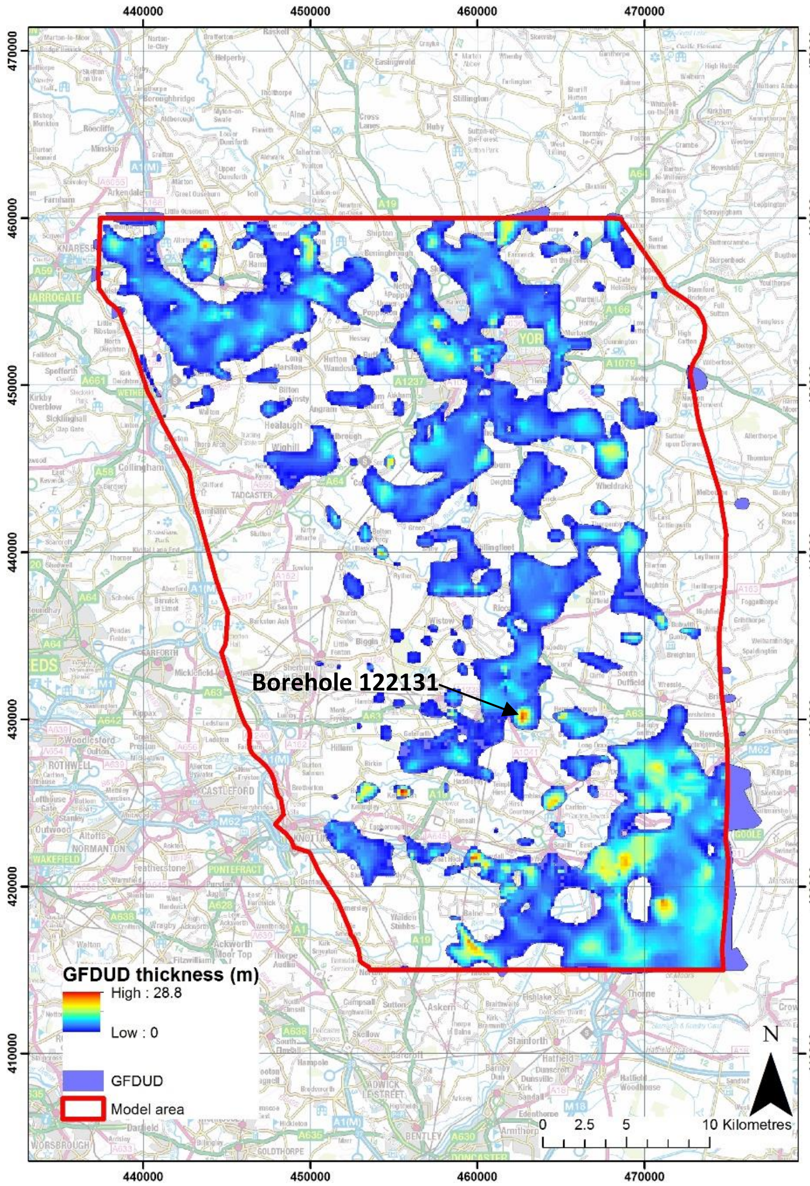

Figure 19 Thickness and distribution map of GFDUD. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.2 Buried valleys

Several buried valleys occur in the Doncaster area to the south, as featured in the Doncaster memoir (Gaunt, 1994). These over-deepened channels are incised into the bedrock and are filled with superficial deposits. These buried valleys are difficult to model because they have little or no surface expression and rely on borehole information to locate them and define their geometry. One such buried channel, named '*Moss Channel*', continues northwards into the south-west corner of the Selby model area (Figure 21). This is modelled as '*Channel*' in the Doncaster model and *TILMP* in the Selby model. There is little borehole evidence to constrain the geometry and infill material of Moss Channel, but borehole 116527 just outside the model area records 27.74 m of clay, sand and gravel. No other buried valleys are proven in boreholes in the rest of the model area, but are inferred from the presence of linear ribbon shaped outcrops of Harrogate Till Formation, so their geometry is uncertain (cf. British Geological Survey, 2011; Bricker *et al*., 2012). These inferred buried valleys are modelled as *TILMP*, but in reality can contain a heterogeneous mix of lithologies, such as sand and gravel, clay and till. Using the current density/distribution of boreholes the geometry, morphology and sediment fill of these buried valleys is poorly constrained. They are likely to be more complex and greater in number than shown in the model.

4.3.3 Harrogate Till Formation

Areas of high ground in the west of the model are capped by patches of Harrogate Till Formation (modelled as *TILMP*) and associated sand and gravel deposits. Gravel that overlies the Harrogate till Formation is modelled as *GFDMP* and *GFDMP0* is used for gravel underneath the till. The Harrogate Till Formation was deposited during an earlier Middle Pleistocene glaciation, between 478 ka and 128 ka (Cooper and Gibson, 2003). The Harrogate Till Formation has a different lithology to the Vale of York till, being composed of slightly sandy clay with blocks of locally derived bedrock units (Cooper & Burgess, 1993). The Harrogate Till Formation reaches a maximum thickness of 31 m (Figure 20); GFDMP is up to 7.4 m thick (Figure 21) and GFDMP0 reaches up to 7.9 m. GFDMP0 is only modelled in two small isolated patches and is therefore not shown in the distribution maps or thickness grids.

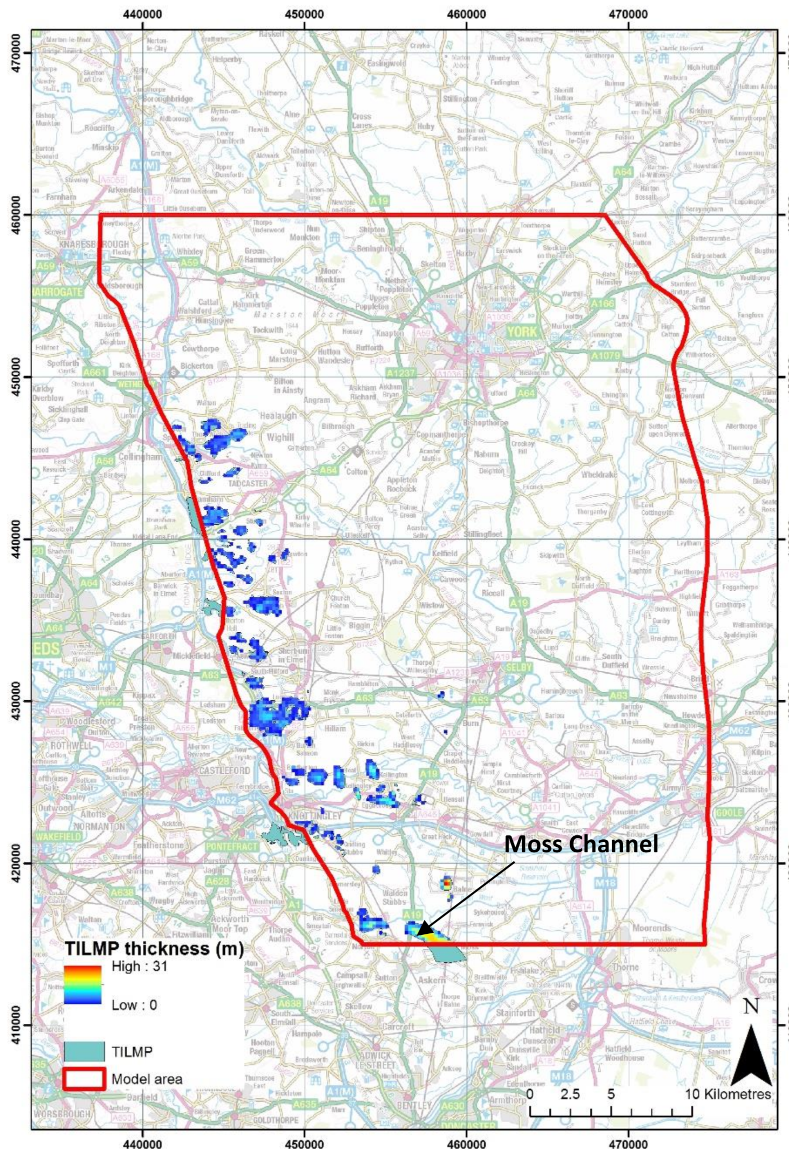

Figure 20 Distribution and thickness of TILMP. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

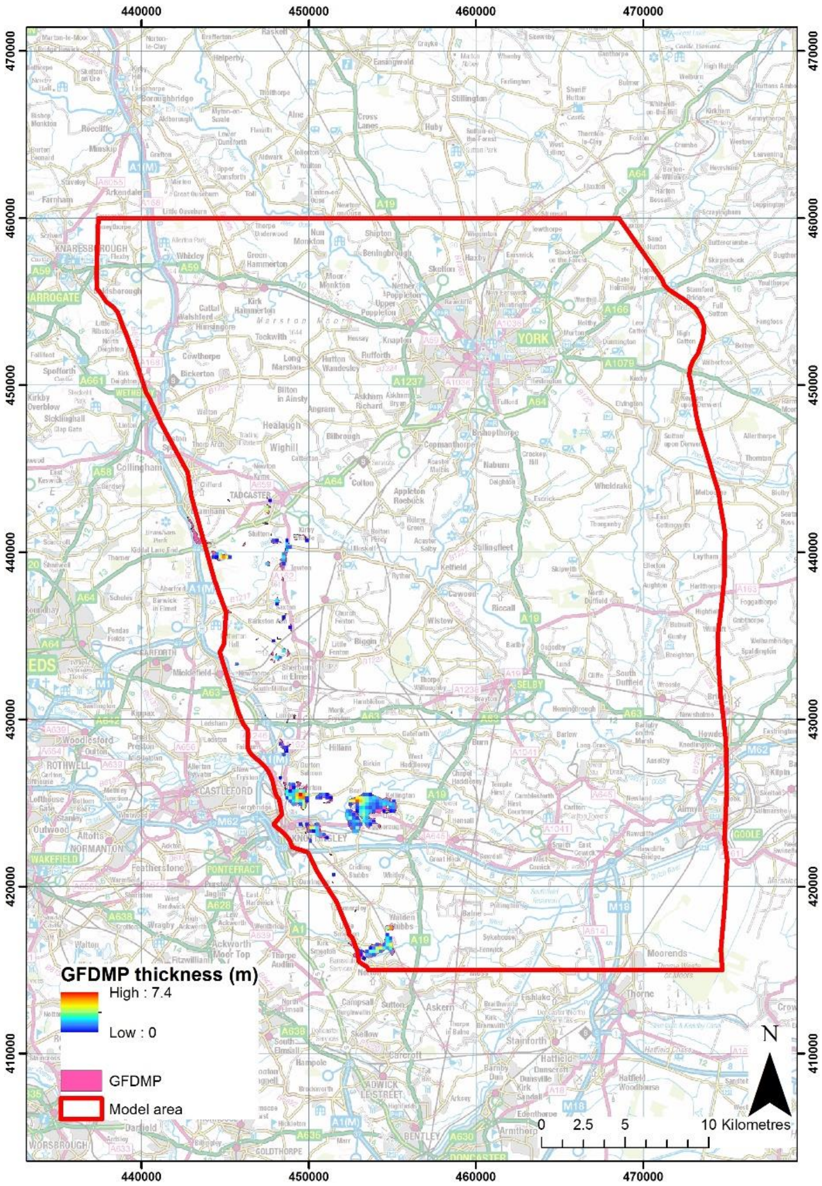

Figure 21 Thickness and distribution of GFDMP. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.4 Lower Till

Gravelly, occasionally cobbly clay is recorded in some boreholes beneath the Hemingbrough Glaciolacustrine Formation in the north of the model area. This lithology is uncharacteristic of the laminated clay, silt and sand succession of the Hemingbrough Glaciolacustrine Formation and is interpreted as till. This till unit is modelled as *Lower_Till* and reaches a maximum thickness of 6.9 m (Figure 22). Lithostratigraphically this till unit has not previously been assigned to a recognised till formation, but because they occur beneath the Hemingbrough Glaciolacustrine Formation they are inferred to be pre-Devensian. However, their relationship to other till units in the region such as the Harrogate Till Formation remains unclear.

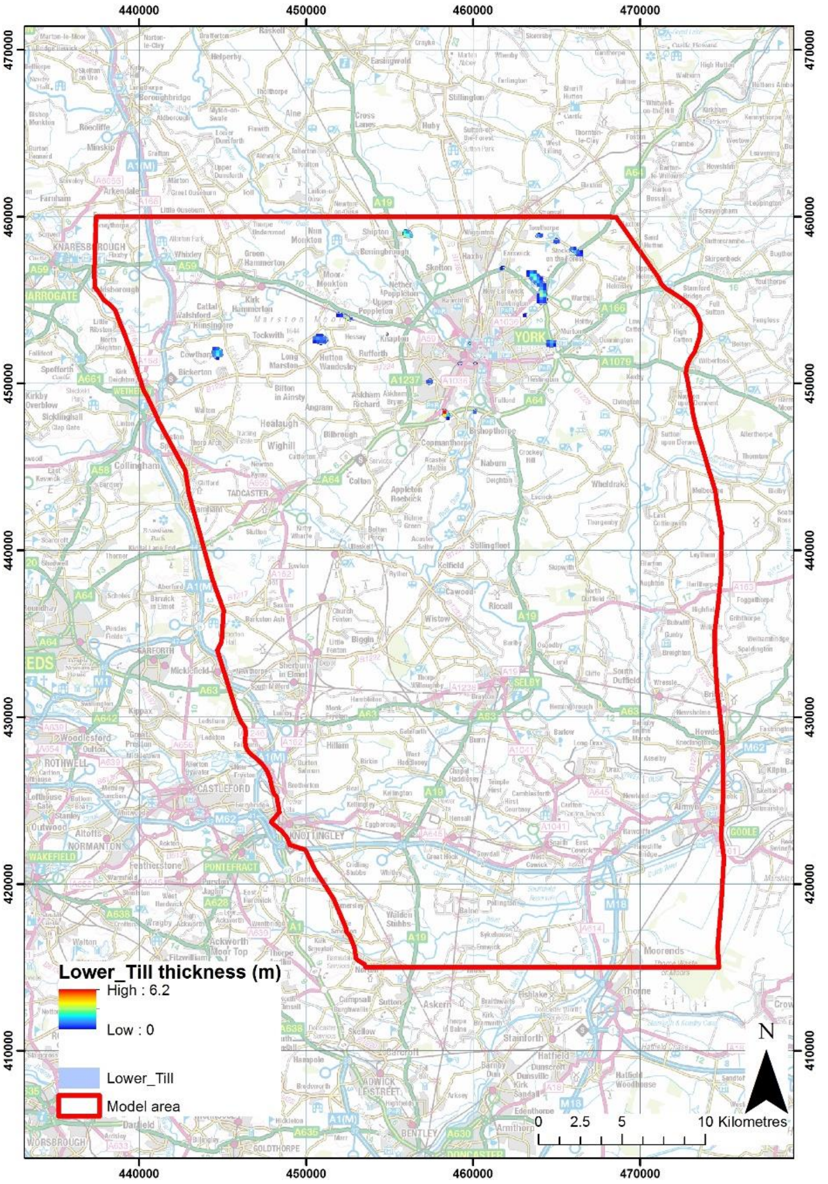

Figure 22 Thickness and distribution map for Lower_Till. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.5 Hemingbrough Glaciolacustrine Formation

Hemingbrough Glaciolacustrine Formation is mapped at surface between Stillingfleet and Doncaster and underlies the Vale of York Formation till (Figure 23). The Hemingbrough Glaciolacustrine Formation comprises an upper and lower laminated clay and silt unit (modelled as *GLLD_1* and *GLLD* respectively) with an intervening layer of running sand (modelled as *GLLD_S*). This running sand unit is modelled only where proven in boreholes, but is likely to cover a much wider area in reality. These units are modelled as steep sided 'basins' in the cross-sections rather than broken correlation lines to improve their calculation.

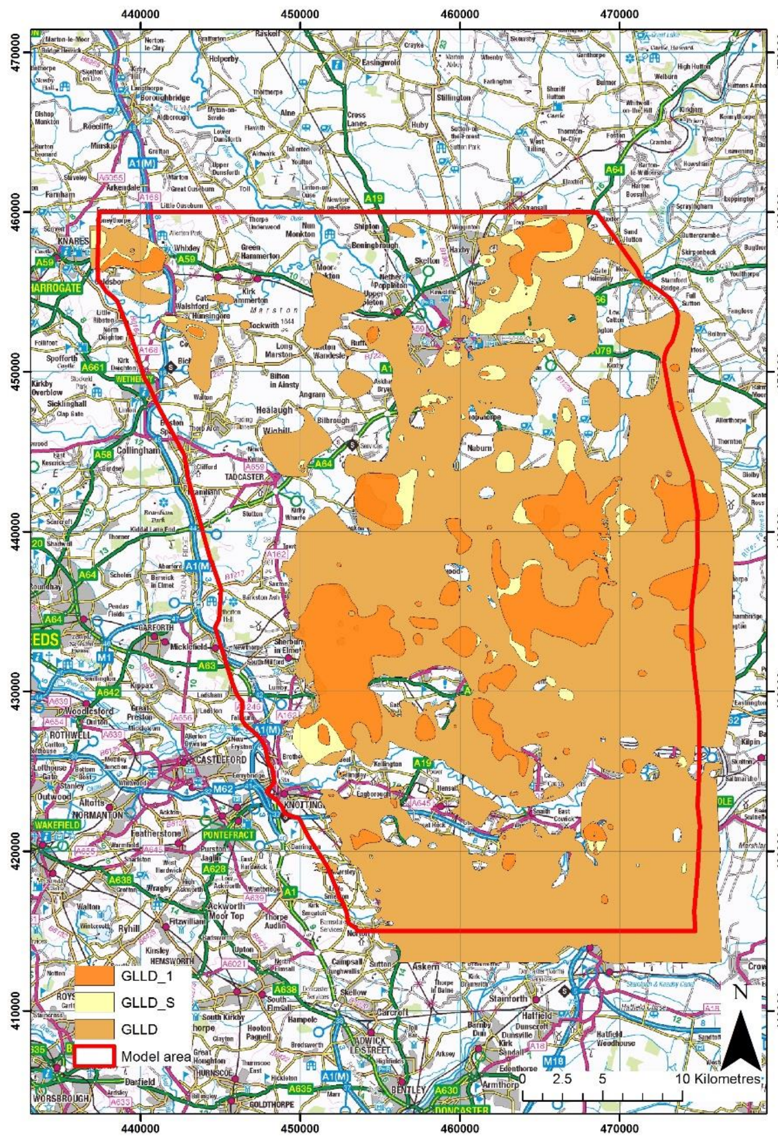

Figure 23 Distribution map of the three component units that make up the Hemingbrough Glaciolacustrine Formation. GLLD_1 is transparent to show the GLLD_S underneath. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

The most widely modelled of these three subunits is GLLD, which is the basal laminated clay unit of the Hemingbrough Glaciolacustrine Formation. Named Park Farm Clay Member on the geological maps, this unit is modelled where the Hemingbrough Glaciolacustrine Formation cannot be subdivided. GLLD has a maximum thickness of 32 m (Figure 24).

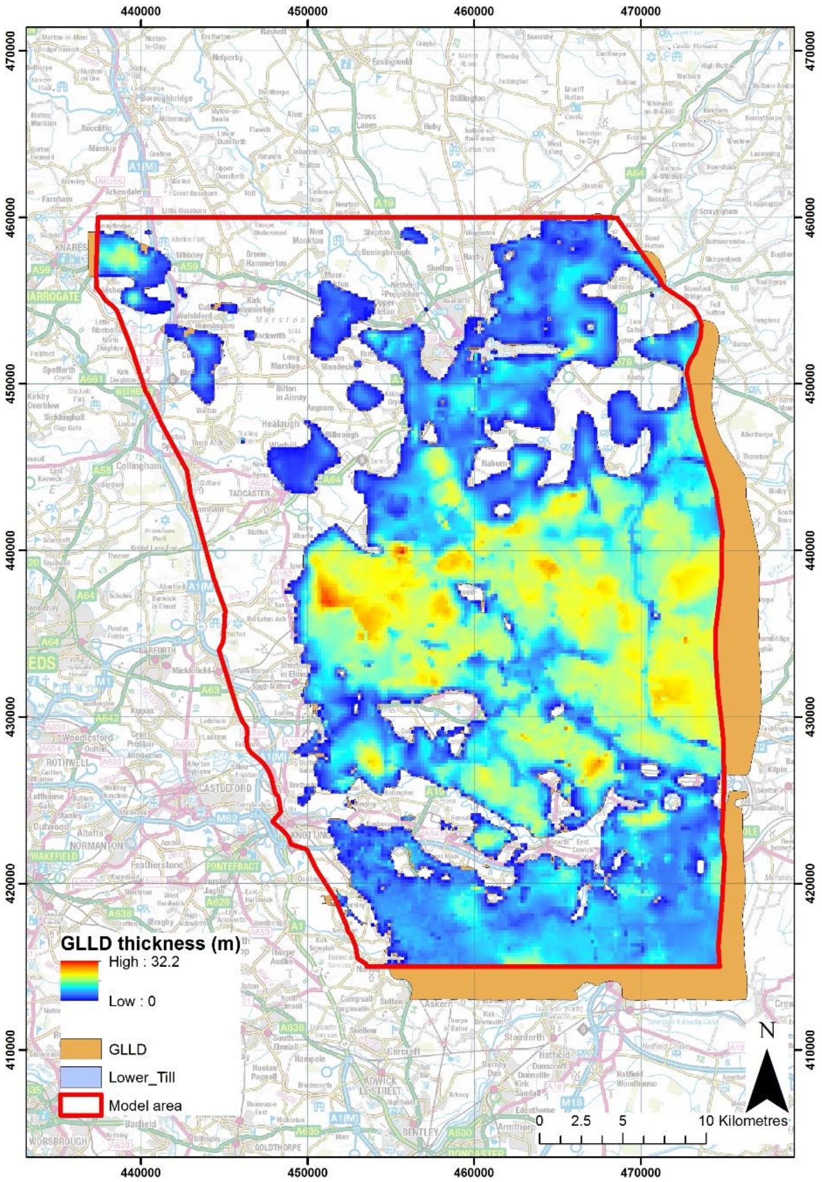

Figure 24 Thickness and distribution of GLLD. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

The intervening sand unit in the Hemingbrough Glaciolacustrine Formation is modelled as GLLD_S. Named Lawns House Farm Sand Member on the geological maps, this is mapped at the ground surface along the sides of river valleys. This outcrop pattern was used along with borehole evidence to inform the modelled distribution of GLLD_S and GLLD_1. GLLD_S has a maximum thickness of 18 m (Figure 25). In some areas, such as around Hillam, boreholes prove that GLLD_S is over-thickened and the GLLD becomes thinner and patchy. Occurrences of over-thickened GLLD_S are likely to correspond with the location of localised deltas that are feeding material into the lake basins.

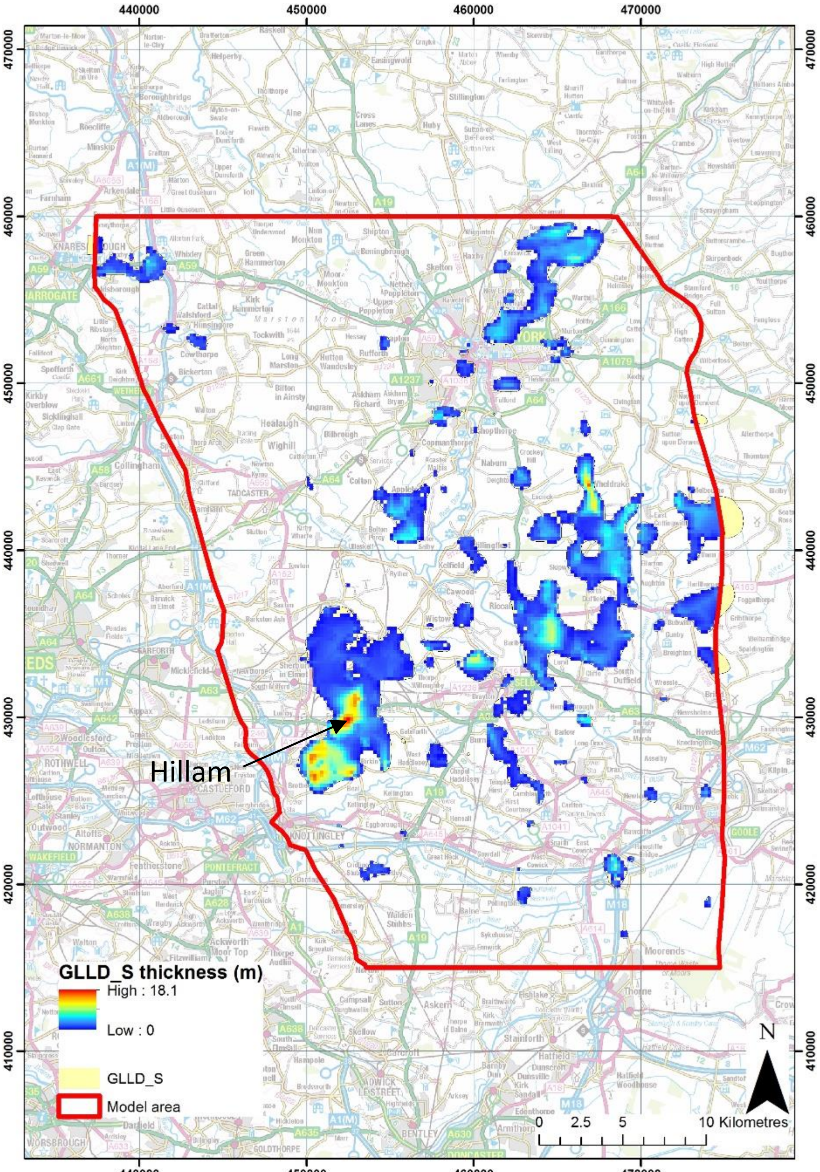

Figure 25 Thickness and distribution of GLLD_S. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

The upper laminated clay unit of the Hemingbrough Glaciolacustrine Formation is modelled as GLLD_1, which reaches a maximum thickness of 21 m. This thickness anomaly corresponds with a backfilled opencast site. Made ground is modelled at this locality, but has not calculated to the edges of the polygon. This upper leaf of the Hemingbrough Glaciolacustrine Formation is named Thorganby Clay Member on the geological maps and an average thickness of 3.4 m (Figure 26).

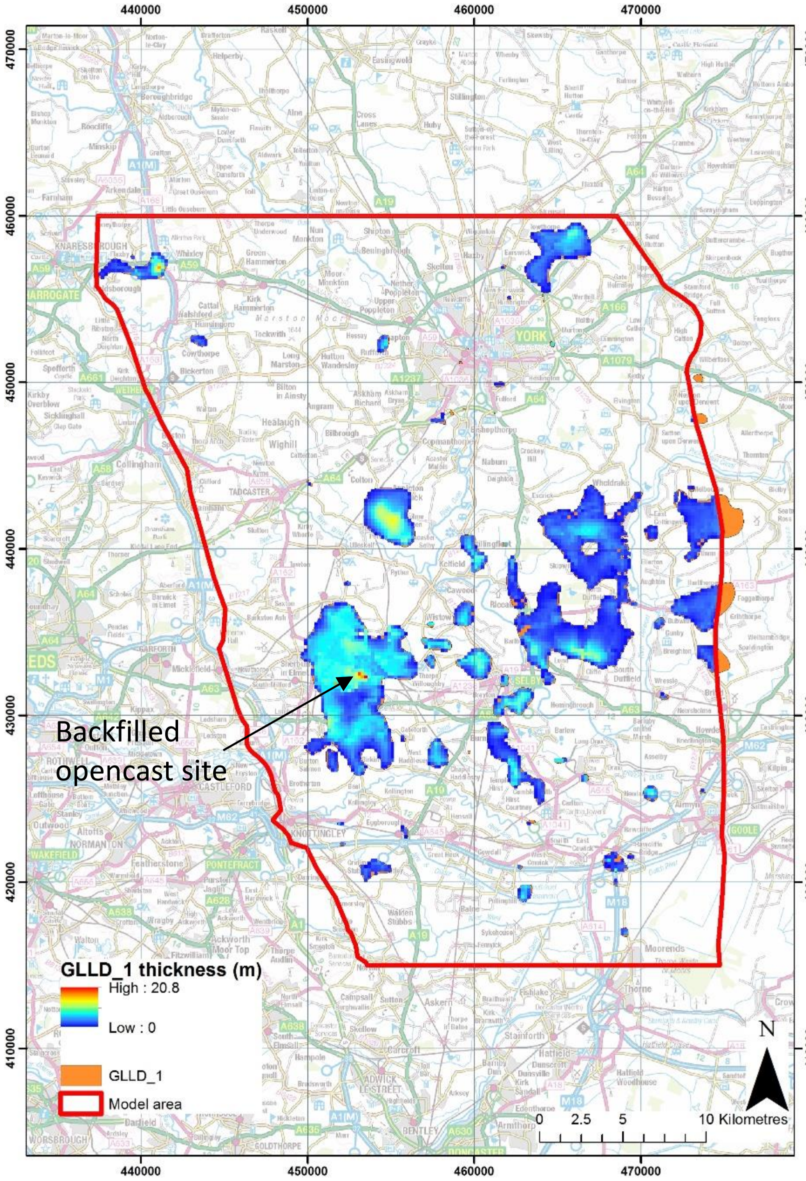

Figure 26 Distribution and thickness of GLLD_1. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

A GIS query was used to calculate the combined thickness of all three modelled units of the Hemingbrough Glaciolacustrine Formation (GLLD, GLLD_S and GLLD_1). These individual thickness grids were added together to give a total maximum thickness of 38.6 m (Figure 27)

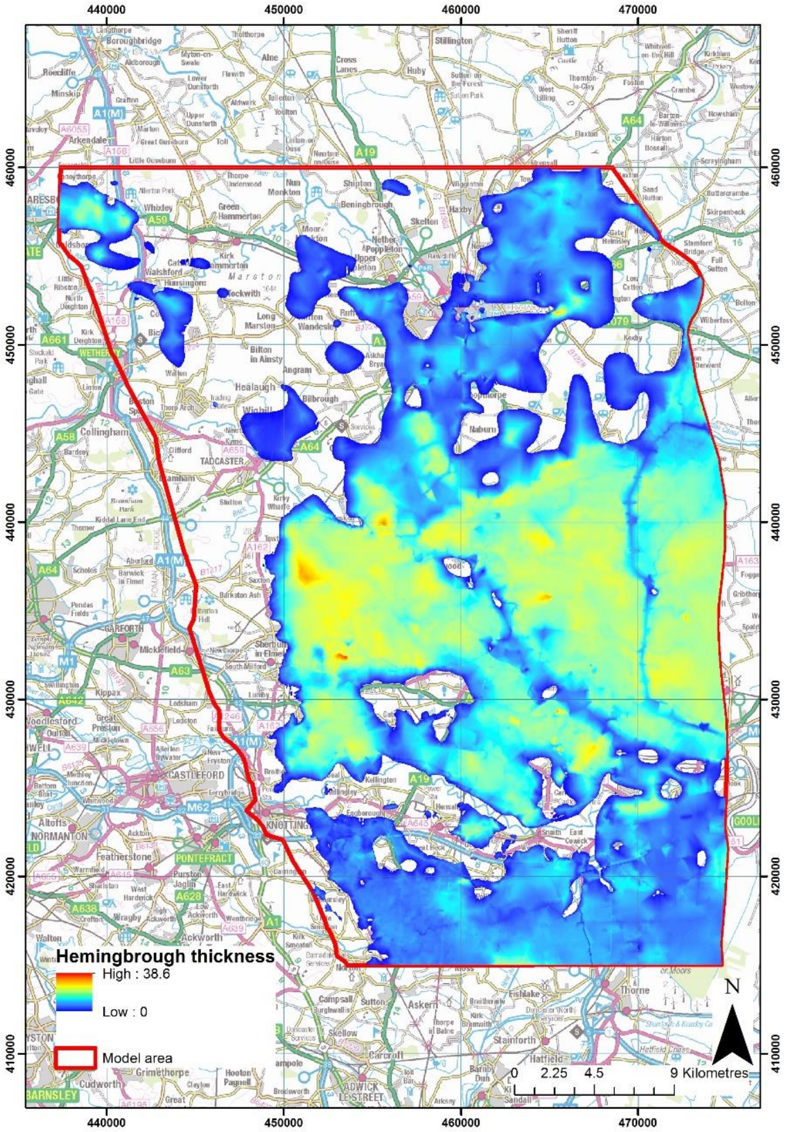

Figure 27 Combined distribution and thickness of the Hemingbrough Glaciolacustrine Formation. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.6 Lacustrine Beach Deposits

A marginal beach deposit of the Hemingbrough Glaciolacustrine Formation is mapped in the Aire valley area around the western margin of glacial Lake Humber, modelled as LABD (Figure 28). This is generally composed of sand and gravel and is likely to interdigitate with the laminated clays and sands of the Hemingbrough Glaciolacustrine Formation. However, because of the limitations of the 3D modelling software these lacustrine beach deposits have been assigned a stratigraphically higher position than the Hemingbrough Formation laminated silt, clay and sand. The lacustrine beach deposits reach a maximum thickness of 11 m.

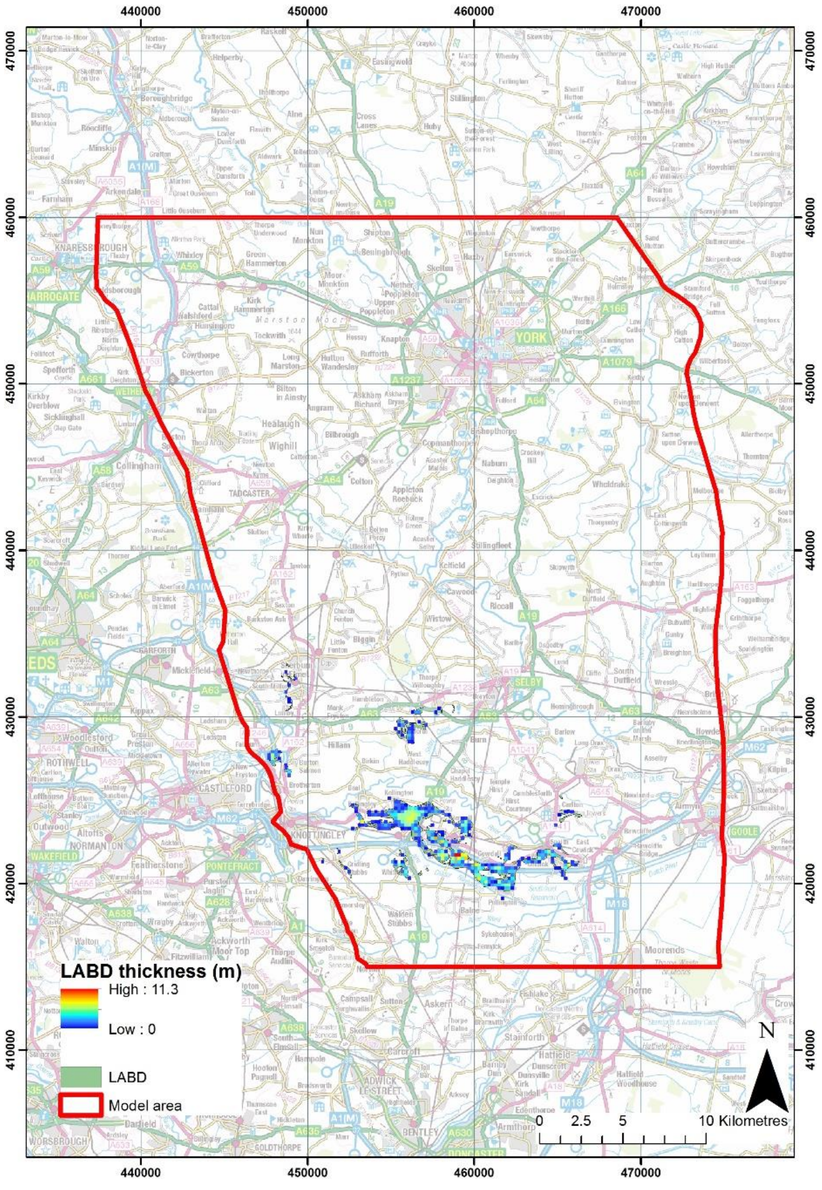

Figure 28 Distribution and thickness of LABD. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.7 Vale of York Formation till

The till of the Vale of York Formation till (modelled as *VYORK*) was laid down as ice advanced southwards through the Vale of York. The southern limit of the Vale of York till is defined by the Escrick Moraine, with its southerly most point located at Stillingfleet. VYORK consists of sandy, gravelly, cobbly clay.

Three discontinuous intra-till lenses are modelled in the cross-sections, but are not calculated as volumes and are therefore included in the overall till volume/thickness. Two lenses of glaciofluvial sand and gravel are modelled in the till as small isolated patches where proven in boreholes. These lenses can make up a significant thickness of the till. Both lenses are represented in cross-section *EA_Selby_WE8_LH_NorthEast*, located in York city centre (Figure 29). *GFDU_Lens* is modelled as the upper lens where both are present and where only one lens is present. *GFDU_Lens2* is used for the lower lens.

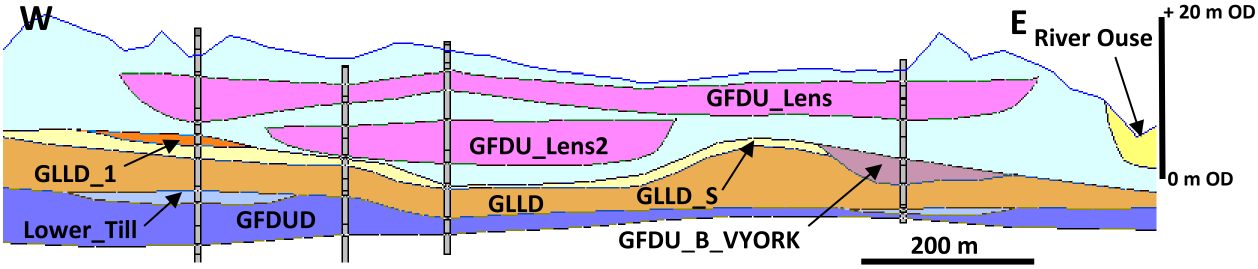

Figure 29 Cross-section *EA_Selby_WE8_LH_NorthEast* showing two stacked lenses of glaciofluvial sand and gravel (coloured pink) within the Vale of York till. Bedrock ribbon not shown. Vertical exaggeration x 10.

A lens of laminated clay also occurs within the till. In some areas this directly overlies a lens of glaciofluvial sand and gravel. This relationship is proven in a borehole 122656 used in cross-section *EA_Selby_WE64_HB_NorthEast*, located in the Crockey Hill area just outside York (Figure 30).

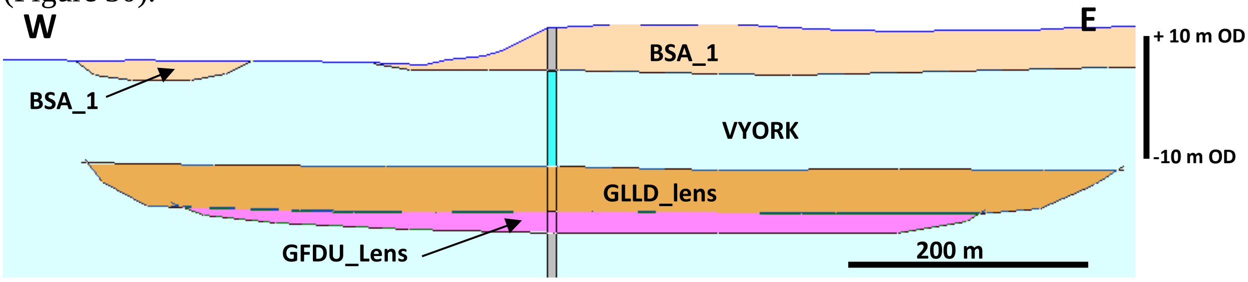

Figure 30 Cross-section *EA_Selby_WE64_HB_NorthEast*, showing a lens of laminated clay directly overlying glaciofluvial sand and gravel within the Vale of York till. Vertical exaggeration x10.

Several eskers are mapped in the Vale of York, such as the Crockey Hill Esker Member that runs north-south between Crockey Hill and Escrick. These sinuous ridges of sand, gravel and cobbles were deposited in glaciofluvial systems beneath (subglacial), within (englacial) and on top (supraglacial) of the glacier (Ford *et al*, 2008). In some areas these eskers are exposed at the ground surface where they form prominent landforms and are interbedded with the Vale of York till. Esker deposits are modelled as *GFDU_T_VYORK*, with *VYORK_T* used to represent the till where the esker is enclosed within the till sheet (Figure 31). (This is covered in more detail in the section on modelling decisions). A thickness and distribution map of VYORK is shown in Figure 32.

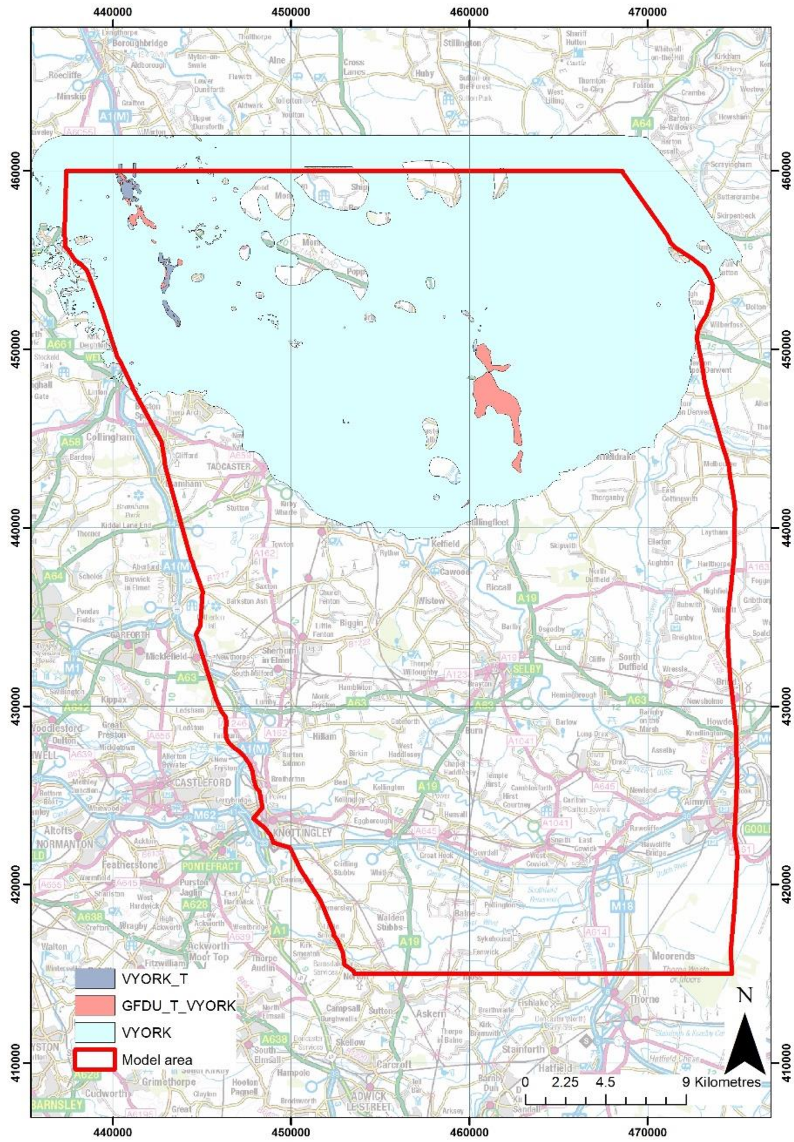

Figure 31 Distribution of the three component till units that make up the Vale of York till. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

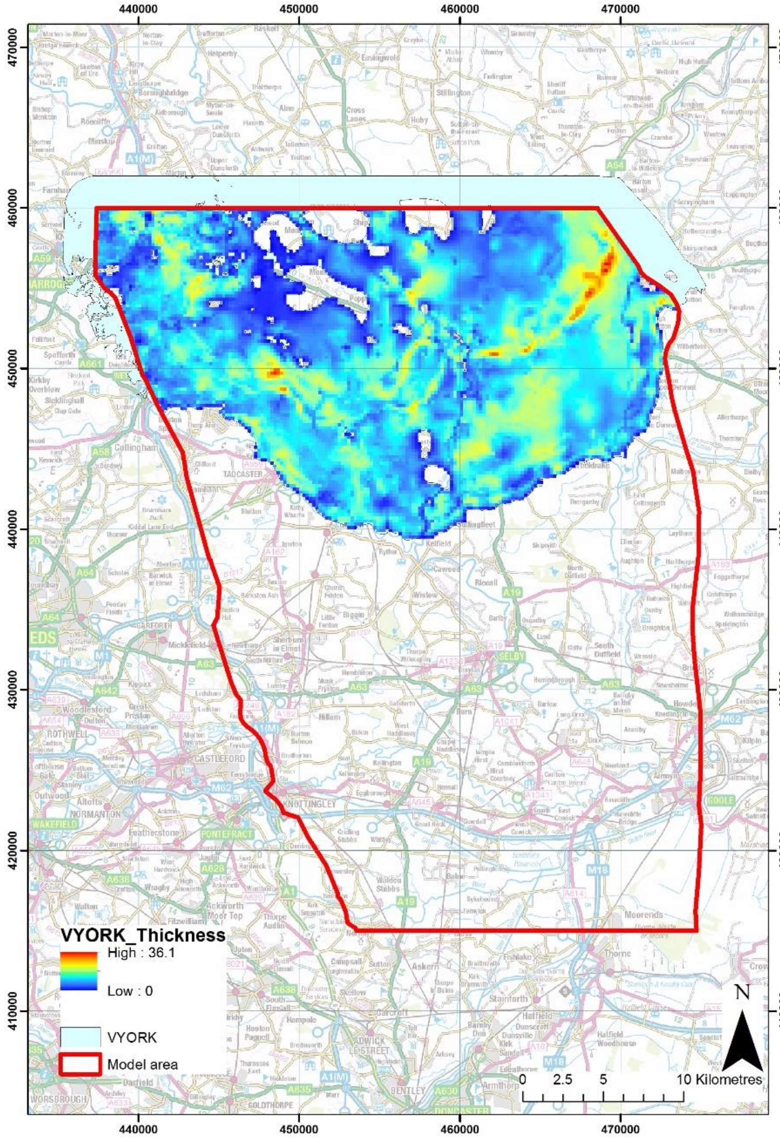

Figure 32 Distribution and thickness of the Vale of York Formation till. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

A basal sand and gravel unit is recorded in some boreholes between the top of the Hemingbrough Glaciolacustrine Formation and the base of the Vale of York till (Figure 33). This is unlikely to be part of the Hemingbrough Glaciolacustrine Formation because of its high energy environment of deposition. It is therefore modelled as *GFDUB_VYORK*. This is modelled in small isolated patches where recorded in boreholes and has a maximum thickness of 12 m.

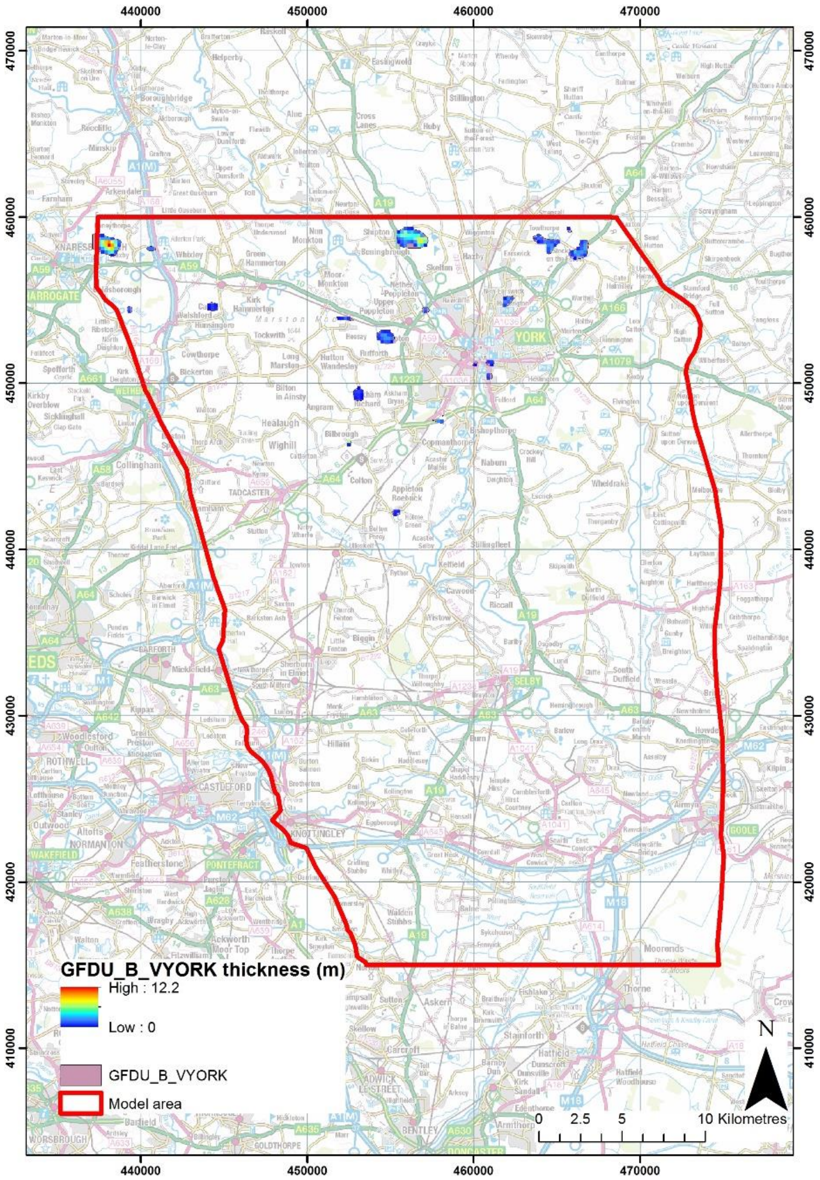

Figure 33 Distribution and thickness of GFDUB_VYORK. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

The cumulative thickness of the Vale of York till was calculated using a GIS query. The thickness grids of the component units were added together (VYORK, GFDU_T_VYORK and VYORK_T). This gives a maximum thickness of 38.5 m (Figure 34).

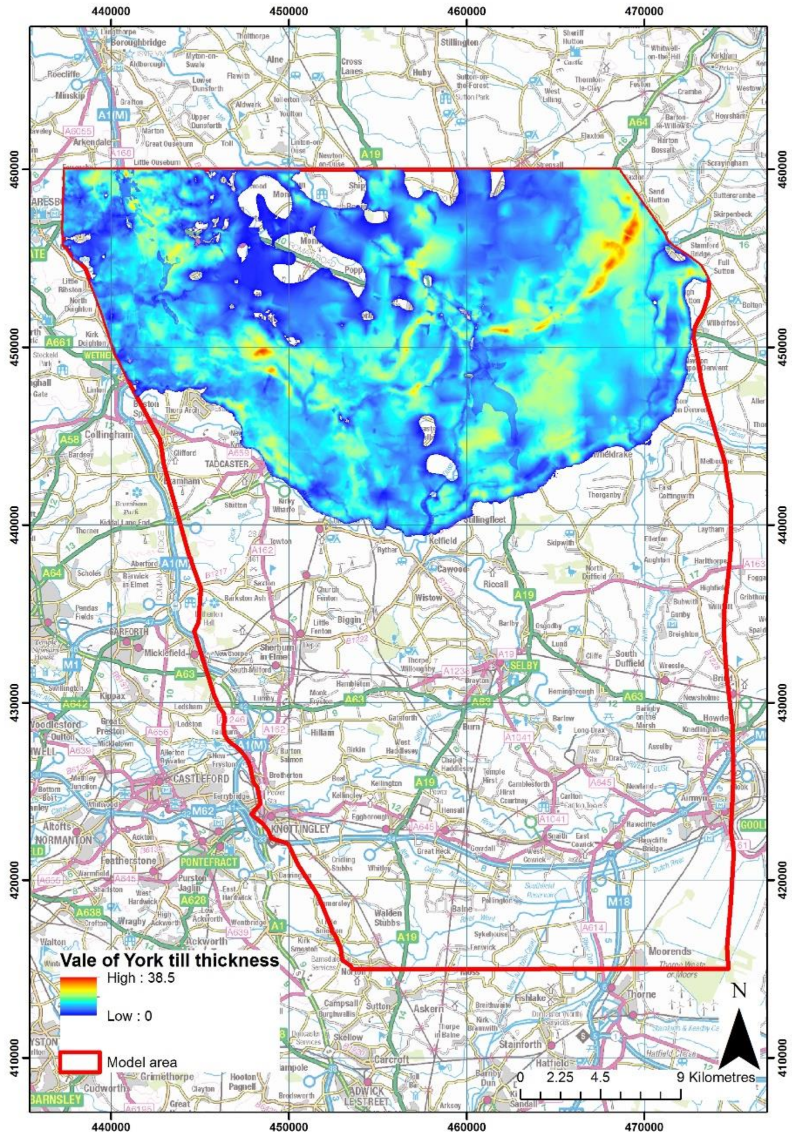

Figure 34 Combined thickness and distribution of the Vale of York till, calculated by adding together the thicknesses of VYORK, GFDU_T_VYORK and VYOTK_T. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.8 Glaciofluvial deposits

Glaciofluvial deposits are modelled as *GFDU* (Figure 35). This comprises several mapped glacial sands and gravels: glaciofluvial terrace deposits, sand and gravel bodies associated with the Vale of York Formation moraines, isolated patches on top of the till sheet and several polygons of glacial sand and gravel around the edges of Lake Humber. (The latter are mapped as GFDUD but may actually be lake shore deposits associated with Lake Humber). GFDUD is also modelled where boreholes record sand and gravel beneath the Alne and Elvington glaciolacustrine deposits.

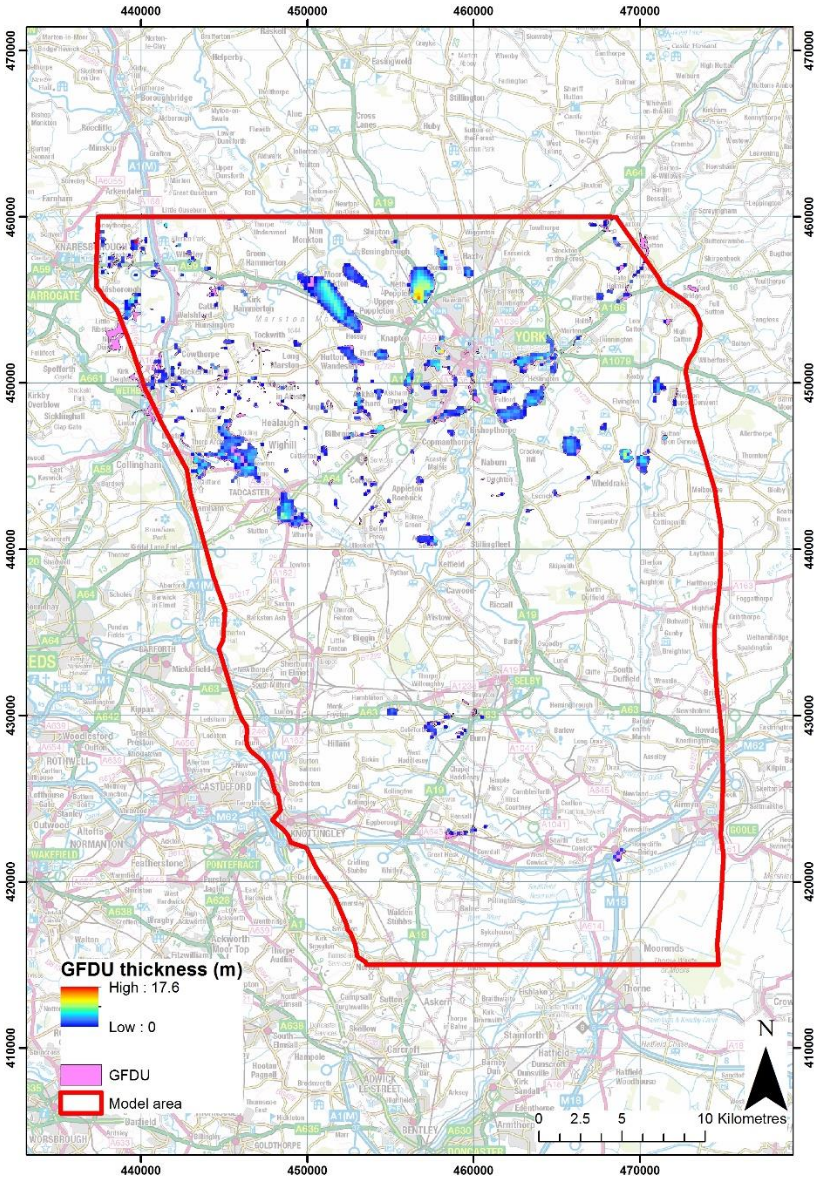

Figure 35 Distribution and thickness of GFDU. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.9 Elvington and Alne Glaciolacustrine Formations

Two cycles of glacial lake sediments overlie the Vale of York till (Figure 36). The southerly-most of these is the Elvington Glaciolacustrine Formation (modelled as *ELV*), which occurs between the Escrick Moraine and York Moraine. The Elvington Glaciolacustrine Formation is composed of laminated silt and clay with a minor sand component. The maximum thickness of ELV recorded in a borehole used in the model is 13.5 m, near Wilberfoss (Figure 37).

The Alne Glaciolacustrine Formation occurs north of the York Moraine and is composed of two lithologically distinct units in the model. A laminated silt and clay unit with occasional sand beds (modelled as *ALNE*) underlies a sand and gravel unit (modelled as *ALNE-SV*). This upper sand and gravel unit is mapped as Poppleton Glaciofluvial Member and is interpreted as a shoreline deposit of glacial lake Alne because a number of boreholes record laminated clay beneath. ALNE-SV reaches a maximum thickness of 22 m (Figure 38).

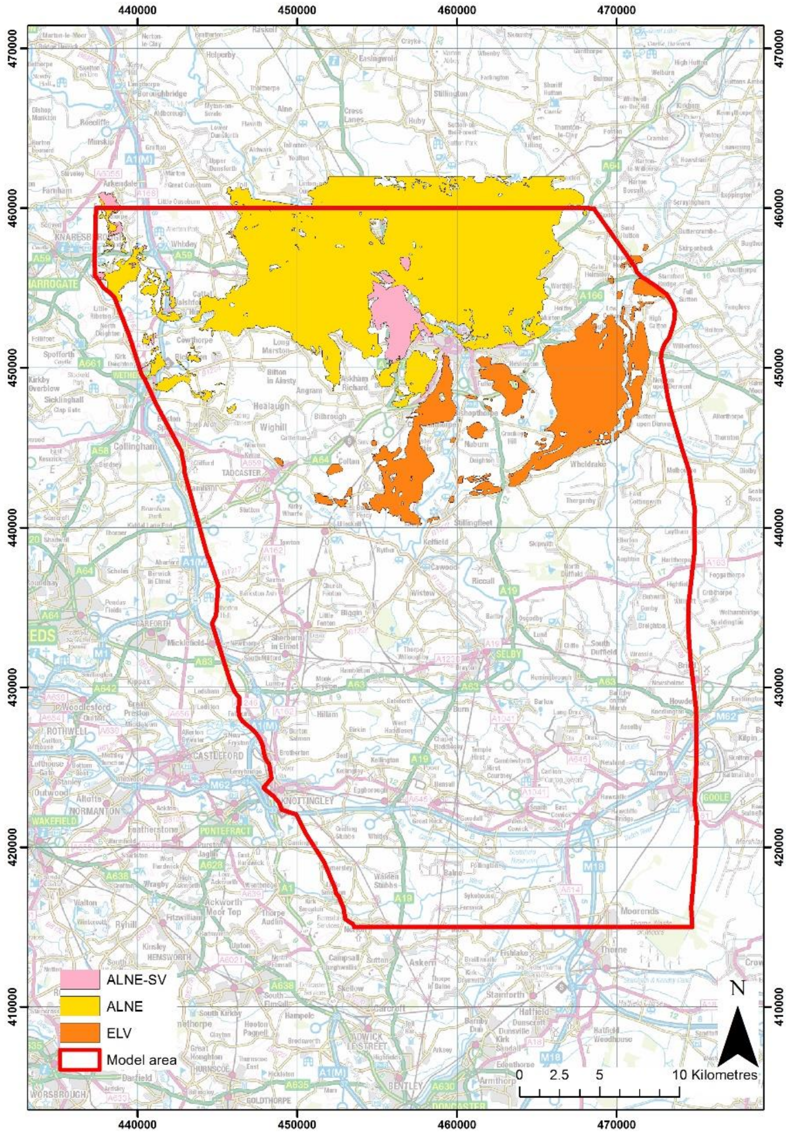

Figure 36 Distribution of ELV (orange), ALNE laminated clay (yellow) and ALNE-SV (pink). © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

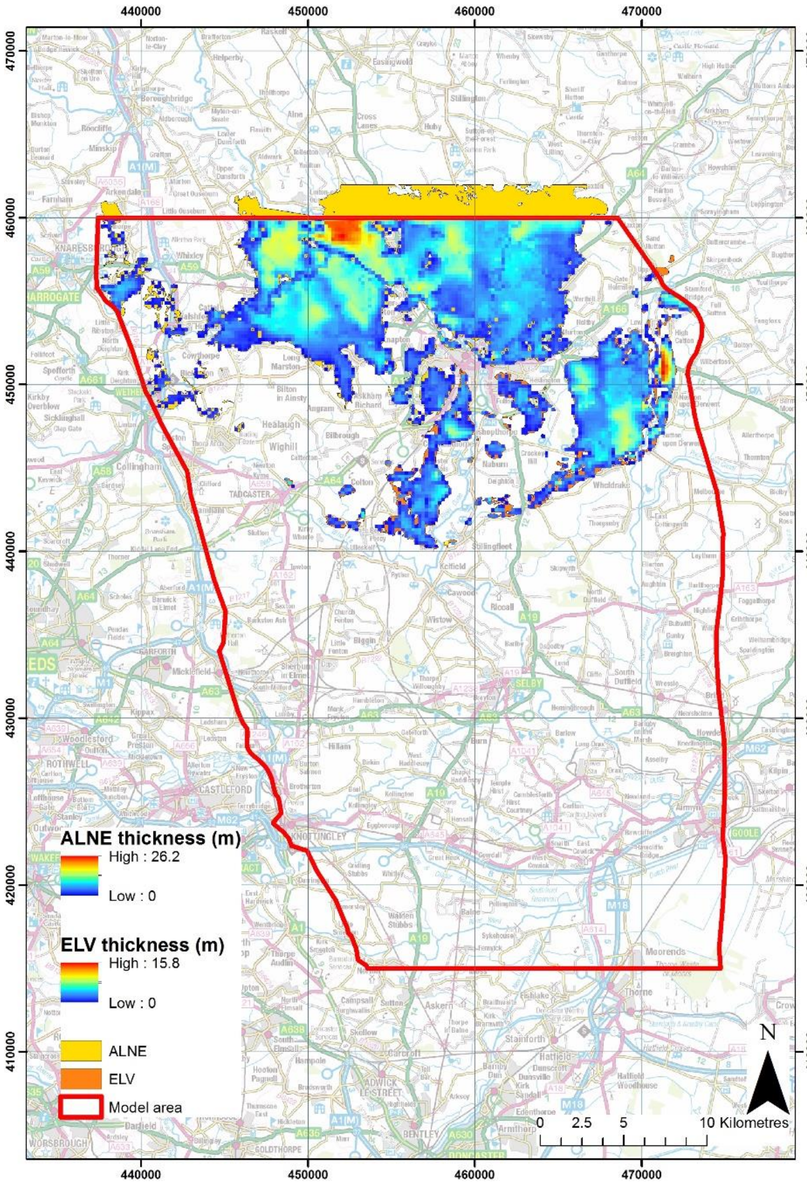

Figure 37 Thickness and distribution of ELV and ALNE laminated clay units. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

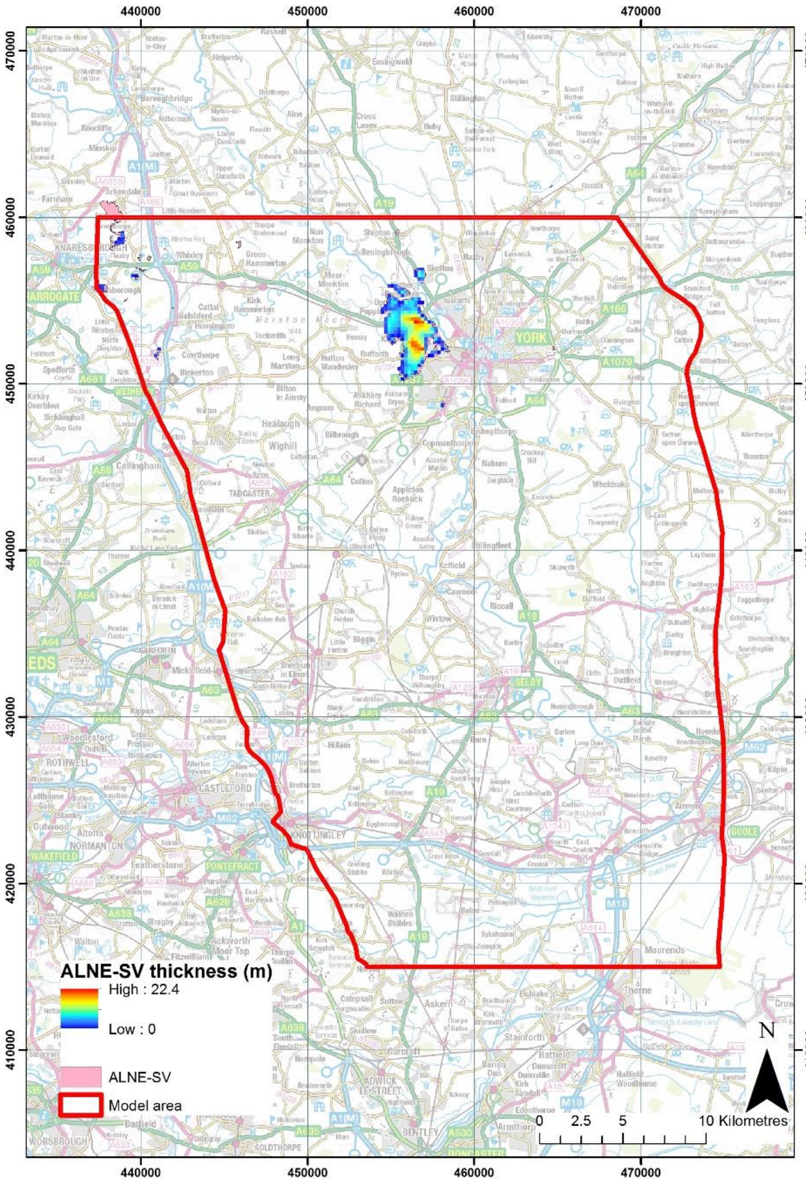

Figure 38 Distribution and thickness of ALNE-SV. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.10 Head

Several scattered ribbon-shaped polygons of head are mapped in the western half of the model. Head is a deposit that accumulated through the down-slope movement of material and typically accumulates towards the base of flops and valley floors. The composition of head varies depending on the parent material. Head is represented in the cross-sections, but no helper sections have been constructed to improve its calculation.

4.3.11 Cover sand

Widespread cover sand deposits occur through most of the model area. These overlie the Hemingbrough, Elvington and Alne glaciolacustrine formations and the Vale of York till (Figure 39). These sands are modelled as a single unit (*BSA_1*) but comprise the Breighton Sand Formation, which is mapped throughout the model area, and Sutton Sand Formation, which mainly overlies the Alne Glaciolacustrine Formation. The geological maps divide the Breighton Sand Formation into three members (Biellby, Naburn, and Skipwith Sand members). The Breighton Sand Formation was laid down under fluvial and aeolian conditions and is composed of clayey/silty sand, laminated in some areas, with an erosive base, which can be gravelly (Ford *et al*, 2008). The Sutton Sand Formation is purely aeolian and also overlies the Breighton Sand

Formation. It ranges in age from the Devensian to the Holocene and re-mobilises under certain conditions in the present day (Ford *et al*, 2008).

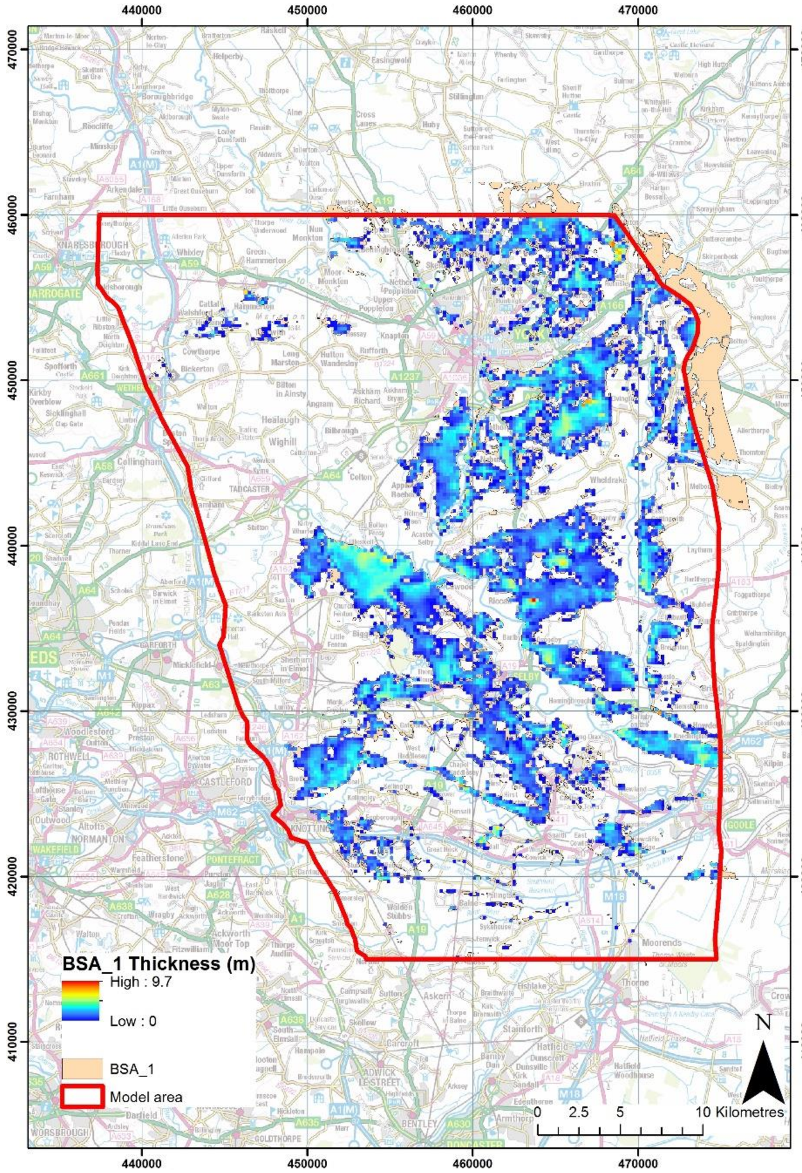

Figure 39 Distribution and thickness of BSA_1. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.12 River deposits

All occurrences of river terrace deposits are modelled as *RTD_1* (Figure 40). This includes sub-alluvial gravel, which is likely to be re-worked glacial sand and gravel. A single polygon of Alluvial Fan Deposits mapped within the model area near Tadcaster is also modelled as RTD_1.

Floodplain alluvium is modelled as *ALV* (Figure 41). The extent of alluvium is defined by the geological mapping and borehole evidence. The Digital Terrain Model does not always fit the extent of mapped alluvium, which appears to ‘climb’ up valley sides in some areas. However, the mapped extent was used in the model because the 50 m horizontal resolution of the Digital Terrain Model is too coarse to pick out subtle changes in land level in flat areas.

Extensive ‘warp’ deposits are mapped in the south-east of the model area around Goole. Warp is a veneer of clay and silt that accumulates in deliberately flooded areas to improve the soil. This is included with alluvium in the model because of its lithological similarity. Some boreholes in this area prove a layer of sand between the base of the warp and the underlying laminated clays of the

Hemingbrough Glaciolacustrine Formation. This sand modelled as alluvium. A thick peat layer occurs within the alluvium, which is modelled as *peat_lens* where proven in boreholes.

It can be difficult to distinguish between alluvium glacial lake deposits in areas where the alluvium directly overlies glaciolacustrine laminated clay and silt, particularly in older borehole logs that provide less detailed lithological descriptions. A colour change from grey or blue (alluvium) to brown (lake clay) has been used to separate the two. Also, the presence of organic matter and peat has been used to indicate the presence of alluvium rather than lake clay.

The calculation of alluvium is not successful in all areas. This is because helper sections were not added to the thinnest tracts of alluvium and the 200 m grids may not be detailed enough to pick them out. Because of these issues, confidence levels in the alluvium grids are variable.

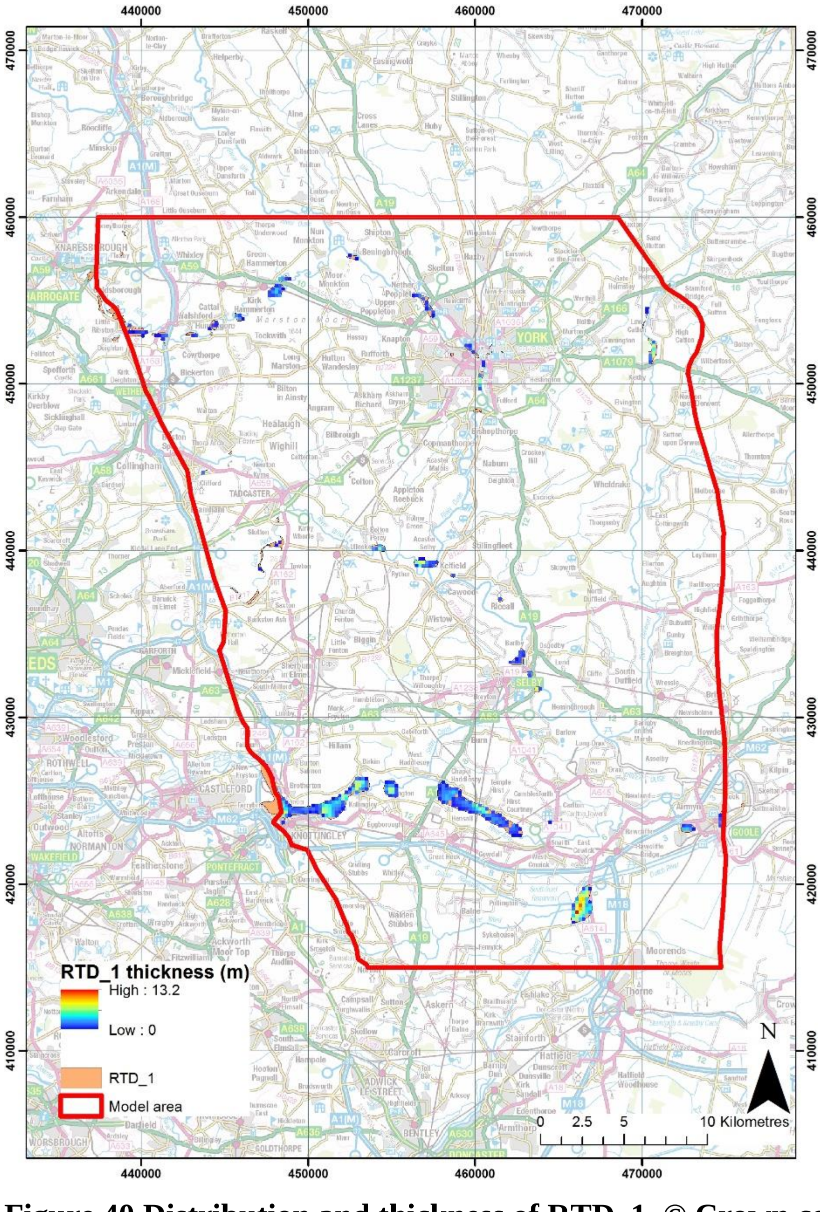

Figure 40 Distribution and thickness of RTD_1. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

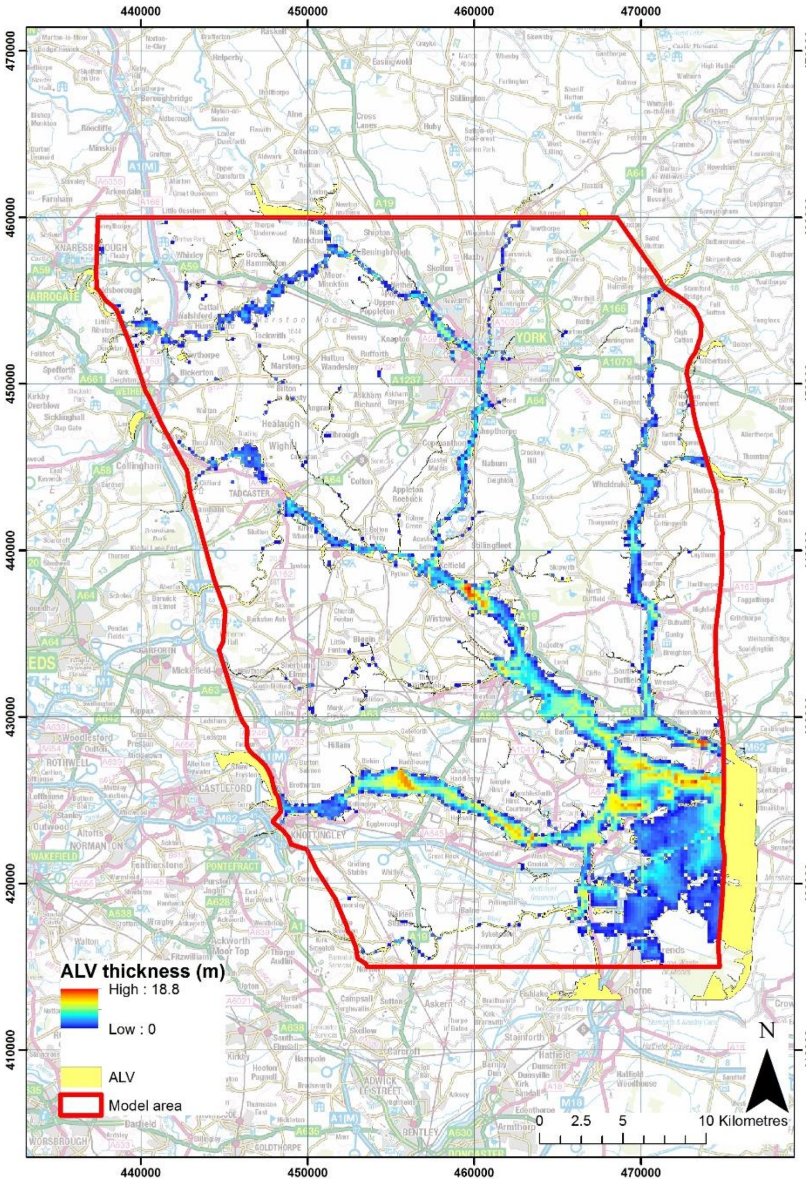

Figure 41 Distribution and thickness of ALV. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.13 Peat

Peat mainly occurs in the south-east corner of the model in the Moorlands area (Figure 42). Isolated patches are modelled where mapped, with additional patches modelled where boreholes describe peat at the ground surface. Peat has a maximum thickness of 4.2 m in the model.

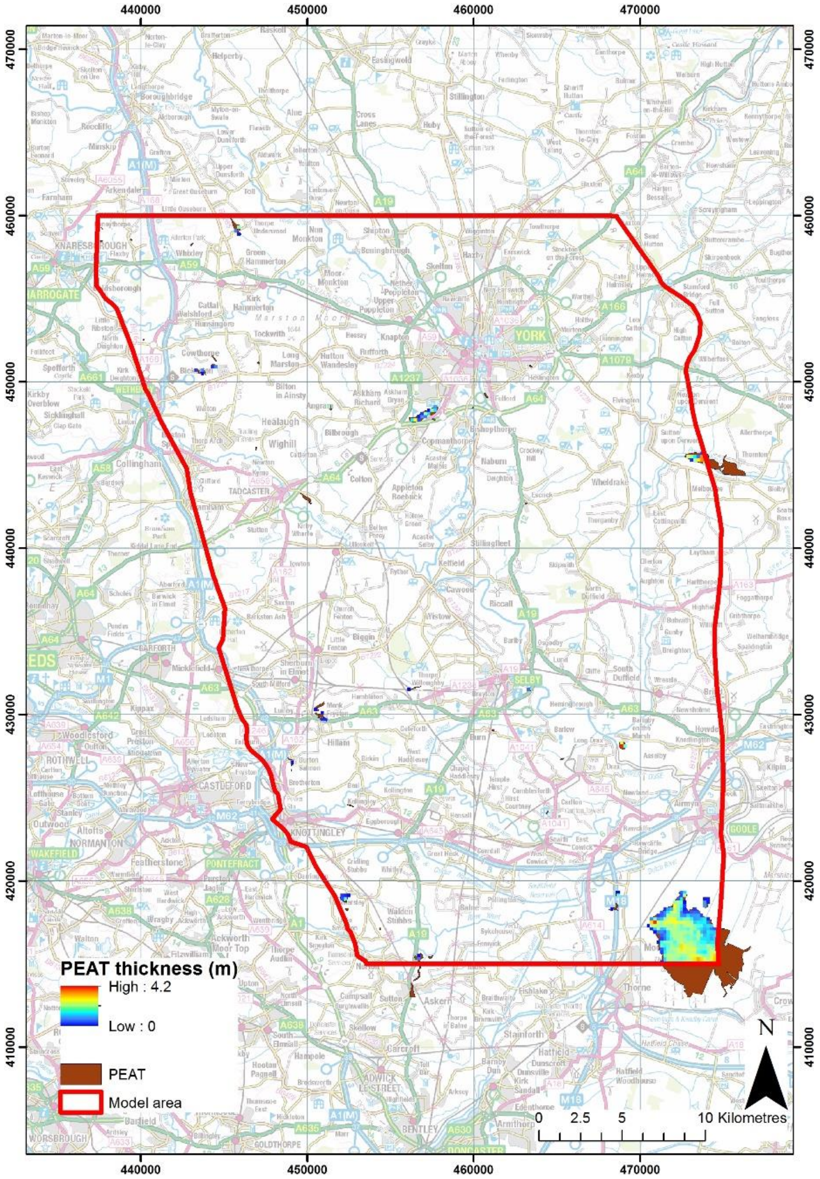

Figure 42 Thickness and distribution of peat. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

4.3.14 Artificially modified ground

Artificially modified ground was not originally considered important for the purposes of the model. However, made ground (*MGR*) is modelled in areas where the ground surface has been artificially raised to form prominent features in the Digital Terrain Model, such as spoil heaps, and where significant thicknesses of made ground are recorded in boreholes (typically over 5 m). This is to prevent the over-thickening of the natural superficial deposits in the model area. Polygons from the DiGMapGB-50 artificial theme were used to define the extent of made ground where it corresponds with these Digital Terrain Model features and borehole thicknesses. Made ground has a maximum thickness of 59 m in the model (Figure 43).

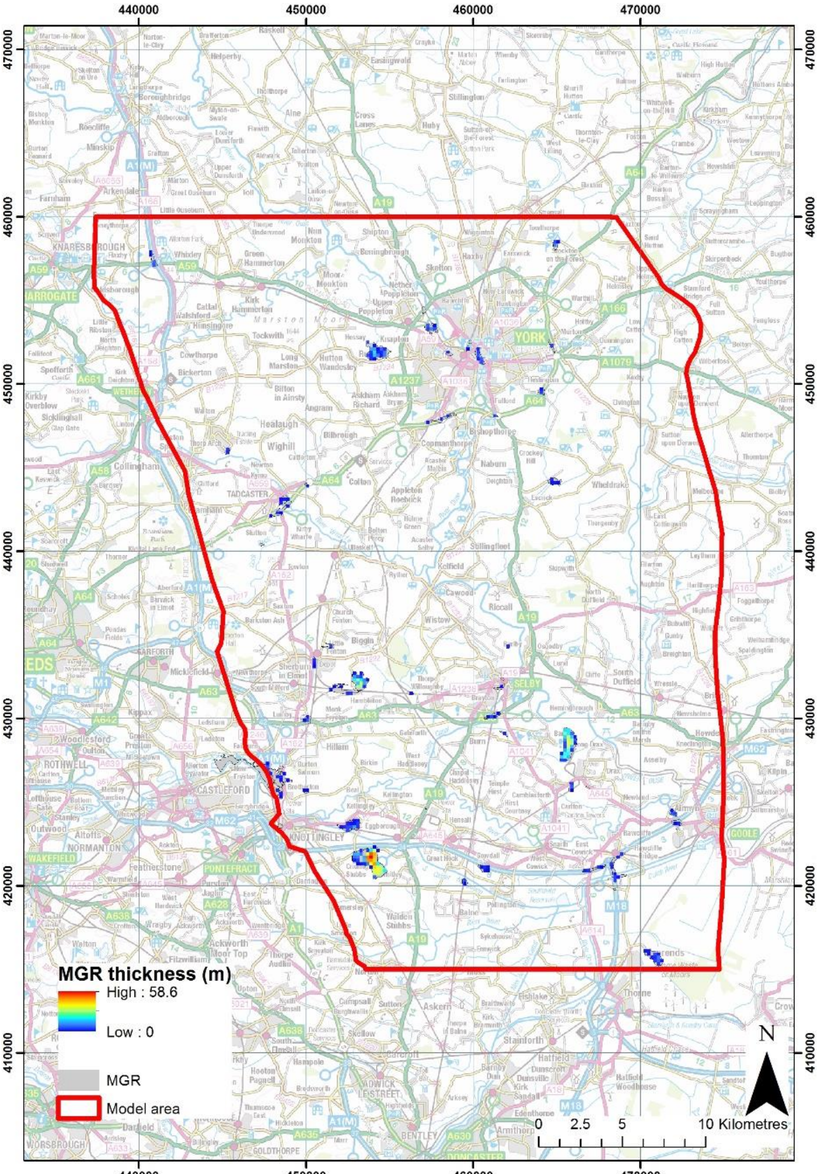

Figure 43 Distribution and thickness of made ground. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

5 Rockhead elevation surface and superficial thickness

A rockhead elevation surface was generated in the model by combining the bases of all Quaternary units in the model (Figure 44). The Digital Terrain Model is used where superficial deposits are absent. This has an elevation range of +80 in the west of the model to -40 m.

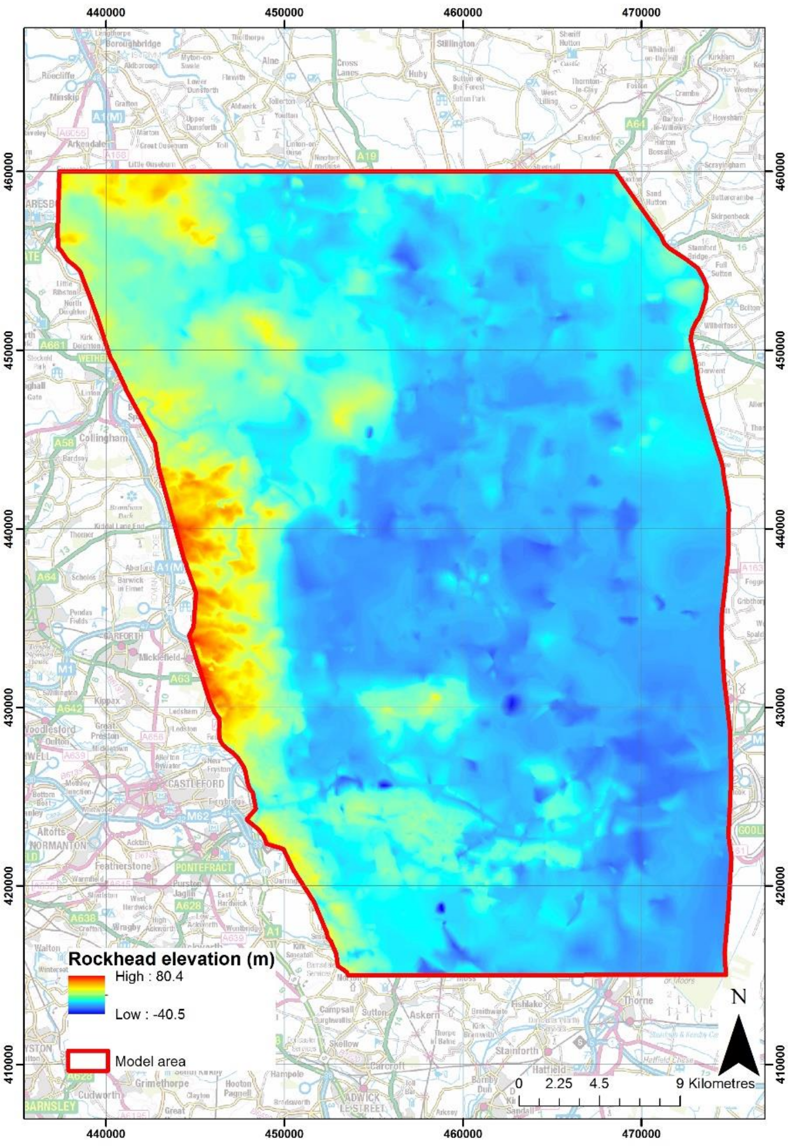

Figure 44 Rockhead elevation surface generated by combining the bases of all modelled Quaternary units. The Digital Terrain Model is used where Quaternary deposits are absent. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

5.1 DRIFT THICKNESS

A drift thickness grid was calculated in the model by subtracting the rockhead surface generated in the model (the bases of all modelled Quaternary units) from the Digital Terrain Model (Figure 45). This shows a maximum thickness of 70 m for the superficial deposits in the model area. High drift thickness values are influenced by the inclusion of completely weathered Sherwood Sandstone Group in the unit GFDUD.

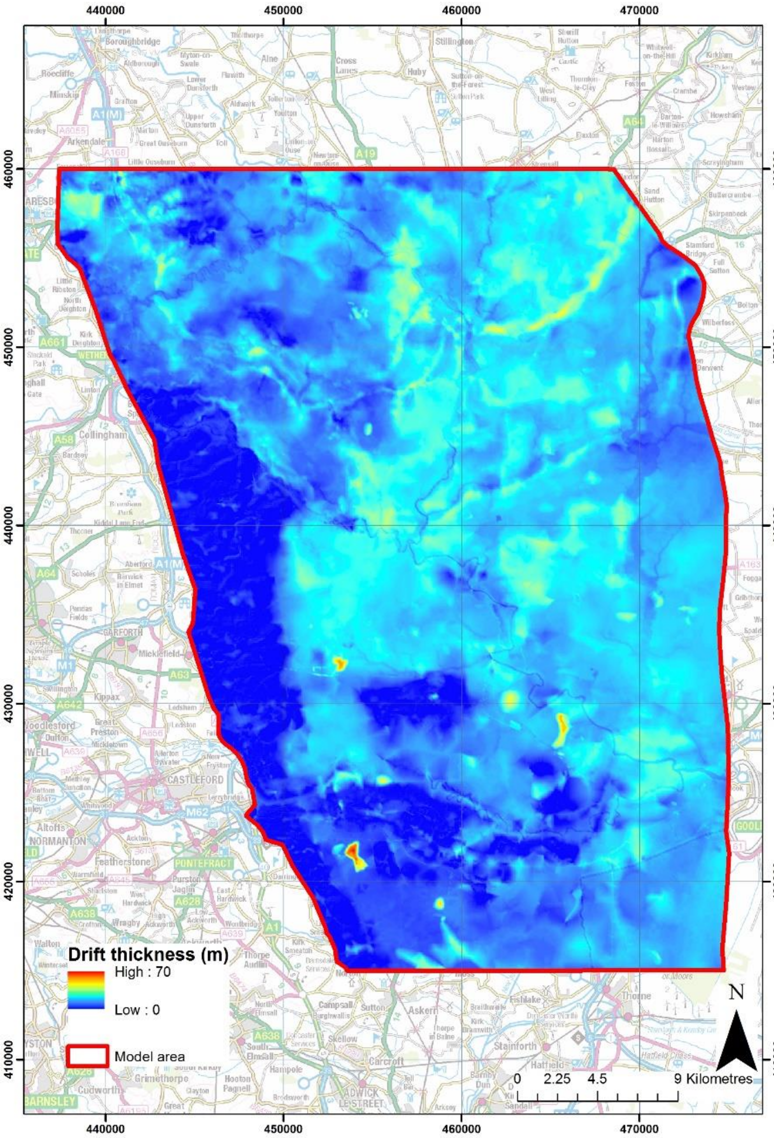

Figure 45 Drift thickness grid for the model area. This was calculated by subtracting the modelled rockhead elevation surface from the Digital Terrain Model. © Crown copyright and database rights (2017) Ordnance Survey (100021290 EUL).

6 Conclusions and Recommendations

The Selby model enables the Quaternary deposits between Thorne and Haxby to be visualised in three dimensions for the first time. This enhances our understanding of both the geological evolution of the region and the impact of superficial and bedrock geology on the hydrogeology.

There is no easy way of measuring or representing uncertainty in a geological model constructed using GSI3D. The model conveys the geological complexity of the area as far as the limits of the 3D modelling software, geological interpretation, baseline data and scale of the model allow, but the geology is generalised for the purposes of the model and is more complex in reality. This is less of a problem in the southern half of the model, where the geological units are more laterally persistent and fewer in number. However, confidence is reduced in the northern half of the model where there are more geological units and their geometric relationships are more complex. In general terms, uncertainty could be reduced by using more borehole logs (898 were used out of 6,191 available in the VYORK coverage area) and increasing the density of cross-sections.

The main unit specific sources of geological uncertainty within the data set are associated with GFDUD, ALV and MGR. Recommendations are made, where appropriate, to indicate how uncertainties can potentially be reduced. GFDUD is used to model basal glaciofluvial sand and gravel deposits and completely weathered Sherwood Sandstone Group bedrock. It is often difficult to distinguish between the two using the borehole descriptions alone because the Sherwood Sandstone Group is commonly the source material for glaciofluvial deposits. This uncertainty impacts on the interpreted position of rockhead in the model, and the maximum possible depth was used. However, due to the spatial variability of weathering there is no known approach that could effectively reduce uncertainty across the entire model area. Alluvium thicknesses across the model area are also variable and potentially too thick in places. This partly reflects difficulties in distinguishing alluvial silts and clays from underlying units. One future approach to reducing this uncertainty would be to use modern thalweg gradients as a structure contour to constrain the alluvium thickness.

The calculation of made ground, thin units such as cover sand and linear units, such as alluvium, could also be improved by using an automated approach and setting a minimum thickness value. However, this approach would override the actual thicknesses recorded in the borehole logs. Therefore 136 ‘helper sections’ were constructed to improve the calculation in the worst affected areas. Despite the addition of these helper sections, this approach has led to the units in some area having zero thickness values.

Geological knowledge gaps also have an impact on the model. Buried valleys are well documented in the Doncaster model area to the south, but have not been researched in the Selby model area and there is insufficient borehole evidence to be able to locate them with certainty. The geological maps themselves contain knowledge gaps. This is apparent in the spatial and attribution mismatches between the Wakefield and Goole sheets, which was resolved in the model by matching the oldest mapping to the newest.

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