British Geological Survey

Hydro-JULES natural superficial deposits hydrogeological typology

Environmental Change, Adaption & Resilience Programme

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BRITISH GEOLOGICAL SURVEY

ENVIRONMENTAL CHANGE, ADAPTION & RESILIENCE
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Summary

This report describes a small work package undertaken as part of the NERC-funded Hydro-JULES project. One of the outputs of this project is a national hydrogeological model and to aid its development a semi-conceptual approach was developed to characterise the natural superficial geology at 1 km^2 scale. This approach effectively attempts to classify the relative permeability and complexity of the natural superficial geology down to bedrock. It is envisaged that the classes developed within this approach can be characterised numerically (with hydrogeological attributes) and used to inform the numerical groundwater model. The approach was trialled in six areas across lowland England to test and refine the approach: (1) Surrey; (2) North Norfolk coast; (3) Breckland; (4) Waveney Valley; (5) UK GEOS site and adjacent parts of Cheshire; and (6) Vale of Eden. Recommendations are made for the roll-out of the methodology across the UK plus several notable data gaps are highlighted. In particular, the development of a robust aquifer-to-surface hydrogeological model requires additional datasets that characterise the basic hydrogeological properties of bedrock at rockhead, and an understanding of the thickness and extent of the zone of bedrock weathering.

1 Introduction

This report is part of the Hydro-JULES research programme supported by NERC National Capability funding (Grant number: NE/S017380/1) to the Centre for Ecology & Hydrology (CEH), British Geological Survey (BGS) and National Centre for Atmospheric Science (NCAS). The five-year programme (April 2019-March 2024) will develop a new generation of terrestrial hydrological models linked to, and in collaboration with, the Joint UK Land Environment Simulator (JULES) model. A primary objective of Hydro-JULES will be to generate a 3-dimensional model of the complete terrestrial water cycle in such a way as to ensure consistency across space and timescales. Through the development of new models that better simulate the movement of water, both vertically and laterally, advances in land surface-boundary layer science will be made. Two scales will be considered for the application of the modelling approach: The British mainland (England, Scotland and Wales including major islands) and global scale.

At the British mainland scale the following questions are to be considered:

1. How can an integrated approach improve the simulation of major flooding events such as the 2013/4 floods?
2. How can a holistic approach be undertaken to assess water resources under drought conditions?

Any outputs from the Hydro-JULES programme are open as well as freely and easily available to ensure transparency and auditability in the development of the scientific approach.

BGS' role is to deliver the sub-surface part of the Hydro-JULES programme by contributing the geological and hydrogeological understanding to inform the appropriate parameterisation to be encapsulated in the groundwater modelling. The aim is to develop a flow, heat and solute transport modelling approach for the British mainland and to incorporate groundwater flow in the JULES model at the global scale.

As part of the Hydro-JULES research program, a numerical groundwater flow model of the shallow sub-surface of the UK will be developed that will link the land-surface to the bedrock geology via the superficial geology. However, whilst our UK-scale understanding of the bedrock geology is modern and fit-for-purpose, our knowledge and understanding of the natural superficial geology is by contrast, more limited. This reflects the 150-year legacy of our superficial geological data, how the information was captured and the underpinning geological assumptions and approaches of the time – many of which are outdated and do not effectively communicate the natural complexity of the geology. Together, these limitations impact our understanding of the spatial complexity of the natural superficial geology (especially in 3D) and in-turn downstream derivatives such as a hydrogeological model.

To help overcome this challenge, this component of the project aims to develop a semi-predictive classification of the natural superficial geology that can then be parameterised numerically and incorporated into the national model. This classification scheme is based upon integrating available geological data (e.g. borehole records, geological map data etc, other published records) with tacit knowledge of the wider geological history, the range of geological processes that have likely occurred and 3D facies architecture to 'predict' the geology. The aim of this classification is to be simple and applicable nationwide at the required scale of the hydrogeological model (1 km^2 resolution). This report provides an overview of this process, outlining the methodology and employing it to six case studies in England. The data for each of these six case study areas is available as a series of GIS shapefiles.

2 Methodology

2.1 INTRODUCTION

The purpose of this module within Hydro-JULES is to numerically model the hydrogeological properties of the natural superficial geology and its interaction with bedrock aquifers at 1 km^2 resolution across the UK. This is complex challenge because whilst knowledge of the bedrock geology across the UK is modern and generally fit-for-purpose, spatial understanding of the natural superficial geology (i.e. the Quaternary) and especially its 3D properties is more variable. This reflects a combination of factors including: (1) inconsistencies in mapping and classification approaches (largely reflecting the diverse age of data, concepts and techniques); (2) a paucity of quantitative descriptive data; (3) a lack of understanding of the complexity of the geology at depth; and (4) limited understanding of the underpinning geological processes (which control the geological properties and allow prediction).

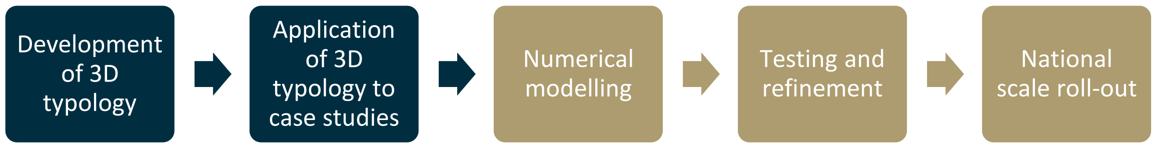

Figure 1. Workflow for the 1 km^2 characterisation of the UK hydrogeological model. The focus of this report is on the first two segments (blue) of this workflow.

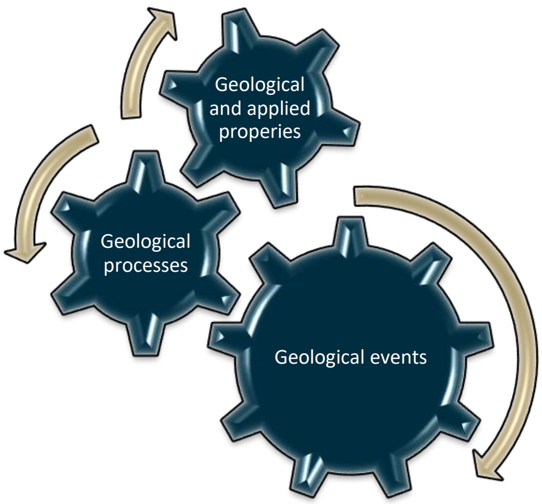

Figure 2. A conceptual 'Earth Systems' approach to geology whereby the three components are interdependent. This effectively means that by understanding the underpinning processes (or properties) of one component within its regional context, it should be possible to predict the other two components. For example, if the presence of an 'ice margin' (geological event' is identified, then the geological processes (i.e. proglacial and subglacial thrusting and folding) and geological (i.e. likely presence of folding, faulting, complex juxtapositions of geological units) and applied (i.e. highly-variable and unpredictable groundwater behaviour) properties can be predicted.

To overcome these issues, a semi-predictive approach is developed and trialled within this study (Figure 1). This approach is underpinned by known information gathered from published geological maps and available borehole records, and enhanced with tacit knowledge based upon regional understanding and an awareness of Quaternary history, processes that have occurred and facies architecture (**Error! Reference source not found.**). It assumes that g eological events, geological processes and geological (and applied) properties are inter-linked.

In other words, that a large-scale geological event (e.g. a glaciation) will initiate one or a range of geological processes that in-turn will produce geology and landform features whose properties and behaviour reflect those higher-level processes. The basic principles of this philosophy are inherited from the 'landsystems' approach developed and widely applied to glaciated terranes (Eyles, 1983; Evans, 2005) but are equally applicable to other aspects of natural superficial geology (Booth *et al*., 2015).

Geological Event	Y/N	Geological Process	Geological Property
Long-term exhumation	Yes	• Uplift • Weathering	• Normal fault reactivation • Fracturing and deep weathering, solution features (carbonate bedrock). • Prolonged subaerial exposure of bedrock (10s millions of years), development of deep *in situ* weathering profiles under long-term temperate climates. • Some downslope remobilisation of upper weathered zone likely under periglacial processes. However, preservation potential of deep weathering profile is high because the area is situated to the south of Quaternary glaciation.
Periglaciation	Yes	• Freeze-thaw • Slope remobilisation	• Mechanical weathering of bedrock and superficial by freeze-thaw under cold stage periglacial climates (Plio-Pleistocene). Mudstones especially frost-susceptible. • Development of a secondary (periglacial) weathering profile superimposed upon the temperate weathering profile. • Some downslope remobilisation of upper weathered zone likely under periglacial processes. However, preservation potential of deep weathering profile is high because the area is situated to the south of Quaternary glaciation.
Glaciation	No	N/A	N/A
Hillslope processes	Yes	• Mass-movement	• Downslope remobilisation of weathered materials under the influence of gravity; geometry of slope deposits (head) likely to be complex reflecting prolonged landscape history and phases of slope instability.
Fluvial processes	Yes	• River incision and terrace aggradation • Modern floodplain	• Established river systems, with well-developed river terraces and valley bottom alluvium. • Reflecting wide valley bottoms and tributary systems; geological fill likely to be complex.
Coastal processes and sea-level change	No	N/A	N/A

Table 1. Application of the semi-predictive approach to geological characterisation for the Surrey Case Study area (Section 3.2). In this example, the 'geological events' were used to predict the 'geological processes' and 'geological properties' that may be encountered within the natural superficial geology. When used in tandem with available geological information, this 'geological risk assessment' can be a powerful tool for characterising the natural superficial geology at the scale required by the Hydro-JULES model.

This relatively simple conceptual approach enables the geologist to use their knowledge of regional scale geological history to very quickly build a picture of the range of geological events and processes that may have affected an area and in-turn construct a 'geological risk assessment' of geological features that may be present in the landscape or sub-surface. An example of the application of this process for one of the case study areas (Surrey) is shown below in Table 1. The application of tacit knowledge to enhance geological characterisation can be a valuable tool. It enables characterisation in areas where data coverage is good to be enhanced further; and general baseline information and properties to be predicted in data-poor areas. In addition, it can be used to predict the existence of geological features that may not be represented on a geological map but nevertheless may inform hydrogeological understanding.

For the purpose of this study, a combination of available data and tacit knowledge was used to develop a relatively crude 'typology' that effectively describes the nature of the superficial geology above a bedrock aquifer. Values can then be applied to this typology to enable the numerical population of the model. It should be noted that the 1 km^2 spatial resolution of this dataset is relatively course and enables the superficial geology to be characterised in only a very generalised way. For instance, the 'feather edge' of geological units and variations in thickness are beyond the scale of this approach. Equally, this resolution is too coarse to detect a number of Quaternary features that could give rise to anomalous groundwater conditions, such as buried (tunnel) valleys, 'drift filled hollows', dolines etc.

As part of this study, a 3D typology was developed to characterise the geological and hydrogeological complexity of natural superficial deposits across the UK. A total of five different geological scenarios or classes (A-E) are defined and these should cover the majority of geological scenarios encountered at a 1 km^2 spatial scale (Table 3).

The approach adopted in this project is similar to that employed by a previous project ('SNIFFER') that examined groundwater vulnerability within Scotland (Ball *et al*., 2004; Ó Dochartaigh *et al*., 2015). This approach classified the interaction of the superficial-bedrock geology via a series of groundwater vulnerability scenarios reflecting the nature of the cover material (if present), thickness, permeability and type of superficial to bedrock groundwater flow (e.g. Figure 1, Ó Dochartaigh *et al*., 2005). The approach adopted here is slightly different for two reasons: (1) the required scale of the data for this dataset is higher; and (2) there is potential to enhance the 3D understanding (both practical and predicted) of the superficial geology. Therefore, for the purpose of this scheme, attribution focussed upon the classification of the natural superficial geology and communicating the vertical complexity of the geology. The classification does not consider the nature of the bedrock geology and the presence of deformation within the bedrock (e.g. weathering, faulting, fracturing etc) that could influence hydraulic conductivity with the natural superficial deposits. For the purpose of the case studies outlined within the following chapter, the bedrock geology and the potential presence of deformation features that could impact its hydrogeological properties are outlined. These factors could be considered further during the numerical attribution of the UK hydrogeological model.

2.2 3D TYPOLOGY

As outlined within the previous section of this report, the characterisation of the natural superficial deposits is semi-predictive, being based upon available data and tacit knowledge based up regional geological knowledge, inferred geological processes and properties. These combine to define the vertical column of natural superficial geology that occurs between the ground surface and the geological rockhead surface (the top of the bedrock surface). Individual units within the vertical column were classified following the permeability indices defined by Lewis *et al*. (2006) and summarised below (Table 2).

These were combined to form the vertical column which was then classified relative to five categories (the typology) according to the superpositional arrangement and variability of the geology to help define its 'Class'. This 'class' therefore incorporates both the sub-surface geology and the surface geology – the latter defined as the most extensively-occurring natural superficial unit (based on DigMap50) within a 1 km^2 cell. For example, if bedrock cropped-out at surface within more than half of the tile area, then the tile was classified as a Class A.

RCS Description	LEX Description	Flow type	Max Perm	Min Perm
Peat	Peat.	Mixed	Low	Very Low
Sand, silt, clay	Alluvium, head, tidal flat deposits.	Intergranular	Very high	High
Sand and gravel	River terrace deposits, glaciofluvial deposits, beach deposits.	Intergranular	Very high	High
Sand	Alluvium, river terrace deposits, glaciofluvial deposits, glaciolacustrine deposits, beach deposits, tidal flat deposits.	Intergranular	Very high	High
Clay and silt	Glaciolacustrine deposits, alluvium – overbank deposits.	Mixed	Low	Very low
Diamicton	Till.	Mixed	High	Low
Gravel	Beach deposits, river terrace deposits.	Intergranular	Very high	High

Table 2. Permeability Indices for common natural superficial lithologies (adapted from Lewis *et al*., 2006).

Class	Colour	Description	Hydrogeological complexity
A		Bedrock at surface	Low
B		Bedrock beneath a high-permeability superficial unit	Low
C		Bedrock beneath a low-permeability superficial unit	Low
D		Bedrock covered by single low- and high-permeability units in superposition	Moderate
E		Multiple low- and high-permeability superficial units in superposition above bedrock AND / OR complex and unpredictable geometry.	High

Table 3. Overview of the typology employed for characterising the natural superficial geology.

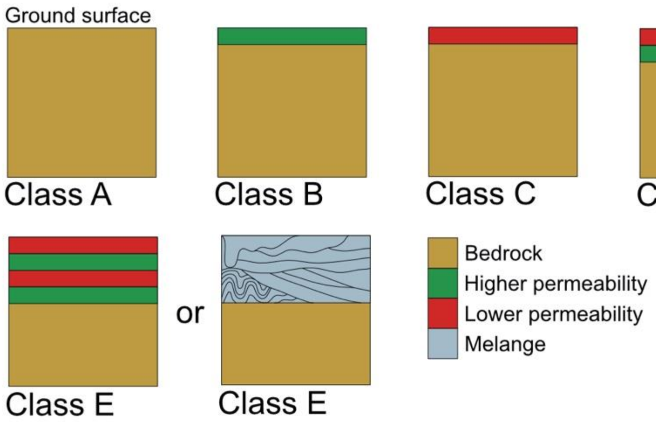

Figure 3. Schematic diagrams showing the general nature of the natural superficial geology outlined by Classes A-E.

For the purposes of this study, a five-class typology (A-E) was developed to classify the broad superpositional relationship between different natural superficial deposits in the shallow surface. In reality, an infinite number of classes are possible depending on the thickness and complexity of the geology. However, the relatively coarse resolution of the study (i.e. 1 km^2 grid) coupled with considerable spatial variability in the quality and quantity of available shallow sub-surface data, would make the application of a more detailed classification impractical and inconsistent, having the effect of increasing uncertainty. It should also be noted that the classification scheme adopted here focuses on the natural superficial geology but does not explore the hydrogeological properties of the underlying bedrock and hydraulic connectivity between the two – which is beyond the scope of this study.

The typology comprises five classes (A-E), with definitions provided together with a crude relative indication of the hydrogeological complexity in Table 3. These definitions are summarised diagrammatically in Figure 3. Class A constitutes occurrences where bedrock crops-out at the ground surface. Class B encompasses the scenario where higher-permeability superficial deposits (e.g. sand or sand and gravel) overlie the bedrock. Class C is defined by superficial deposits of lower-permeability (i.e. till, clay, peat) overlying the bedrock. Class D corresponds to the scenario where lower- and higher-permeability units occur in superposition above the bedrock although this can be with either the lower-permeability unit at the base or top of the superficial sequence. The final class, Class E, corresponds to zones of highly-complex superficial cover overlying the bedrock. Two scenarios are envisaged: (1) multiple units of lower- and higher-permeability occurring in superposition above the bedrock; and (2) complex arrangements of glacitectonically deformed lower- and higher-permeability strata.

2.3 MODEL ATTRIBUTION

For the purpose of trialling the methodology, six case study areas were carefully chosen to provide a broad spatial spread of sites across England and to test the approach relative to different types of natural superficial geology that occur in association with several of the UK's primary aquifers. All of the case studies incorporate different types (and combinations) of natural superficial geology (Table 4) and in-turn different geological complexities and issues that can impact the hydrogeology.

	Non-Glaciated	Glaciated	Complex ice-marginal	Buried valleys	Long-term weathering	Coastal	Rivers
Surrey	■				■		■
North Norfolk		■	■	■		■	
Waveney Valley		■		■			■
Breckland		■			■		
UKGEOS		■	■	■	■	■	■
Eden Valley		■	■	■			■

Table 4. Comparison of the six trialled case study sites showing the main types of natural superficial geology that are present.

For each case study site, a 1km^2 grid was set-up and each grid square were classed (A-E) based upon the interpretation of the natural superficial geology between the ground surface and geological rockhead. In cases where the surficial geology varied across the grid square, the dominant surficial geology was adopted as the surface geology.

3 Case Studies

3.1 INTRODUCTION

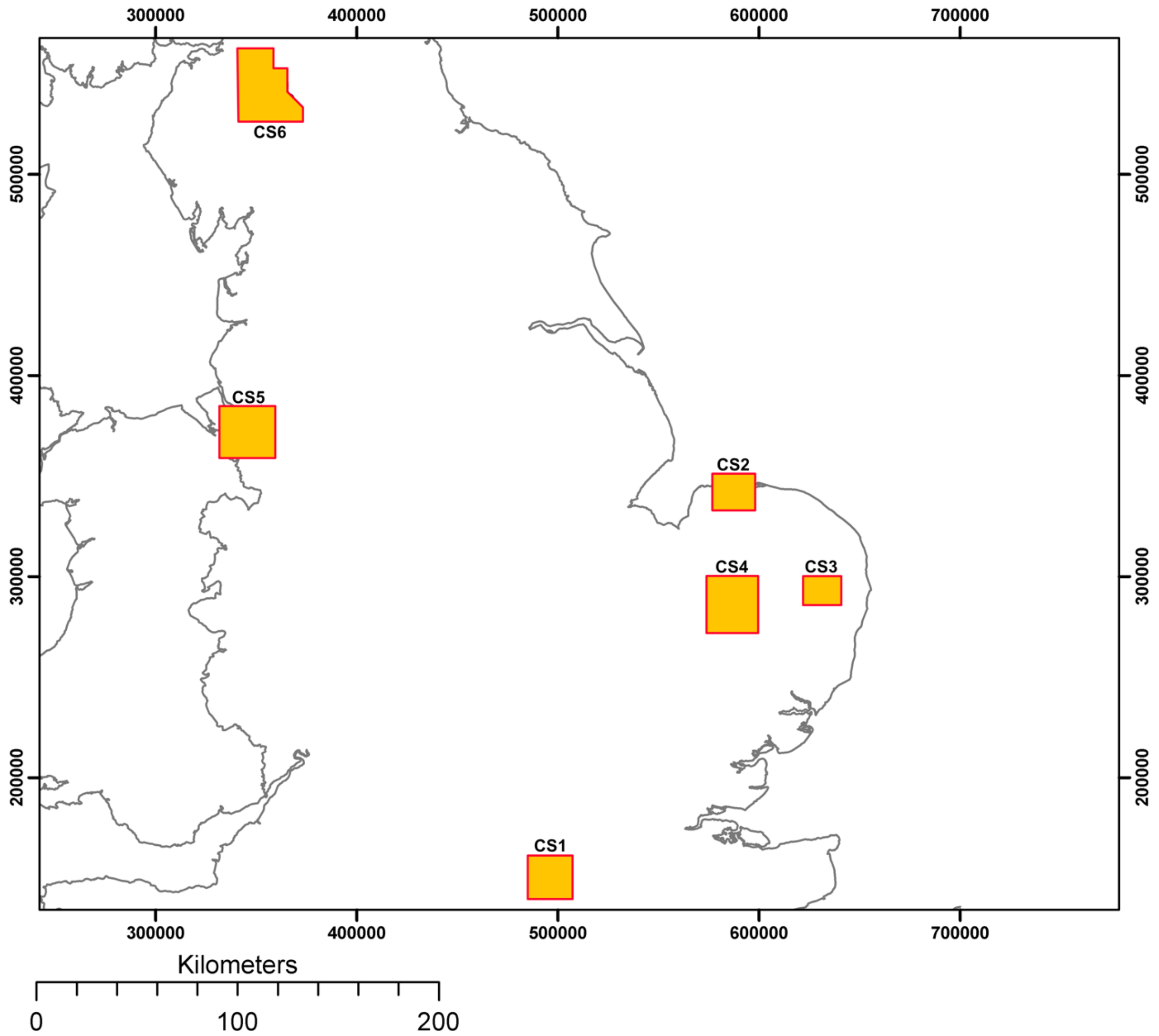

Figure 4. Map of England and Wales showing the six case study (CS*n*) locations for the Hydro-Jules superficial geology attribution. CS1 – Surrey; CS2 – North Norfolk; CS3 – Waveney Valley; CS4 – Breckland; CS5 – UKGEOS; CS6 – Eden Valley (north).

As mentioned within the previous section, six case studies in England were carefully chosen to test the methodology relative to different types of natural superficial geology (Figure 4). Within each case study, a brief geological overview is provided which outlines the primary characteristics of the natural superficial geology and its basic hydrogeological properties. Geological features that are known to affect the hydrogeology are also mentioned including where they occur at a finer resolution than the model. A brief description of the HYDRO-Jules classification is then provided within the second section, linking the typology to the described geology.

3.2 CASE STUDY 1: SURREY

3.2.1 Geological overview

The first case study is located in Surrey, to the southwest of London, covering an area of 210 km^2 between Guildford (east), Aldershot (west), Woking (north) and Godalming (south). A semi-predictive 'geological risk assessment' for the case study is shown in Table 1. Natural superficial deposits within the case study area are comparatively thin (c.<10 m) and of variable spatial complexity. The area lies some 50 km south of the known maximum extent of Quaternary glaciation so was unaffected by glacial processes. Instead, the area is likely to have remained emergent throughout much of the Neogene and Quaternary and as such, its history is dominated by: (1) ongoing uplift and exhumation driven by ongoing northwards-directed Alpine crustal compression (Palaeogene-Neogene) and erosional isostasy (Neogene-Quaternary); (2) prolonged *in-situ* weathering (temperate and periglacial) of pre-existing bedrock materials; and (3) active hillslope and fluvial processes that have acted to remobilise sediment downslope and through local drainage networks.

Regarding the bedrock geology, the case study area is characterised by Cretaceous and Palaeogene rocks that strike west-east and young towards the north, forming part of the northern limb of the Weald anticline. The bedrock geology encompasses, from south to north, Lower Greensand (medium permeability; primary aquifer), Gault Clay (low permeability; non-aquifer), Upper Greensand and Chalk groups (high permeability; primary aquifer) which occur in hydraulic conductivity; and finally, the Thames (low permeability; non-aquifer) and Bracklesham groups of Palaeogene age. These rocks crop-out at surface across c.60% of the case study area but have undergone extensive long-term weathering by both periglacial and temperate processes. These weathering processes will have weakened many of the rocks and led to the partial- or complete degradation of chemical cements that act to bind the sediments together. Mudstone lithologies, including the Gault Clay and Thames Group (including the London Clay Formation), are highly frost-susceptible (due to their geotechnical properties) which makes them prone to the development of segregated pore-ice under periglacial climates (Quaternary) and potential freeze-thaw disruption.

Accordingly, the natural superficial deposits are dominated by 'head' which occurs as isolated patches throughout the study area. 'Head' are weathered materials that have moved downslope under the influence of gravity and typically possess a variable lithology reflecting admixtures of locally-derived source materials including bedrock and superficial deposits. The depth and extent of weathered materials across the study area (so-called 'regolith' or 'saprolite') are not known nor within the geological maps. Other aspects of the natural superficial geology include alluvium and river terrace deposits associated with the River Wey. 'River terrace deposits' are typically composed of sand and sand and gravel but locally may contain lenses of silt, clay and peat. They occur as elongate bodies that flank the River Wey valley above the level of the modern floodplain. 'Alluvium' records the recent depositional behaviour of the River Wey and is dominated by fine-grained sediments such as clay, silt, fine sand with occasional horizons of gravel. The sub-surface variability and sediment facies architecture of the alluvium is likely to be complex and this means that the hydrogeological properties of the alluvium are likely to be equally complicated.

3.2.2 Hydro-JULES classification

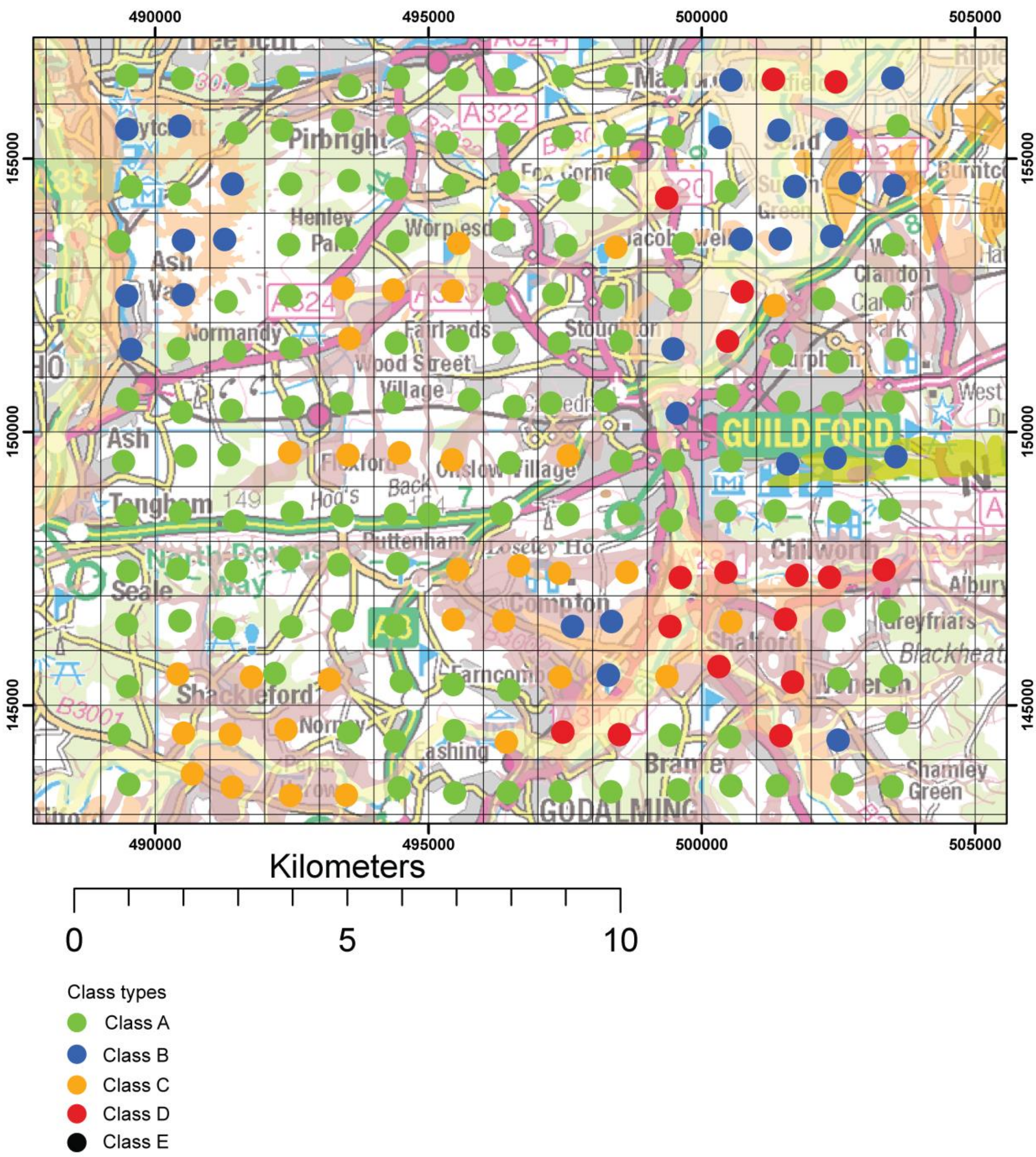

Figure 5. Application of the Hydro-JULES typology to the natural superficial deposits within the Surrey case study area. Contains Ordnance Survey data © Crown Copyright and database rights [2021]. Ordnance Survey Licence no. 100021290.

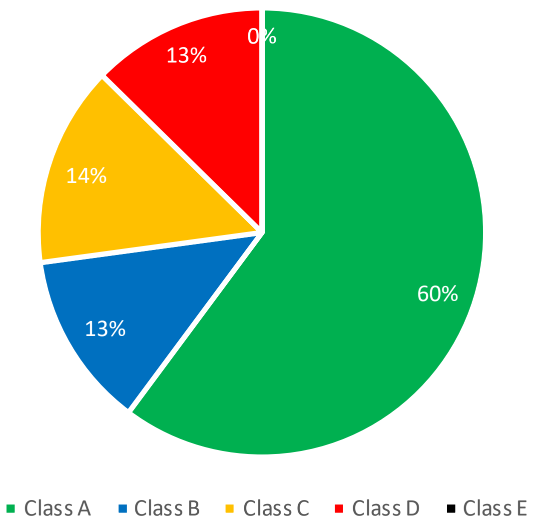

Figure 6. Summary pie chart showing the proportion of different typology classes within the Surrey case study.

The typology developed to define the natural superficial geology bedrock cover for the Surrey case study is shown in Figure 5 and summarised in Figure 6. The data demonstrates that bedrock geology crops-out (Class A) extensively across 60% of the case study area. The overlying superficial geology, where present, has relatively low complexity being overlain by either thin, highly-permeable units (i.e. river terrace sands and gravels) (14%, Class C) or thin low-permeability units (i.e. head) (13%, Class D). In the area of the River Wey, the complexity of the superficial deposits is higher, comprising Class D (13%) materials. This reflects the complex and often chaotic arrangements of clay, silt, sand, sand and gravel and peat within the alluvium and / or river terrace deposits plus local interaction with head.

3.3 CASE STUDY 2: NORTH NORFOLK

3.3.1 Geological overview

The North Norfolk case study area cover as an area of 168 km^2, extending southwards from the coast to South Creake, west to Burnham Deepdale and east to Great Walsingham. The bedrock geology across the entire study area is defined by the Chalk Group, the principal bedrock aquifer of southern and eastern England. The Chalk Group strikes broadly north-south across the study area with bedding dipping gently (<1^o) eastwards and is largely concealed by natural superficial deposits. The Chalk Group crops-out in the sides of several north-south river valleys including the River Stiffkey and the River Burn.

The natural superficial geology comprises a broad four-fold sub-division of geological units: (1) Anglian glacial deposits; (2) Late Devensian glacial deposits; (3) Holocene coastal deposits; and (4) modern river deposits. Anglian-age glacial sediments forming the Sheringham Cliffs and Britons Lane formation form much of the elevated relief in the south of the study area. The Sheringham Cliffs Formation comprises a highly-complex glacitectonic melange of glaciolacustrine clays, silts and sand with beds of sandy clay till (with chalk pebbles) upto 13 m thickness. It rests unconformably upon Chalk Group bedrock and extends discontinuously northwards beneath the Holocene coastal deposits. There is no clear superpositional relationship within these beds and instead they typically form thrust-bound stacks of sediment. Accordingly, their hydrogeological properties are likely to be complex and difficult to discern in detail. The Britons Lane Formation is a thin (upto 5 m thick) sequence of glaciofluvial sands, sands and gravels and cobble-rich horizons. The unit forms a heavily-dissected drape, sitting on top of and cutting down into the underlying Sheringham Cliffs Formation. The Holderness

Formation comprises till and glaciofluvial units laid-down during the Late Devensian glaciation with the most southern extent of this glaciation defined by the till limit within this case study area which runs broadly west-east between Burnham Deepdale, Burnham Overy and Stiffkey (Pawley *et al*., 2006; Evans *et al*., 2019). Two till units, upto c. 6 m thickness, occur within the case study area. The Holkham Till Member is a reddish-brown, massive, sandy clay with common gravel clasts and cobbles of flint (Pawley *et al*., 2006). The Red Lion Till is a highly chalky sandy clay with numerous clasts of the chalk and flint (Pawley *et al*., 2006). Both till units are heavily fractured. The Ringstead Sands and Gravels are flint-rich glaciofluvial sands and gravels, upto 3 m thick, that generally rest-upon the underlying tills.

Within the northern half of the study area, the dominant natural superficial sediments form a broad coastal prism that is between 2-3 km wide. Sediments that form part of this Holocene-age prism overlie either Chalk Group bedrock or locally, glacial sediments belonging to the Sheringham Cliffs or Holderness formations. This coastal prism forms part of a more extensive and classic barrier coastline that extends along the north Norfolk coastline from Weybourne to Hunstanton. Within the case study area, the coastline exhibits a double coastal barrier: (1) a seaward outer barrier comprising a narrow low barrier ridge (c.20-30 m wide) formed of small coastal dunes; (2) a much wider (c. 200-300 m wide) inner barrier composed of large sand dunes often planted (artificially) by conifers and deciduous trees. Behind (landward) the inner barrier, the area typically comprises reclaimed (i.e. partly drained) intertidal salt mash with the geology dominated by peats, silts and clays. Between the two barriers is the intertidal area comprising intertidal sand and mud flats with salt marsh and tidal creeks (clay, silt, peat). Seaward of the outer barrier are beach and shoreface deposits comprising sands, sands and gravels. At depth, the geology of this coastal prism reflects the progressive landward migration of these facies as Holocene sea-levels have risen. Accordingly, the geology of this coastal prism is likely to be highly-complex and spatially variably which logically will be reflected in their hydrogeological properties and behaviour. Valleys throughout the case study area are commonly partly infilled by head which variably rests upon the underlying superficial sediments and / or chalk bedrock. The head is likely to be relatively thin, upto 2 m thick, and formed by the downslope movement of remobilised materials such as clay, till, sand, sand and gravel. It commonly occurs on the flanks of the major river valleys above the level of the modern floodplain. These major river valleys are often incised directly in to Chalk bedrock, with the valley bottoms typically infilled with Holocene alluvium, upto 4 m thickness, composed of lenses of silt, clay, sand and peat.

3.3.2 Hydro-JULES classification

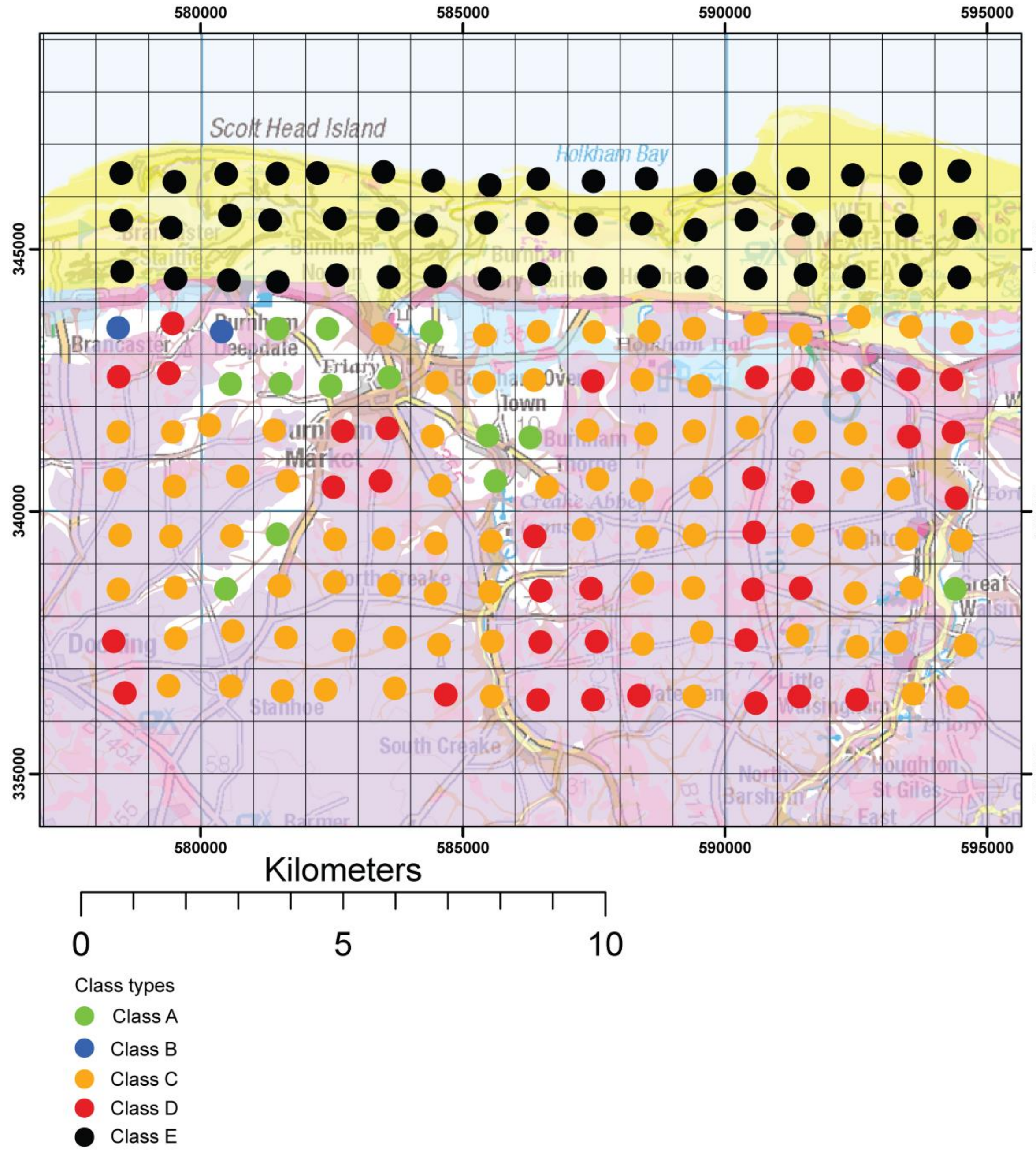

Figure 7. Application of the Hydro-JULES typology to the natural superficial deposits within the North Norfolk case study area. Contains Ordnance Survey data © Crown Copyright and database rights [2021]. Ordnance Survey Licence no. 100021290.

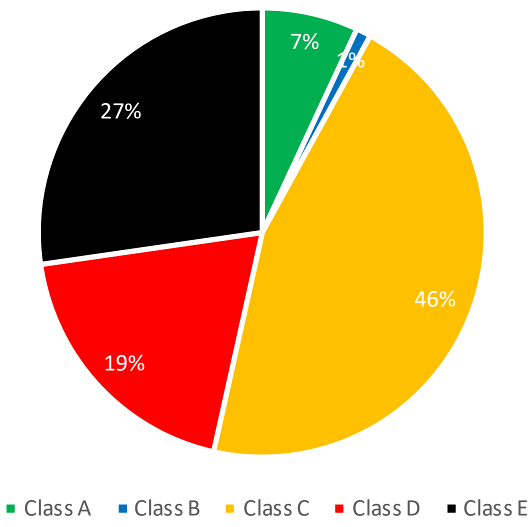

Figure 8. Summary pie chart showing the proportion of different typology classes within the North Norfolk case study.

The typology developed to define the natural superficial geology bedrock cover for the North Norfolk case study is shown in Figure 7 and summarised in Figure 8. The data demonstrates that bedrock geology crops-out over a relatively small part of the study area (7%, Class A) and locally is commonly concealed (46%, Class C) by low-permeability materials such as till. Across 19% of the case study area, the bedrock is concealed by single units of both low-permeability (i.e. till) and higher-permeability (i.e. sand and gravel) materials (Class D). Within the coastal prism in the northern part of the case study (27%), the superficial geology falls into Class E where bedrock is buried beneath multiple units of low- (i.e. clay, peat) and high-permeability (i.e. sand and sand and gravel) geology and the hydrogeological properties are likely to be complex reflecting the highly variable nature of the superficial geology at depth.

3.4 CASE STUDY 3: WAVENEY VALLEY

3.4.1 Geological overview

The Waveney Valley case study extends across an area of 104 km^2 in central East Anglia, situated between Bungay (south), Mundham (north), Hempnall (west) and Ellingham (east). The bedrock geology comprises Cretaceous-age Chalk Group, the principal bedrock aquifer of southern and eastern England, with strata dipping gently eastwards (<1°). The Chalk Group has no surface outcrop within the case study area and is concealed beneath Quaternary deposits. Progressive uplift and exhumation of central East Anglia through the Late Cretaceous and Cenozoic mean that the Chalk Group has undergone significant long-term erosion and intense weathering. Borehole records demonstrate a highly-undulating geological rockhead surface with extensive dissolution and deep-weathering profiles (upto 30 m). The thickness and spatial variability of this dissolution and weathering profile remains poorly understood.

An additional feature of the rockhead surface is the presence of a significant incised valley (Lee *et al*., 2020). The modern expression of this valley is indicated by the River Waveney and associated sediments that flank the valley sides (described later). However, this modern valley is superimposed upon a much older buried valley system that has existed for at least the past one million years (Figure 9). The initial formation of the buried valley is associated with the course of a major preglacial river system that drained central and eastern England into the North Sea Basin of the time (Lee *et al*., 2020). The headwaters of this river, the Bytham River, were situated within the Stratford-upon-Avon area of the West Midlands and the river system prior to the Anglian Glaciation (c.450-430 ka) was the largest river system within southern

Britain. Deposits associated with the river comprise reddish-brown sands and gravels rich in flint, vein quartz and quartzite and in places reaches thicknesses of 20 metres. Within the case study area, boreholes indicate these sands and gravels occur within the central, southern and southeast of the area. They are covered by flint- and chalk-rich glaciofluvial outwash sands and gravels (upto 7 metres thick) and in-turn the Lowestoft Till. The Lowestoft Till is a dark grey (when unweathered) silty clay diamicton with common pebbles of chalk, flint, vein quartz and quartzite (Hopson and Bridge, 1987). Locally it can reach thicknesses of upto 20 metres thickness and often contains discrete lenses of sand and sand and gravel. The till is often heavily fractured.

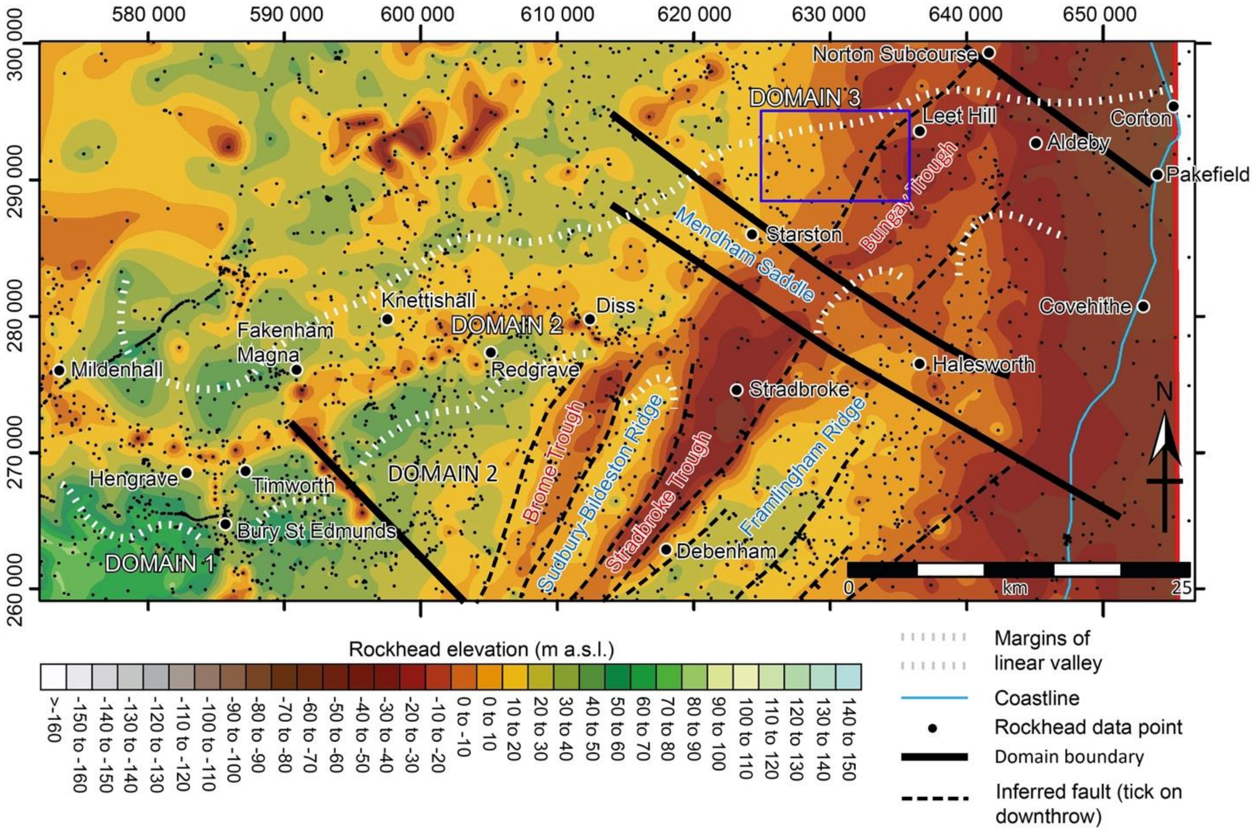

Figure 9. Geological rockhead (bedrock) surface across central East Anglia showing the case study area (blue rectangle) and the position of the Bytham River buried valley indicated by the white dashed line (from Lee *et al*., 2020).

The youngest superficial deposits include slope deposits and river deposits associated with the modern River Waveney (Holmes *et al*., 2018). Slope deposits includes 'head' which occurs in the bases of small, often dry valleys that feed into the Waveney Valley. "Head' material, typically upto 2 metres thick, comprises silty, sandy clay with occasional flint pebbles. River deposits occupy the lower flanks and base of the River Waveney valley. River terrace deposits occur on the flanks of the valley and are upto 8 metres thick, comprising tabular bodies of coarse sand and sand and gravel. Lenses of clay and peat, reflecting localised overbank deposits are common. Modern 'alluvium' occurs beneath the floodplain of the Waveney. It typically forms a fining-upwards sequence of gravel to sand to silt and clay with common lenses of other lithologies including peat.

3.4.2 Hydro-JULES classification

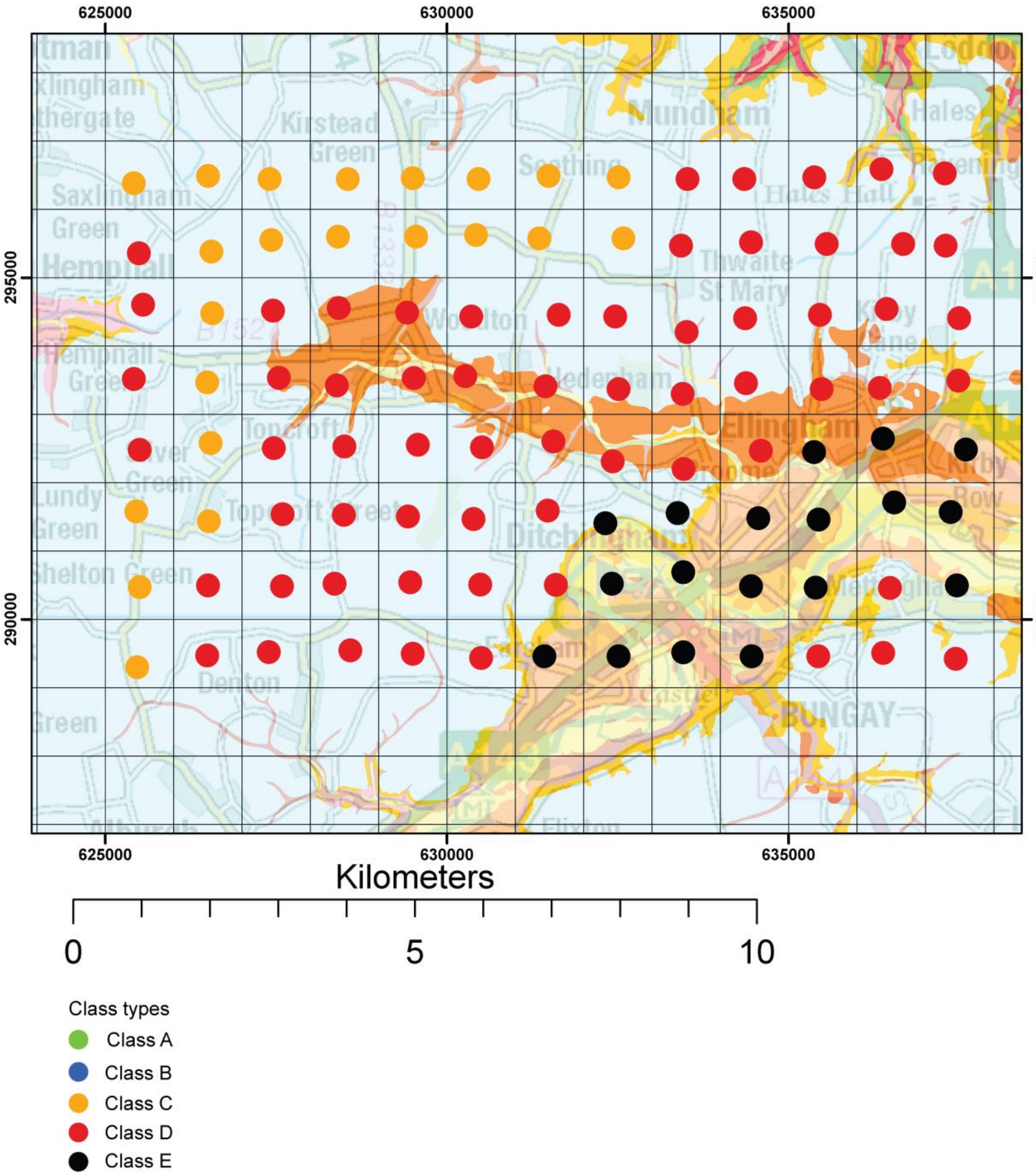

Figure 10. Application of the Hydro-JULES typology to the natural superficial deposits within the Waveney case study area. Contains Ordnance Survey data © Crown Copyright and database rights [2021]. Ordnance Survey Licence no. 100021290.

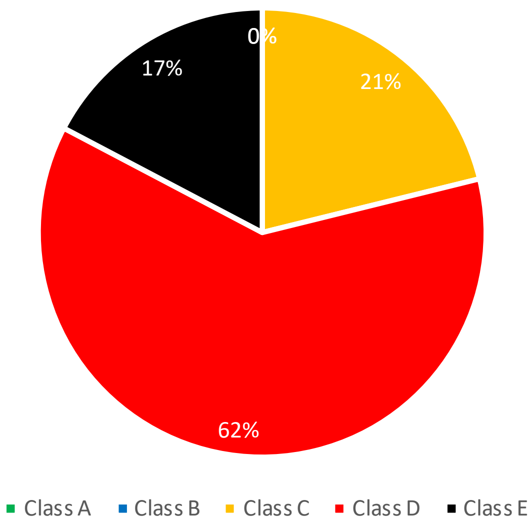

Figure 11. Summary pie chart showing the proportion of different typology classes within the Waveney case study.

The typology developed to define the natural superficial geology bedrock cover for the North Norfolk case study is shown in Figure 10 and summarised in Figure 11. Classification of the superficial geology demonstrates that bedrock does not crop-out at surface (Class A) nor is buried beneath a single higher-permeability unit (Class B) such as a single sand and gravel. Across much of the study area (62%), the bedrock geology is buried beneath higher-permeability sediments (i.e. preglacial and glacial sand and gravel) capped by low-permeability sediments (i.e. till) (Class D). In the north and west of the case study area (21%), the preglacial / glacial sand and gravel is absent from beneath the till so this sector generally falls into Class C. The southeast of the study area incorporating the

3.5 CASE STUDY 4: BRECKLAND

3.5.1 Geological Overview

The Breckland case study comprises an area of 396 km^2 centred on the Suffolk market town of Thetford. It extends northwards encompassing the village of Mundford and southwards incorporating the extensive Elveden and Euston estates. The bedrock geology of the study area is the Chalk Group, the principal bedrock aquifer of southern and eastern England. The Chalk Group occurs extensively at outcrop throughout central and eastern parts of the study area, or is overlain elsewhere by thin and / or patchy superficial deposits.

Throughout the study area, the upper horizons of the Chalk Group have undergone extensive weathering reflected prolonged Cenozoic subaerial exposure and periglacial and temperate weathering. The thickness of this weathering is spatially-variable but borehole records indicate that thicknesses of between 10-15 metres are not un-common. Within these weathering zones, the chalk is often de-structured (often resulting in reduced pore space) and evidence for dissolution (e.g. dolines, solution pipes) is common. The extent and thickness of dissolution is often greater where the chalk is overlain by permeable superficial sediments such as coversand, glaciofluvial sand and gravel and river terrace sands and gravels.

Locally, the chalk surface beneath the study area is dissected by several deeply-incised ‘tunnel valleys’. Tunnel valleys are eroded beneath glaciers by meltwater under immense hydraulic gradients. Within the study area, several occur as irregular keel-shaped (long-profile) valleys of upto 25 metre depth and 600 metre length. A more continuous deeply-incised (upto 90 metres beneath sea-level) tunnel valley occurs beneath the modern Black Bourne river between Euston and Ixworth. The infill of these valleys, whilst conventionally mapped as till, often contains highly-complex and unpredictable admixtures of till (see also Lowestoft Till), clay, sand and sand and gravel. From a hydrogeological perspective, the presence of tunnel valleys and their sediment infills typically places the chalk aquifer into direct juxtaposition with lithologies of variable permeability and this can lead to highly unpredictable and anomalous groundwater conditions.

The superficial geology is dominated by glacial deposits, that with the exception of the tunnel valleys, discontinuously drape the chalk bedrock. The Lowestoft Till occurs widely but discontinuously across the study area where it unconformably overlies the Chalk Group (Hopson and Bridge, 1987). It is a matrix-supported, highly-consolidated dark grey (weathers to brown) diamicton (a poorly-sorted admixture of sediment) dominated by clay derived from Jurassic mudstones excavated from beneath the Fen Basin to the west, and clasts including chalk and flint (dominantly) and sub-ordinate quantities of vein quartz, quartzite, Jurassic limestone, ironstone and occasional far-travelled clast types. The thickness of the Lowestoft Till varies across the study area between 1 metre (i.e. mappable) and 7-8 metre thickness. Its bulk properties imply that the unit generally has low permeability; however; the till can be heavily fractured (relating to its genesis and subsequent unloaded) with both vertical and horizontal fractures enabling enhanced groundwater mobility. Glaciolacustrine deposits cap the elevated relief to the north of Thetford and comprise upto 8 metres of stratified sand, clay and silt. They are overlain by a thin (upto 4 metres thick) sequence of glaciofluvial sands and gravels that form a highly permeable and discontinuous drape that extends partly over the chalk bedrock.

3.5.2 Hydro-JULES Characterisation

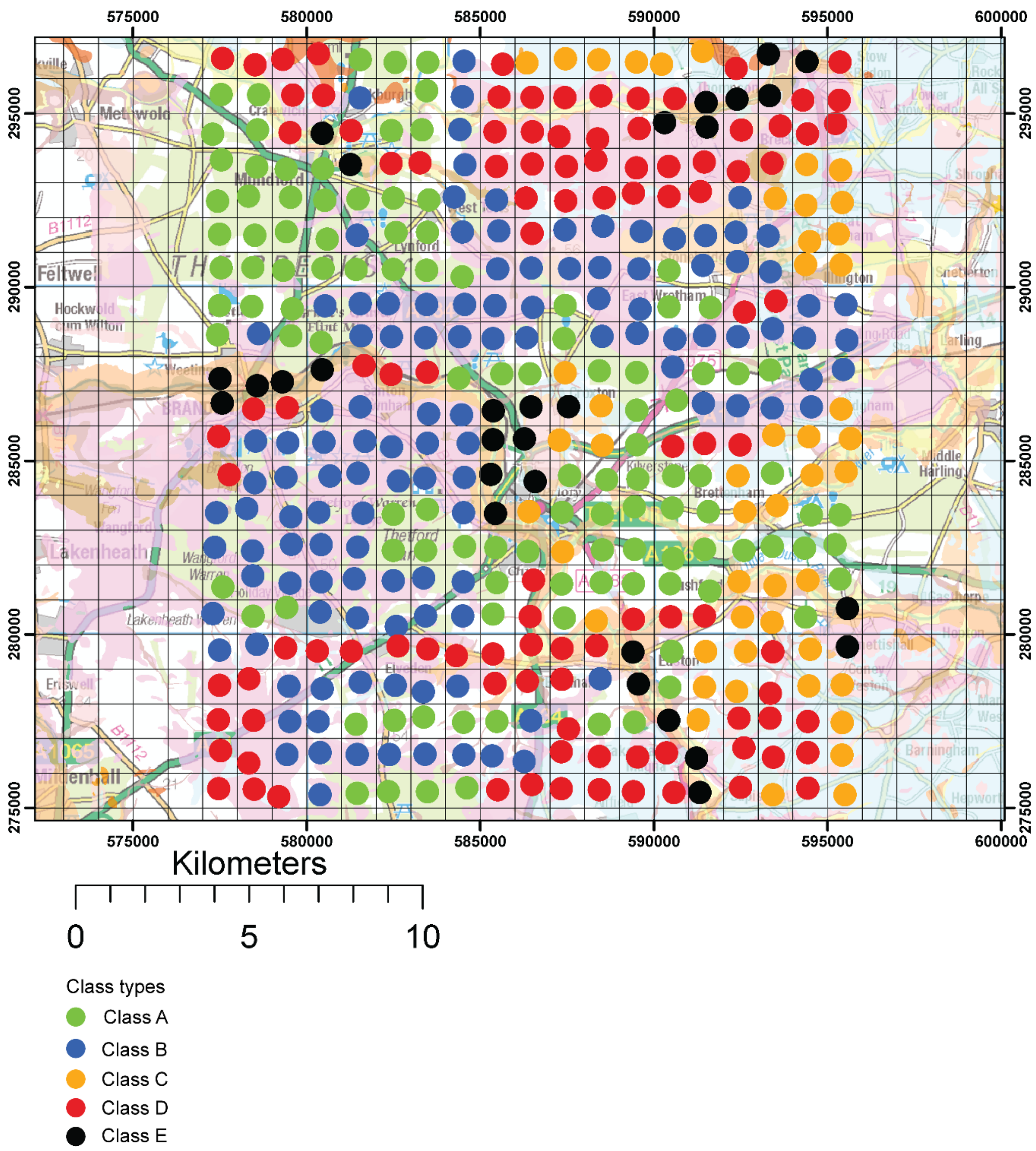

Figure 12. Application of the Hydro-Jules typology to the natural superficial deposits within the Breckland case study area. Contains Ordnance Survey data © Crown Copyright and database rights [2021]. Ordnance Survey Licence no. 100021290.

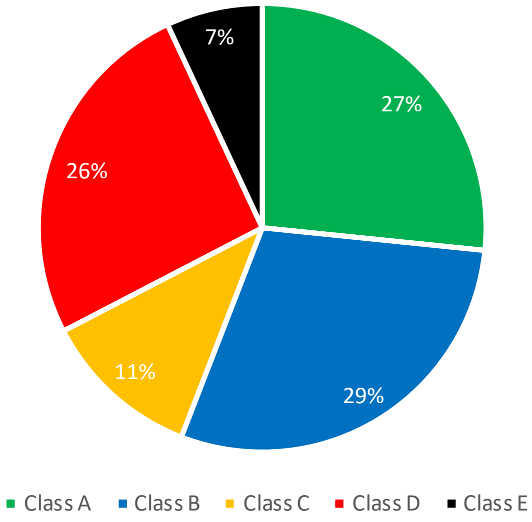

Figure 13. Summary pie chart showing the proportion of different typology classes within the Breckland case study.

The typology developed to define the natural superficial geology bedrock cover for the Breckland case study is shown in Figure 12 and summarised in Figure 13. Bedrock geology (Chalk) crops-out across 29% (Class A) of the case study area, with a further 29% concealed beneath highly-permeable (cover sand, sand and gravel) superficial cover (Class B). Key areas of enhanced aquifer vulnerability occur within the west and central parts of the case study area. Areas where the bedrock geology are concealed by a single low-permeability superficial cover unit (i.e. till) represents 11% (Class C) of the total aerial coverage and occurs in the southeast and northwest and north of the case study area. Elsewhere, 26% of the bedrock geology is concealed beneath single units of lower-permeability units overlain by high-permeability units or vice versa (Class D). Most commonly, this coincides with occurrences of sand and gravel either beneath (i.e. eastern side of area) or above (i.e. western side of area) till. 7% of the area is classified as bedrock concealed by multiple units of lower- and higher-permeability (Class E). These commonly occur locally in association with major river valleys and their complex fluvial fills (i.e. Little Ouse) or over-deepened tunnel valleys (i.e. Black Bourne). In the northeast of the case study area, an additional area classified as Class E occurs within the River Wissey at Thompson Common. Here the fluvial valley fill is further complicated by the presence of relict palsa (although often referred to – incorrectly, in this area as pingos). Palsa are a periglacial landform formed by the development of segregated ice within peat which forms low, often oval-shaped mounds. Subsequent melting of the permafrost causes the mounds to collapse forming depressions which often become lakes and ponds.

3.6 CASE STUDY 5: UKGEOS AND CHESHIRE

3.6.1 Geological Overview

Case Study 5 encompasses parts of Cheshire and northwest Wales bordering the Mersey Estuary including Ellesmere Port and Chester, extending west to Queensferry, south to Eccleston and east to Delamere. Covering an area of 440 km^2, the case study also includes the UKGEOS site at Thornton. The bedrock geology of the case study area is Permian age sandstone (Sherwood Sandstone Group) and mudstone (Mercia Mudstone Group). The Mercia Mudstone Group occurs within the southwest corner of the case study area to the west and southwest of Chester, and as localised thin north-south wedges to the east of Ellesmere Port.

The superficial geology of the case study area is characterised by glacial deposits of Late Devensian age and fluvial and estuarine deposits of Holocene age. The bedrock and superficial geology is therefore separated by a major unconformity reflecting Cenozoic exhumation and erosion of the Mesozoic bedrock. No evidence for Neogene or Quaternary climatic events prior to the Late Devensian are known to be preserved within the case study area. Nevertheless, the broader evolution of the wider region implies that the case study area has been subjected to repeated cycles of climatic and environmental change (i.e. cold, temperate, warm) and in-turn geological processes (i.e. glaciation, permafrost, tropical weathering, river activity, sea-level change) (Lee and Hough, 2017). An understanding of these processes is critical because the provide clues to how the bedrock geology may have been weathered and deformed altering its properties and behaviour. This is reflected in-part by the geometry and properties of the rockhead surface beneath the case study area which is highly-regular combined by the presence of a variably-preserved zone of weathering (a regolith or saprolite) which in places is 40 m thick (Lee and Hough, 2017). Chemical cements, particularly within the sandstone, have been partly- or wholly- removed by dissolution causing the sandstone to be heavily degraded and in places forming a loose sand (i.e. the porosity and packing of the material has been changed). The Mercia Mudstone by contrast is highly frost-susceptible so much of the upper horizons of the unit have been degraded by freeze-thaw processes causing the expansion of voids and fractures. The spatial preservation of this regolith varies across the case study area having in places been eroded by the activity of glaciers and rivers. Thus, the preserved rockhead surface is highly variable in shape and form (Burke *et al*., 2016).

Published geological maps demonstrate that this undulating rockhead relief is largely buried beneath glacial till. This till is of Late Devensian age and was laid-down partly be glaciers emanating eastwards from neighbouring North Wales, but also by a major ice stream (Irish Sea Ice Stream) that extended south-southeastwards across the area (Chiverrell *et al*., 2020). The composition and properties of the till largely reflect the local geology and the current area of sea floor within the Irish Sea which the glacier has overridden and entrained. Accordingly, the tills of the case study area are reddish brown muddy sands with or sandy muds with common pebbles of sandstone, mudstone, quartzite and more exotic lithologies but are often heavily fractured. The Irish Sea Ice Stream extended south-southeastwards across Cheshire into the Staffordshire and the West Midlands. Subglacial meltwater streams beneath the ice stream incised channels called tunnel valley into the bedrock and collectively these fan outwards from the coastline at Ellesmere Port. Tunnel valleys can have important implications for groundwater by acting as highly-localised pathways through parts of the superficial and bedrock sequences.

As the margins of the glacier retreated back across Cheshire, temporary ice-marginal still-stands developed indicated by a series of curved morainic landforms (Chiverrell *et al*., 2020). These still-stand positions represent temporary zones of traction between the glacier and its bed. Based on analogous landforms elsewhere in the UK, it is likely that enhanced ice-bed traction caused the pre-existing superficial and bedrock geology to be deformed through folding, fracturing and faulting. This type of deformation, known as glacitectonic deformation, can cause the geometry and relative juxtaposition of geological units to be dramatically altered and can form additional pathways for groundwater movement.

Since the end of last glaciation, sea-levels have risen progressively around the coastline of the UK and have resulted in the progressive drowning of the Irish Sea Basin and margins including the Mersey and Dee estuaries. Extensive areas of Holocene-age tidal flat sediments occur and are highly-complex in composition reflecting spatial and temporal variability in the palaeogeography and patterns of sedimentation (Lee and Hough, 2017). These tidal flat sediments transition upwards and landwards into alluvium reflecting sea-level change and modern land reclamation. Examination of available borehole logs demonstrate that beds of sand, silt, clay, peat and occasionally gravel occur suggesting that the hydrogeological properties of this material are likely to be variable and complex. Major tracts of alluvium occur along the river valley of the River Dee, which is superimposed upon a glacial tunnel valley (Burke *et al*., 2016). No river terraces flank the River Dee demonstrating that the modern form of the river is a relatively recent post-glacial addition to the landscape. Sediments that infill the Dee valley in general show a fining-upwards from sands and sands and gravels (immediate post-glacial and early Holocene) to sand, silts, clays and peats (recent).

3.6.2 Hydro-JULES Classification

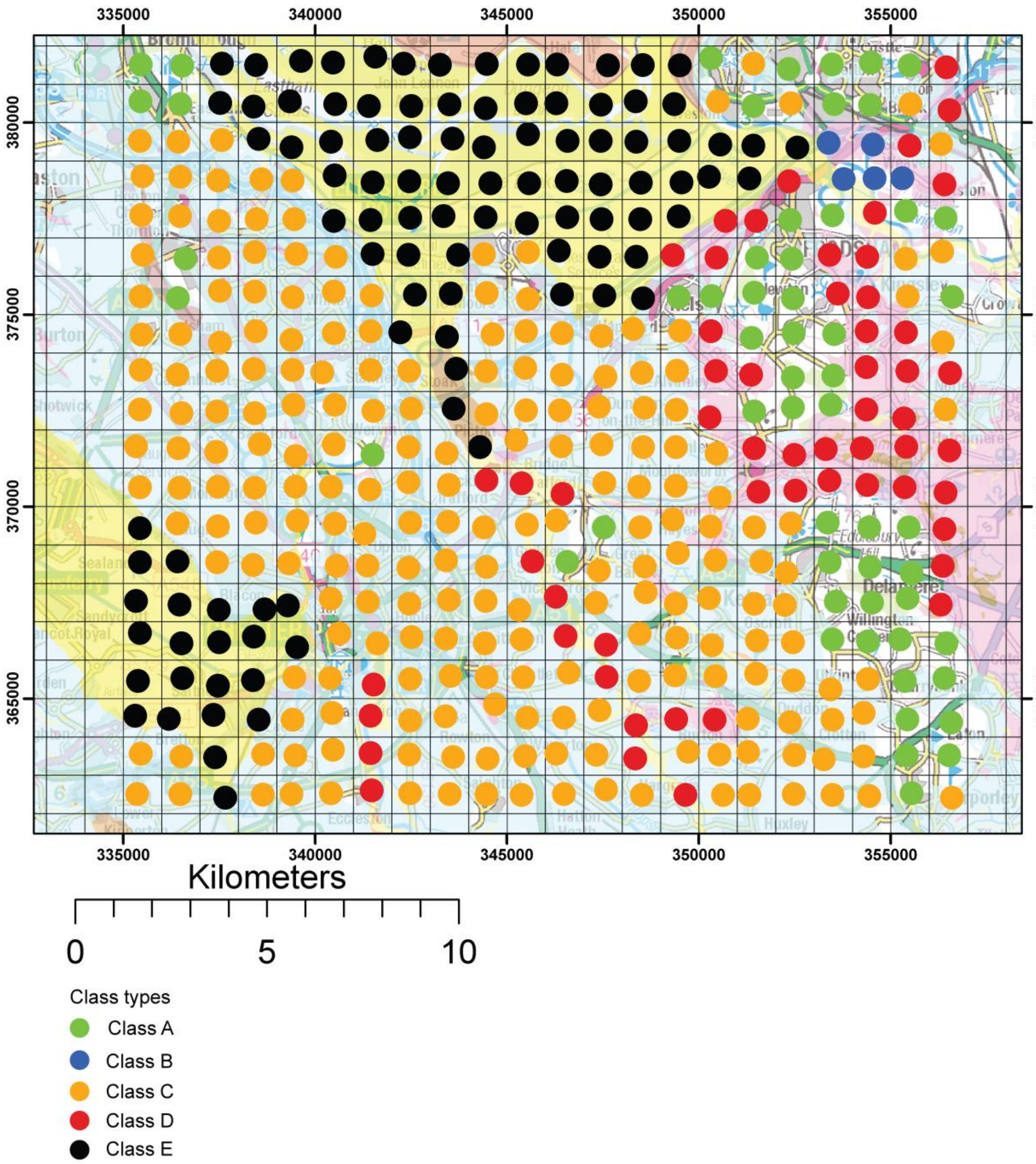

Figure 14. Application of the Hydro-JULES typology to the natural superficial deposits within the UKGEOS case study area. Contains Ordnance Survey data © Crown Copyright and database rights [2021]. Ordnance Survey Licence no. 100021290.

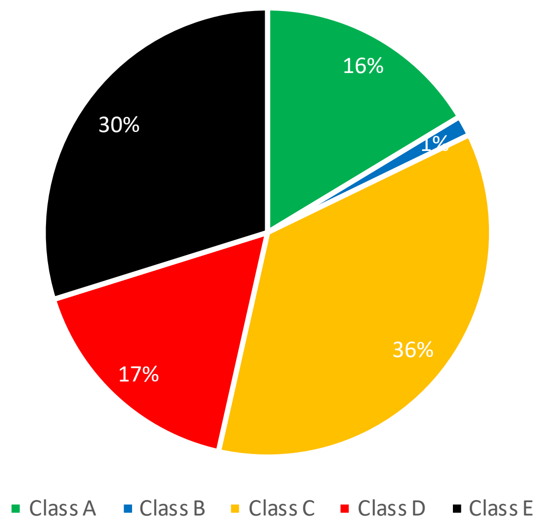

Figure 15. Summary pie chart showing the proportion of different typology classes within the UGEOS case study.

The typology developed to define the natural superficial geology bedrock cover for the UK GEOS case study is shown in Figure 14 and summarised in Figure 15. Bedrock geology (Class A), Sherwood Sandstone Group, crops-out at the land surface across 16% of the case study area – mainly, but not exclusively, in the eastern of region. Burial of the bedrock by a single higher-permeability (sand and gravel) (Class B) occurs across only 1% of the case study area in a small zone around Frodsham. Throughout the majority of the case study area, bedrock is overlain by lower-permeability units (36%, Class C), namely till. 17% of the case study area incorporates areas where both single higher- and lower-permeability units occur in superposition overlying bedrock (Class D). This relationship is evident along the main river valley of the River Dee and more commonly, in the east of the case study area, where glacial sand and gravels overlies till. Zones where multiple layers of lower- and higher-permeability superficial geology occur in superposition (30%, Class E) include areas of tidal flat sedimentation including the Mersey and Dee estuaries.

3.7 CASE STUDY 6: EDEN VALLEY

3.7.1 Geological Overview

Case Study 6 covers an area of approximately 517km^2 within the Eden Valley, Cumbria between Wetheral (northwest), Cumrew (northeast), Melmerby (east) and Penrith (south). The bedrock geology of the study area is characterised by Carboniferous to Triassic age sedimentary rocks that strike broadly north-northwest to south-southeast. Carboniferous-age rocks underlie the western part of the case study area comprising beds of mudstone, limestone and sandstone which form the Yoredale Group (Stainmore Formation and Alston Formation). These rocks pass eastwards into the Pennine Coal Measures Group, composed of mudstones, siltstones and sandstones. Permian and Triassic bedrock units form a sub-crop and localised outcrop through the central and eastern parts of the case study area. The Penrith Sandstone Formation (Permian) forms a broad sub-crop, 6-8 km wide, extending northwards from Penrith and constitutes a major groundwater aquifer. The sandstone is overlain to the east by the Eden Shales Formation (Cumbrian Coast Group), and along the western margins of the case study area, by a second major groundwater aquifer the Early Triassic Chester Formation sandstone. Carboniferous, Permian and Early Triassic sediments are deformed by extensive large-scale normal faulting which forms part of the Pennine Fault System.

The Eden Valley has a complex Quaternary history although only the recent geology from the past 25 ka years such that a major unconformity therefore exists between the bedrock and Quaternary. Given the known climate history of the UK over the past 3 million years, it is anticipated that much of the uppermost bedrock has been highly-weathered probably resulting in the breakdown of chemical cements and the development of fractures. The preservation of this weathered zone is unknown but comparison with analogous areas of bedrock geology suggest that several tens of metres of weathering could in theory be present. However, the low mechanical durability of this weathered zone makes it susceptible to erosion by fluvial and glacial processes so its presence is likely to be highly-discontinuous - if preserved. Prior to 25 ka years ago, the Eden Valley is likely to have formed a prominent river valley draining the eastern Lake District and northwest Pennines northwards towards the Solway. The Eden Valley is also likely to have been previous glaciated, particularly during the Anglian Glaciation and other significant glacial events, although there is no clear geological evidence to validate this.

During the Late Devensian glaciation (c. 25-17 ka), the Eden Valley was glaciated on several occasions by glaciers emanating from dispersal centres in the Southern Uplands and later by a glacier from the Lake District. This means that the Eden Valley was glaciated initially by ice flowing from north and south and subsequently from south to north (Livingstone *et al*., 2010). This rather unique glacial context reflects the progressive evolution of the main ice accumulation centres for the Last British-Irish Ice Sheet in northern England and southern Scotland during the Late Devensian – specifically the purging of ice from the Southern Uplands and the collapse of major ice divide which led to the development of independent valley glaciers in the Lake District (Livingstone *et al*., 2012).

Much of the surficial glacial geology corresponds to this latter phase of the glaciation and the northwards-directed flow of glacier ice towards the Solway Lowlands and its subsequent retreat and mass-wastage. Much of the surficial geology in the Eden Valley is mapped as 'till', with localised 'glaciolacustrine' deposits exposed in river cuttings and the sequence capped by a discontinuous drape of sand and gravel. This description is likely to be a highly-simplified representation of the geology and in reality, the till is probably highly heterogeneous containing localised inclusions of sand, sand and gravel and silt and clay. The style of mass-wasting (i.e. collapse of the glacier) is likely to have led to the development of 'buried ice' where successive glacier snouts are abandoned due to the speed of ice-marginal retreat and buried by glacial outwash sand and gravel. Subsequent melting of this 'dead ice' produced localised inversion (subsidence) of the landscape and the development of a 'kettle hole' (egg box) relief. Although evidence for much of this 'kettle hole' relief within the landscape has degraded, in cross-section it is likely that a marked lithological and structural heterogeneity exists within the sands and gravels with localised basins (metres to a few tens of metres scales) probably containing fine-grained (i.e. silt and clays) and peat infills.

3.7.2 Hydro-JULES Classification

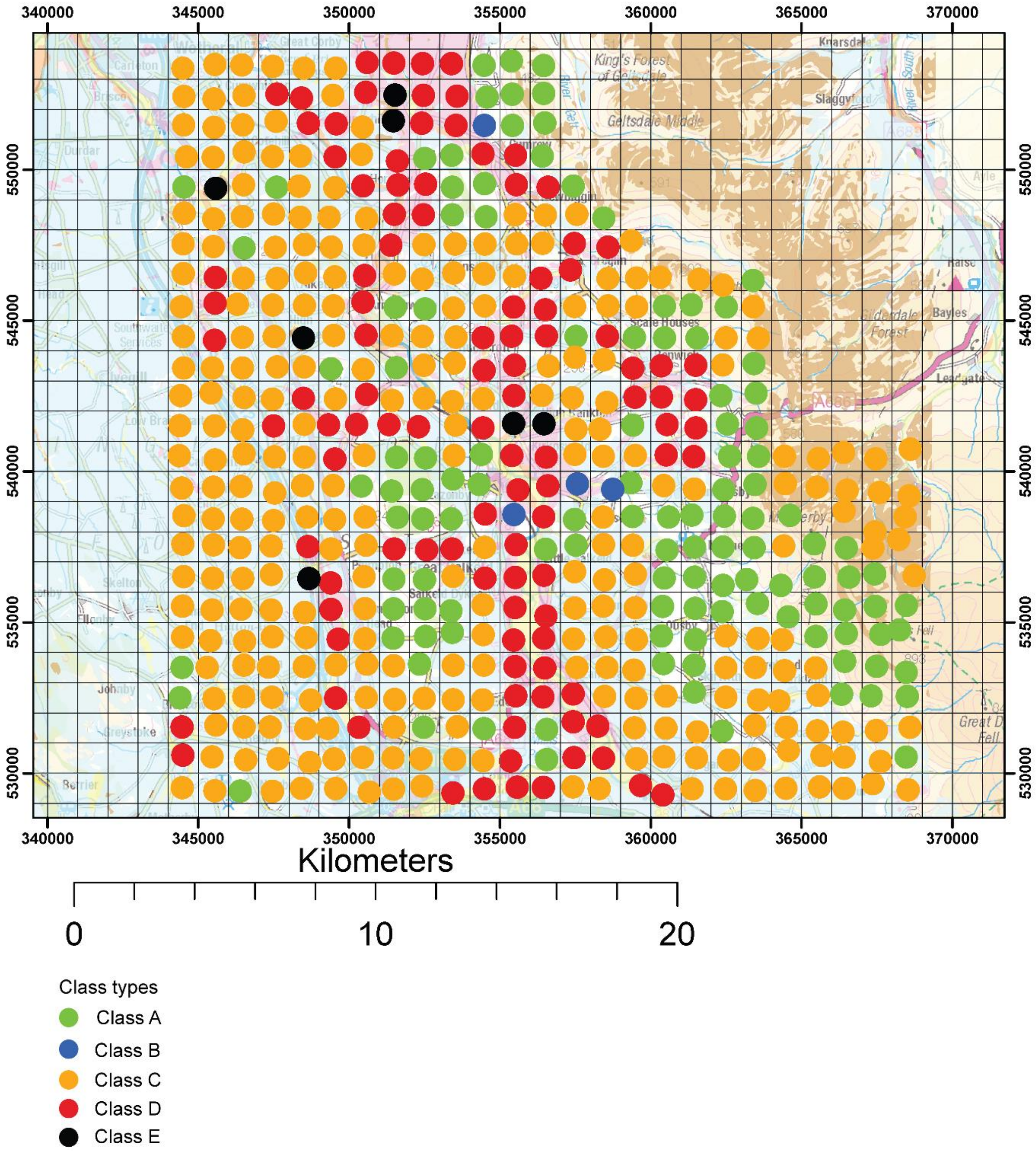

Figure 16. Application of the Hydro-JULES typology to the natural superficial deposits within the Eden Valley case study area. Contains Ordnance Survey data © Crown Copyright and database rights [2021]. Ordnance Survey Licence no. 100021290.

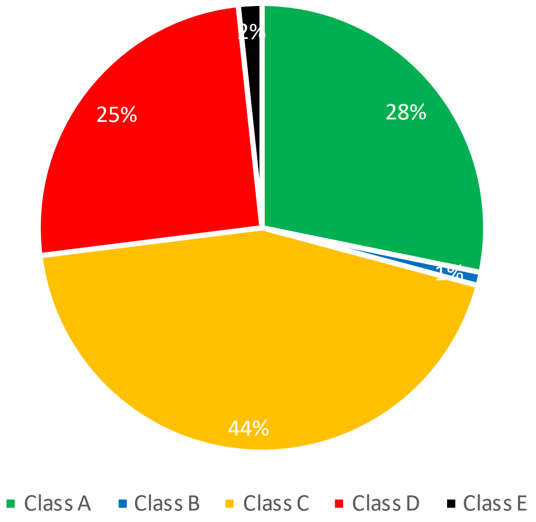

Figure 17. Summary pie chart showing the proportion of different typology classes within the Eden Valley case study.

The typology developed to define the natural superficial geology bedrock cover for the Eden Valley case study is shown in Figure 16 and summarised in Figure 17. Bedrock geology (Class A), including sandstone, mudstone and limestone, crops-out at the land surface across 28% of the case study area. This occurs mainly in the eastern part of the case study are forming an area of undulating relief. Burial of the bedrock by a single higher-permeability (sand and gravel) (Class B) occurs across only 1% of the case study area in two small zones around Cumrew (north) and Gamblesby (south). Throughout the majority of the case study area, bedrock is overlain by lower-permeability units (44%, Class C), namely till and glaciolacustrine deposits. 25% of the case study area incorporates areas where both single higher- and lower-permeability units occur in superposition overlying bedrock (Class D). This relationship occurs predominantly adjacent to the River Eden with fluvial and outwash sands and gravels overlying till. Zones where multiple layers of lower- and higher-permeability superficial geology occur in superposition (2%, Class E) include areas where fluvial sands and gravel / alluvium occur in association with glacial outwash sands and gravels, till and glaciolacustrine deposits.

The classification reported here was based principally upon the published geological map. However, it is likely that this dataset under-represents the heterogeneity of the geology and Classes E should be considerably higher relative to Class C. The availability of additional borehole data and geophysics would help to conceptualise and characterise the geology more effectively.

4 Observations and recommendations

- The methodology outlined within Section 2 for classifying the natural superficial geology was successfully applied to six case studies across England (Section 3), selected to provide a broad spatial spread and geological diversity. Application of the methodology was relatively quick and straight-forward and could with relative ease be applied across the UK. However, this is not an automated process and would require a team of geologists to manually populate the UK grid at the required 1 km^2 scale. This roll-out would require a team of geologists with suitable understanding of the UK Quaternary. This could be more easily and efficiently be facilitated by utilising the UK Quaternary Domains classification (Booth *et al*., 2015) classification to sub-divide the UK into more manageable segments.
- The five classes (A-E) deployed within the methodology provide a qualitative measure of the complexity of the superficial geology between geological rockhead (top bedrock surface) and the ground surface. To be fully incorporated into the Hydro-JULES model, this qualitative dataset could be reattributed with basic quantitative hydrogeological information to enable numerical parameterisation.
- This methodology focuses purely upon the geological complexity within the natural superficial deposits. The basic hydrogeological properties of the bedrock (at rockhead) are not included within the methodology but are required for the broader Hydro-JULES model and will effectively enable the natural superficial geology and its hydrogeological properties to be coupled to the bedrock geology.
- Within the descriptions of the natural superficial geology of the individual case studies, it is evident from borehole records that much of the upper horizons of bedrock exhibit varying degrees of weathering. Weathering is significant because it alters the geological and hydrogeological properties of the bedrock by altering its composition (in some instances), pore-space (i.e. removal or generation of chemical cements) and structure (i.e. closing or infilling of fractures, development of new fractures). Its thickness and preservation vary across the UK reflecting the longer-term (Cenozoic and Quaternary) landscape history and especially the influence of glaciation and rivers which can readily erode this material, but weathering thicknesses of upto 80 m are not uncommon (Hall, 1985). Major aquifers including the Chalk Group (Mortimore, 2014) and Sherwood Sandstone often exhibit deep weathering profiles, whilst major aquitards (i.e. mud rocks) are highly frost-susceptible and prone to mechanical failure (i.e. fracturing). Studies to investigate the spatial extent and thickness of this weathered zone could help develop a more robust geological model by including the ‘transition zone’ between the natural superficial and bedrock geology.

5 Conclusions

- This report documents a semi-conceptual approach to characterising the natural superficial geology above bedrock at 1 km^2 resolution. This classification can be translated into numerical hydrogeological values and used to generate a numerical groundwater model – one of the required outputs of the NERC-funded Hydro Joules project.
- The semi-conceptual approach utilised published geological map information but also utilises borehole information (where available) and tacit knowledge to enhance the characterisation. This is important because a geological map only records the top 1m of the geological column but for the context of the downstream hydrogeological model, needs a more complete characterisation of the vertical natural superficial column down to bedrock.
- The approach has been trialled in 6 areas of lowland England: (1) Surrey; (2) North Norfolk coast; (3) Breckland; (4) Waveney Valley; (5) UK GEOS and parts of adjacent Cheshire; and (6) Eden Valley in Cumbria. Each case study area was carefully selected to test the approach relative to different types and complexities of natural superficial geology.
- Outputs for each of the 6 case study areas are shown within the report and are available as GIS shapefiles. The approached worked well and was relatively simple to apply in 5 of the 6 case study areas (1-5). However, in the Eden Valley, the characterisation is considered to under-represent the true geological complexity. This reflects a combination of the paucity of information available to help qualify the interpretation, but also the coarse scale of the exercise (1 km^2) relative to the scale of geological complexity (m-scale).
- A robust geological model is needed to underpin and give integrity to the Hydro-JULES hydrogeological model. Any robust coupled geological model that covers the geology between the ground surface and our major groundwater aquifers at depth needs to encompass the natural superficial geology, the bedrock geology and the transition zone (i.e. the zone of weathering) between the two. This report highlights a methodology for characterising the natural superficial geology for the Hydro-JULES model. However, it is recommended that similar datasets are required to characterise the bedrock geology (at rockhead) and the weathered transition zone.
- Several recommendations are made for up-scaling the current methodology to enable full UK coverage of the natural superficial geology.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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