Permeability classification for UK Natural Superficial Deposits - a Hydro-JULES dataset

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J R Lee

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Executive Summary

This report describes the outputs of a work package which forms part of the NERC-funded Hydro-JULES project. One of the core outputs for the Hydro-JULES project is a km-scale national hydrogeological model that couples the ground surface to the bedrock. Part of this geological column, which occurs between the ground surface and the bedrock surface (rockhead), is the natural superficial geology or the geology that formed during the current geological period – the Quaternary (0 to 2.6 Ma). Characterising the natural superficial geology for the purposes of the national hydrogeological model is challenging. This is due in-part to the spatial complexity of this part of the geological record, but also the quality of published geological map data (superficial) which is variable reflecting the historical legacy (150 years) of Quaternary understanding, data capture and mapping approaches.

To overcome these issues and produce a national-scale dataset that is relevant to the hydrogeological model, a holistic approach was undertaken to characterise the natural superficial geology. This approach utilised published geological map data (superficial), together with other surface (aerial photography, digital terrane models) and sub-surface (borehole records, superficial thickness model) information, combined with tacit knowledge of geological processes and events that have occurred in the UK during recent Earth History. This semi-predictive approach therefore combines observations and tacit knowledge to inform the characterisation. The characterisation of the natural superficial deposits is shown as a relative measure of permeability based upon the interpreted vertical stack of different geological units and lithologies between the ground and bedrock surface. The primary outputs are a series of gridded GIS data layers which can be enhanced with numerical hydrogeological attributes to underpin future numerical modelling.

Within this report, a brief overview of the aims of the study and methodology are presented together with a brief description of the results. Key assumptions in the interpretation and areas of uncertainty within the final dataset are also discussed. For further information on the scope of the study and methodology – including testing of the approach in six case study areas, readers are directed to a companion report (Lee, 2021).

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 natural superficial geology. Spatial understanding of the natural superficial geology of the UK is highly variable, reflecting the legacy of geological mapping over the past 150 years and the inherent differences in accuracy, precision and underpinning scientific assumptions. In addition, geological maps conventionally record the uppermost superficial geology and do not communicate the heterogeneity of the superficial geology or the nature of this geology at depth. These limitations impact our understanding of the spatial complexity of the superficial geology and derived datasets such as a hydrogeological model.

To help overcome this challenge, this component of the Hydro-JULES projects aims to characterise the natural superficial geology of the UK between the bedrock (rockhead) and ground surfaces. A methodology and rational was developed within a previous report (Lee, 2021a) and applied to six case study areas which collectively encompass many different aspects of the UK superficial geology. The approach utilises a combination of published geological map data, supplemented by borehole data and tacit knowledge of regional history and known events / processes to either infer or predict the nature of the geological column between rockhead and the ground surface (Lee, 2021). For the purpose of this exercise, the data has been captured as a 1 km^2 resolution grid across mainland UK and converted into a relative permeability class. The purpose of this report is to summarise the findings of the UK-wide dataset and also to outline some of the key assumption and limitations of the approach.

2 Permeability Categories

2.1 INTRODUCTION

The concept of ‘permeability classes’ was introduced by Lee (2021) to classify the UK natural superficial deposits for the purposes of the Hydro-JULES research programme. It adopts a semi-predictive approach for characterising the dominant natural superficial geology (where that information is lacking from published geological map data) and communicates this in terms of a five-fold relative permeability classification.

Attribution of this relative permeability classification is undertaken primarily through the utilisation of surface (published 1:50,000 geological maps) geological map data supplemented with additional surface (aerial photographs, digital terrain models) and sub-surface data (borehole records, superficial drift thickness model) and tacit knowledge (Lee, 2021).

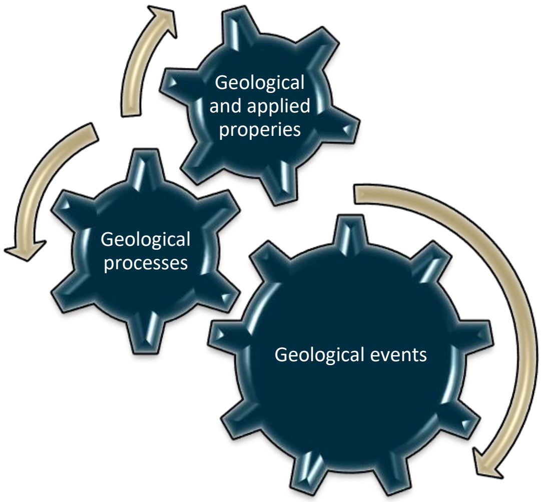


Figure 1. A conceptual ‘Earth Systems’ approach to geology whereby the three components are interdependent. This effectively means that by understanding the underpinning processes (or properties) of one component within its regional context, it should be possible to predict the other two components. 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. Figure from Lee (2021).

The use of tacit knowledge based upon an understanding of recent geological processes and UK Earth History enables the geologist to infer or predict the superficial geology in areas where data is limited or of poor quality. The approach embraces the philosophy of the ‘glacial landsystems’ concept whereby specific glacial events drive a predictable set of glacial processes, which in-turn, produce a predictable geological and geomorphological signature within the landscape and vice-versa (Evans and Rea, 1999; Evans, 2003; Benn and Evans, 2014). Within this study, the ‘landsystems’ concept is applied more holistically to the broader superficial geology of the UK whereby a specific event in recent Earth History drives a predictable set of geological processes, which in-turn produce a predictive geological and geomorphological signature within the landscape and vice versa (Figure 1) (Lee, 2021).

The application of this type of semi-predictive conceptual approach to characterising the superficial geology and identifying potential geological risks has been previously applied at a site scale (Lee and Hough, 2017) and is recommended for ground investigations where the site has been impacted by periglacial (Murton and Ballantyne, 2017) and glacial (Evans, 2017) processes.

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 1. Overview of the typology employed for characterising the natural superficial geology.

A basic five-fold typology (Classes A-E) was introduced by (Lee, 2021) to characterise the relative permeability of the natural superficial deposits based upon their bulk geological properties (Table 1). This has been applied across mainland England, Wales and Scotland at 1 km^2 resolution based upon the dominant natural superficial geology within that square. Class A is defined as where bedrock crops-out at the ground surface. Class B occurs where the bedrock is concealed by higher permeability superficial deposits such as sand and sand and gravel. Class C relates to where bedrock is concealed by a lower permeability superficial deposits such as a till or silt and clay. Class D describes occurrence of the bedrock being concealed by both lower and higher permeability units in any superpositional order, such as sand and gravel overlying clay or vice versa. Class E comprise zones of highly-complex superficial deposits where the lithology / permeability and degree of heterogeneity cannot be reconstructed with a high level of accuracy or precision. This includes thick, heterogeneous sequences composed of contrasting sediment type and zones where the superficial deposits may be structurally deformed, encompassing complex and unpredictable relative juxtapositions of sediment types and / or the presence of structures such as fractures, faults and folds that may influence groundwater behaviour.

2.2 UTILISED DIGITAL DATA

A range of digital datasets were used in the compilation of this dataset (Table 2) both to directly influence attribution and to underpin the tacit decision-making process. The baseline dataset was DigMapGB-50 (1) which provided information of the surficial geology. The Super Thickness Model (3) and Buried Valleys (4) provided basic information on the spatial distribution of thickened superficial succession, where the Single Onshore Borehole Index (2) was then helped to characterise the vertical succession. A Digital Terrain Model (5) and aerial photograph (6) licenced to BGS were also utilised to refine interpretations and help infer the geology (in combination with 2, 3, 4 and tacit knowledge) where DiGMapGB-50 coverage was of poor quality or provided limited information on the 3D geology.

DATA SET		SOURCE	ACCESS
1	DiGMapGB-50 v8, superficial geology	https://www.bgs.ac.uk/datasets/bgs-geology-50k-digmapgb/	Open
2	Single Onshore Borehole Index (SOBI)	https://www.bgs.ac.uk/datasets/boreholes-index/	Open
3	Superficial Thickness Model	https://www.bgs.ac.uk/datasets/superficial-thickness-model/	Open
4	Buried Valleys	https://www.bgs.ac.uk/datasets/buried-valleys/	Open
5	Bluesky Digital Terrain Model, 5m, v1.5	Bluesky	Licence
6	Aerial photographs	APGB_RGB_12.5cm	Licence

Table 2. Datasets used in the generation of this Hydro-JULES dataset.

2.3 LIMITATIONS AND UNCERTAINTIES

This dataset is underpinned by several pre-existing datasets and tacit knowledge. Whilst care has been taken to ensure that the dataset has been interpreted consistently and objectively using the best available data, information and knowledge, inherent limitations and uncertainties do exist and these are outlined below.

- The dataset was completed for mainland areas of the UK and large islands where modern geological data existed. Owing to the paucity of data, the Outer Hebrides, Orkney and Shetland Islands were not included.
- The quality and precision of superficial data within DiGMapGB-50 v8 is variable reflecting the historical legacy of the underpinning data and primary 1:50,000 map compilation. The data is based on maps published between 1870-2020 and accordingly there is considerable variation in the survey methods employed, the quality of the topographic base and broader Quaternary understanding together. In very general terms, data that was published after WW2 tend to have greater accuracy and precision than earlier maps because data capture was enhanced by the use of aerial photography and better-quality topographic bases. Similarly, the quality and precision of data is even higher for data published after c.2000, because linework was enhanced by the use of digital elevation models (DEMs).
- There is considerable inconsistency in the type of superficial geology recorded on published 1:50,000 map sheets and within DiGMapGB v8, reflecting the different aims and scope of individual mapping projects and the variable application of the '1 m rule' (the minimum mappable thickness of units). Most commonly, these issues are reflected in how some types of geology were under recorded, for instance residual materials (e.g. saprolite and weathered bedrock), slope deposits (so-called 'head' and 'colluvium'), windblown sediments (e.g. loess and coversand), peat and alluvium.
- In some parts of the UK, glacial deposits have also been generalised and grouped together as high-level 'morpho-genetic units' (e.g. 'glacial deposits', 'till and morainic deposits') which do not lend themselves to lithological (and permeability) characterisation. In these situations, assumptions are made about the lithological and permeability properties informed by 'text book properties'. Such assumptions, where made, are outlined within the various classes below.
- Boreholes are used to inform the grid attribution where geological map quality is deemed poor, to help characterise specific units and to better understand the superficial geology at depth. However, the distribution of boreholes across the UK is variable, with greatest concentrations occurring in urban areas, along transport corridors and associated with large infrastructure. In rural and upland areas, by contrast, the density of boreholes can typically be very low.
- The development of a saprolite or weathering profile within the uppermost bedrock can also impact its hydrogeological properties including permeability. In the UK, the long-term drivers of weathering that have operated during the Cenozoic are increasingly understood. However, the spatial extent and variability of weathered bedrock remains poorly constrained and documented in only local-scale studies and inconsistently on published geological maps (Lee, 2021). Accordingly, the impact of weathering is not considered within this dataset.

3 Permeability Classification

Within this section of the report, the five relative permeability classes (Classes A-E) are outlined with a particular focus on how the classes are defined, any underpinning assumptions and a brief description of their distribution.

3.1.1 CLASS A

3.1.1.1 Classification and Assumptions

Class A corresponds to areas of where *in situ* bedrock crops-out at the ground surface and is the dominant characterisation within a grid square. According to this definition, the bedrock will have either no or a very thin (i.e. sub-mapping scale) superficial sediment cover. No attempt has been made within this dataset to characterise the type of bedrock or its permeability.

The apparent distribution of ‘rock at surface’ (see 3.1.1.2) across the UK is likely to be an over-representation (c.10-25%) of the real situation and this is especially the case in several non-glaciated and upland areas. In non-glaciated areas such as Cornwall and Devon, the bedrock surface is likely to be extensively mantled by a variable veneer of saprolite (*in situ* weathered bedrock) and on the lower concave parts of hillslopes by colluvium (weathered bedrock that has moved downslope under gravity). Similarly, in upland areas of Wales, Scotland and northern England, the bedrock is likely to be partly covered by veneer of saprolite, colluvium and till (derived from the saprolite).

3.1.1.2 Distribution

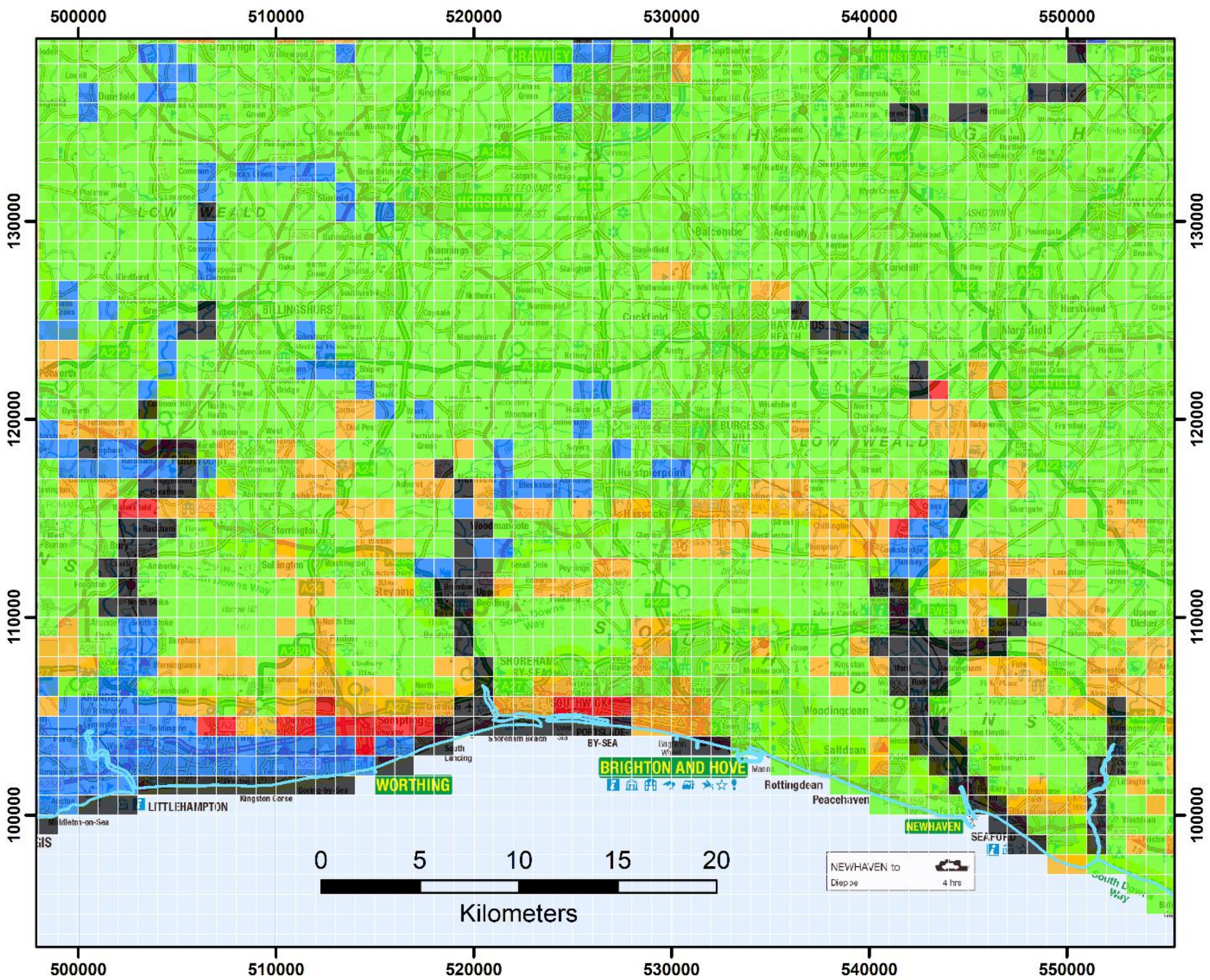


Figure 2. An example output from the superficial geology Hydro-JULES dataset for parts of Sussex. The dataset demonstrates that bedrock (Class A, green) crops-out at the ground surface across much of the

area. Bedrock is locally concealed beneath sands and gravels (Class B, blue) that correspond to modern and relict ‘river terrace deposits’ including extensive deposits of the relict Pleistocene ‘Solent’ river system which occur in the vicinity of Worthing and Littlehampton. In places, ‘clay-with-flints’ and ‘head’ form areas where the bedrock is concealed beneath lower permeability (Class C, orange) geology. The small number of Class D (red) areas correspond to areas where ‘head’ overlies ‘river terrace deposits’ giving rise to lower permeability overlying higher permeability geology. The Class E (black) attributed squares equate to areas of ‘alluvium’ in river valleys and ‘tidal flat deposits’ fringing parts of the coastline that possess a complex and heterogeneous geology. Contains Ordnance Survey data © Crown Copyright and database rights [2021]. Ordnance Survey Licence no. 100021290.

Class A occurs across 94,114 km^2 tiles of mainland England, Wales and Scotland, 40.9% of the total 1 km^2 national grid squares (Appendix 1). It occurs widely across western Scotland, Southern Uplands, Pennines, Wales, southern and southwest England. A typical example of an area where Class A attributed grid squares occur extensively is shown for Sussex in Figure 2.

3.1.2 Class B

3.1.2.1 Classification and Assumptions

Class B corresponds to where *in situ* bedrock is concealed beneath a mappable veneer of higher permeability sediment (e.g. sand, sand and gravel).

It has been assumed that Mapped superficial unit types that fall into the classification by way of their lithological properties include: ‘blown sand’, ‘talus’, ‘beach deposits’, ‘marine beach deposits’, ‘raised beach deposits, ‘alluvial fan deposits’, ‘river terrace deposits’, ‘glaciofluvial deposits’, ‘glaciofluvial ice contact deposits’.

3.1.2.2 UK Distribution

Class B occurs across 12,059 km^2 tiles of England, Wales and Scotland, 5.2% of the total 1 km^2 national grid squares (Appendix 2). Much of the occurrence of this permeability classes is associated with river terrace deposits that directly rest upon bedrock and these occur predominantly across parts of southern, central and eastern England and Wales. In Scotland, occurrence of this class typically relates to the talus (in upland areas) and around the coast by marine beach (modern) and raised beach (relict) deposits.

3.1.3 Class C

3.1.3.1 Classification and Assumptions

Class C corresponds to where *in situ* bedrock is concealed beneath a mappable veneer of lower permeability sediment that are rich in silt and clay.

It is assumed in this dataset, that that lower permeability materials which fall into this category are rich in silt and clay and typically includes ‘till’, ‘lacustrine deposits’, ‘glaciolacustrine deposits’, ‘head’ and ‘clay-with-flints’. Note that peat has previously been highlighted as a material with very low to low permeability (cf. Lewis et al., 2006) but typically this only relates to peats with a very high carbon content. More commonly, peats in the UK tend to have a variable carbon content reflecting their presence as lenses within other types of stratified inorganic sediment (e.g. till, sand and gravel, silt and clay, ‘talus’). As such peat is included within Class E rather than Class C.

The apparent distribution of lower permeability attributed grid squares is inferred to be an under-representation (c.10-25%) of the real situation. This largely reflects the over-representation of ‘rock at surface’ (i.e. Class A) on published geological maps and the under recording of slope deposits (colluvium) and till.

3.1.3.2 UK Distribution

Class C occurs across 60,506 km^2 tiles of England, Wales and Scotland, 26.3% of the total 1 km^2 national grid squares (Appendix 3). The greatest distribution of Class C attributed grid squares occurs to the north of the Late Devensian ice limit indicating the strong influence of till and to a lesser extent glaciolacustrine deposits on the spatial coverage. To the south of the Late Devensian ice limit, the occurrence of Class C attributed grid squares is more limited but linked to the occurrence of preserved remnants of older glacial tills, slope ('colluvium') and residual deposits such as clay-with-flints.

The paucity of Class C grid squares in northwest and west Scotland is considered to be a significant underestimation and a consequence of the grouping of all glacial deposits into a single category on published geological maps.

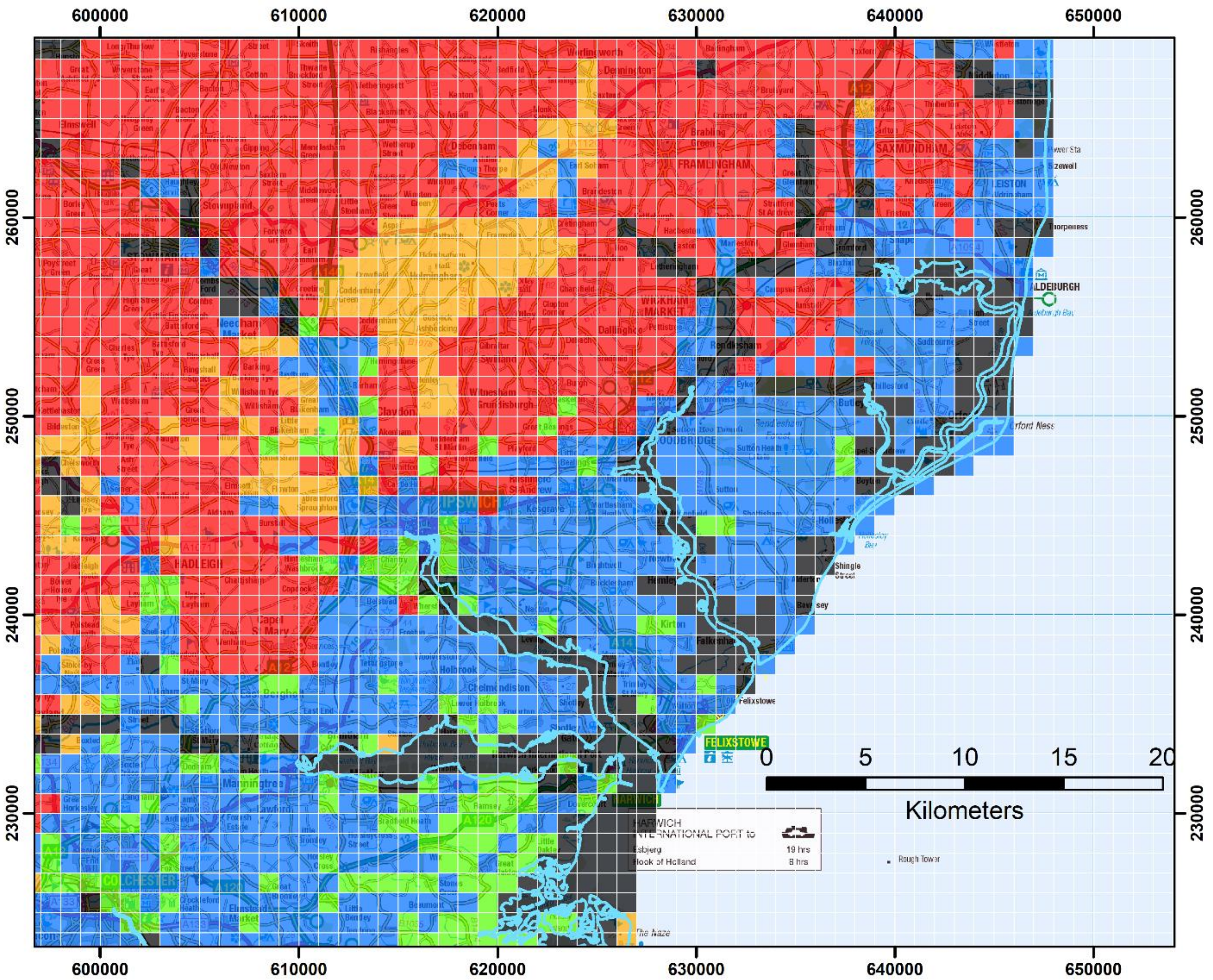


Figure 3. An example output from the superficial geology Hydro-JULES dataset for parts of northern Essex and southern Suffolk demonstrating the relationship between Class B, C and D. Class B (blue) coded grid squares correspond to areas of bedrock overlain by higher permeability 'river terrace deposits' laid-down by ancestral (preglacial) River Thames. The superseding lower permeability glacial till was deposited extensively across the north and northwest of the area. Where this glacial till overlies the river terrace deposits, it forms the extensive areas attributed as Class D (red) where both lower and higher permeability units occur in superposition. Where the river terrace deposits have been removed by erosion and the glacial till (lower permeability) rests directly on the bedrock, this zone has been classified as Class C. Contains Ordnance Survey data © Crown Copyright and database rights [2021]. Ordnance Survey Licence no. 100021290.

3.1.4 Class D

3.1.4.1 Classification and Assumptions

Class D occurs where *in situ* bedrock is concealed beneath both single lower and higher permeability layers in superposition. No distinction is made between lower permeability overlying higher permeability units or vice versa.

It is assumed that Class D corresponds to occurrences of 'till' or 'glaciolacustrine deposits' overlying or underlying sand and / or sand and gravel (e.g. 'river terrace deposits', 'glaciofluvial deposits', 'raised beach deposits' or 'talus').

3.1.4.2 UK Distribution

Class D occurs across 14,471 km^2 tiles of England, Wales and Scotland, 6.3% of the total 1 km^2 national grid squares (Appendix 4). The most common occurrence of Class D occurs within former ice-marginal areas and is associated with till occurring in juxtaposition with either river terrace deposits or glaciofluvial deposits (Figure 3).

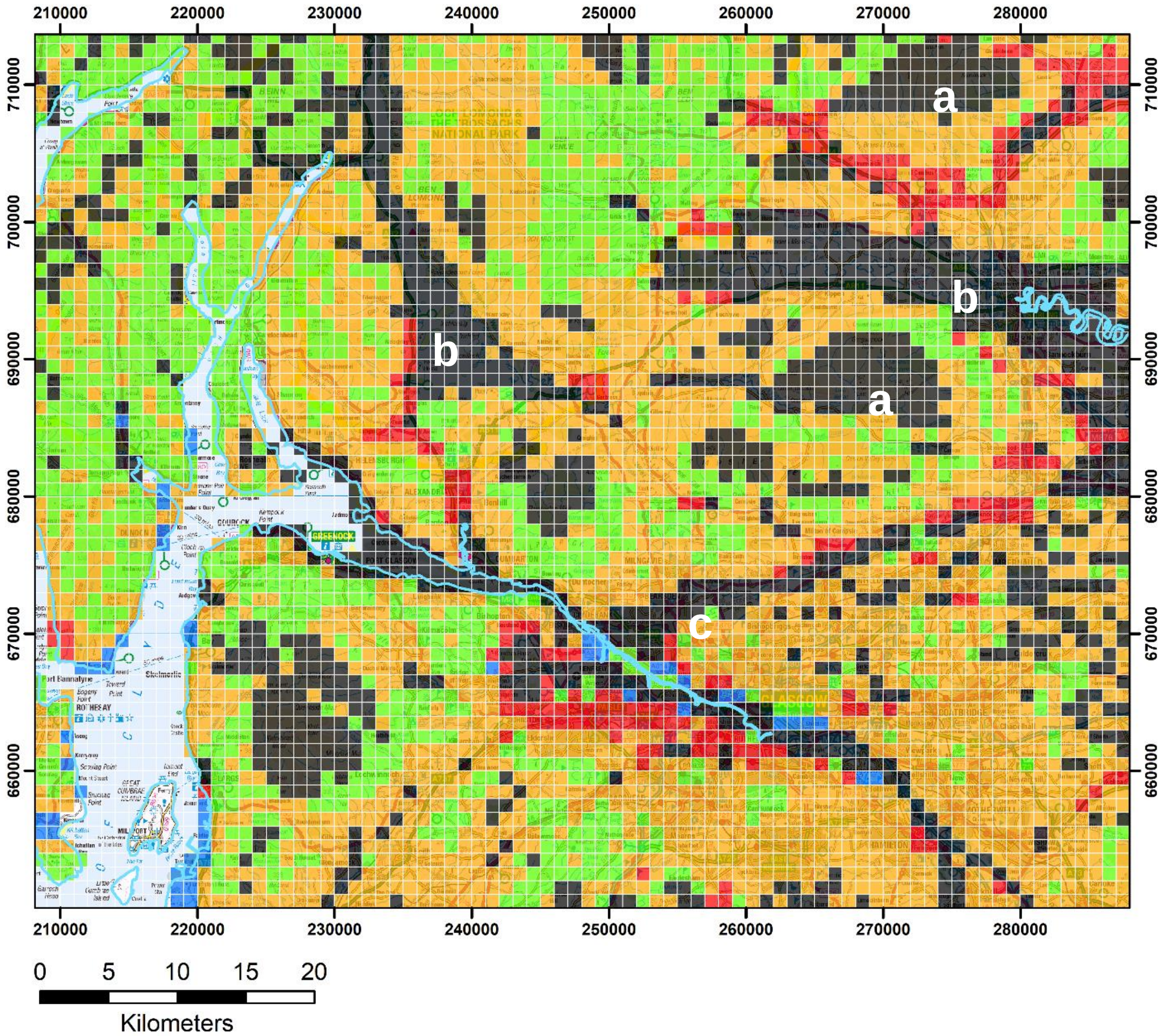


Figure 4. An example output from the superficial geology Hydro-JULES dataset for part of the Midland Valley including Glasgow. Of particular note is the occurrence of extensive areas of Class E (highly heterogeneous) attributed grid squares. These grid squares include areas of upland peat (a), alluvium (b) in large river valleys and subglacial tunnel valleys (c). Contains Ordnance Survey data © Crown Copyright and database rights [2021]. Ordnance Survey Licence no. 100021290.

3.1.5 Class E

3.1.5.1 Classification and Assumptions

Class E corresponds to where bedrock is concealed beneath a heterogeneous (both lithologically and structurally) sediment pile of superficial sediments. This heterogeneity could reflect: (1) excessive thickness of the superficial sequence and occurrence of multiple units of varying permeability in superposition; (2) a single superficial unit with a pronounced lithological and / or structural heterogeneity.

It is assumed in this dataset that the following single units have a pronounced lithological and / or structural complexity that places them within Class E: 'peat' (see 3.1.3.1), 'alluvium', 'till and morainic deposits', 'hummocky (moundy) glacial deposits', 'tidal flat deposits', 'intertidal deposits', 'reclaimed intertidal deposits' and 'beach and tidal flat deposits'.

It has also been assumed that sequences deposited within certain specific geological settings also qualify for Class E characterisation as their geology is renowned for both lithological and structural complexity. These include 'buried valleys' (data sourced from the BGS Buried Valleys dataset) and large morainic complexes like the Cromer Ridge in north Norfolk.

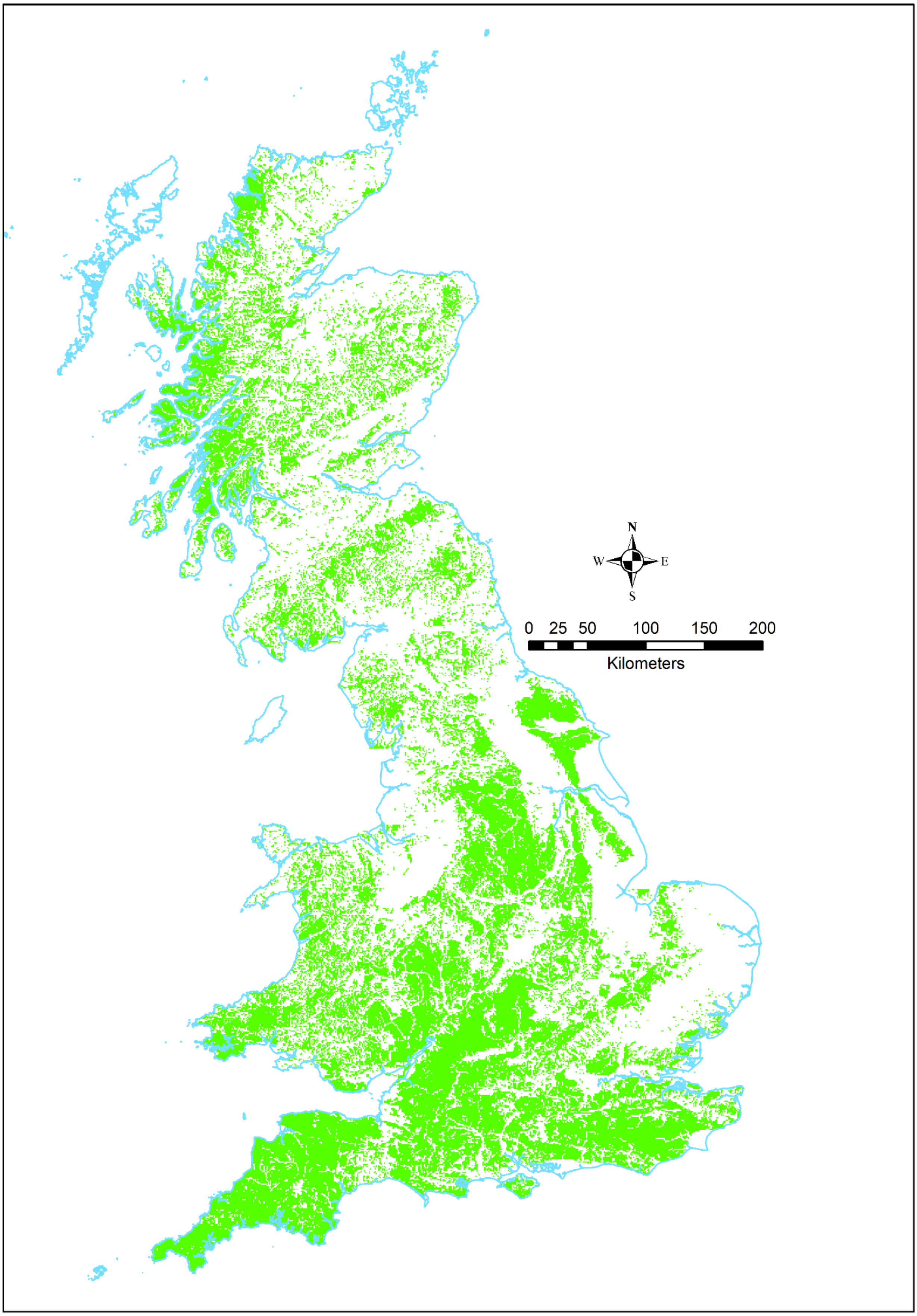
3.1.5.2 UK Distribution

Class E occurs across 48,725 km^2 tiles of England, Wales and Scotland, 21.2% of the total 1 km^2 national grid squares (Appendix 5). The areas of greatest density occur in association with several large coastal embayments (e.g. Fens, Wash, Norfolk Broads, Somerset Levels); estuaries (e.g. Severn, Humber); and peatlands that occur in upland (e.g. Pennines, Scottish Highlands) and neighbouring lowland areas (e.g. Argyll, Ross and Cromarty, Caithness and Sutherland). The paucity of Class E grid squares within the upland areas of southwest England (e.g. Dartmoor and Bodmin moors) where peats are known to be widespread demonstrates a specific inadequacy in the published geological map data for these areas.

4 Conclusions

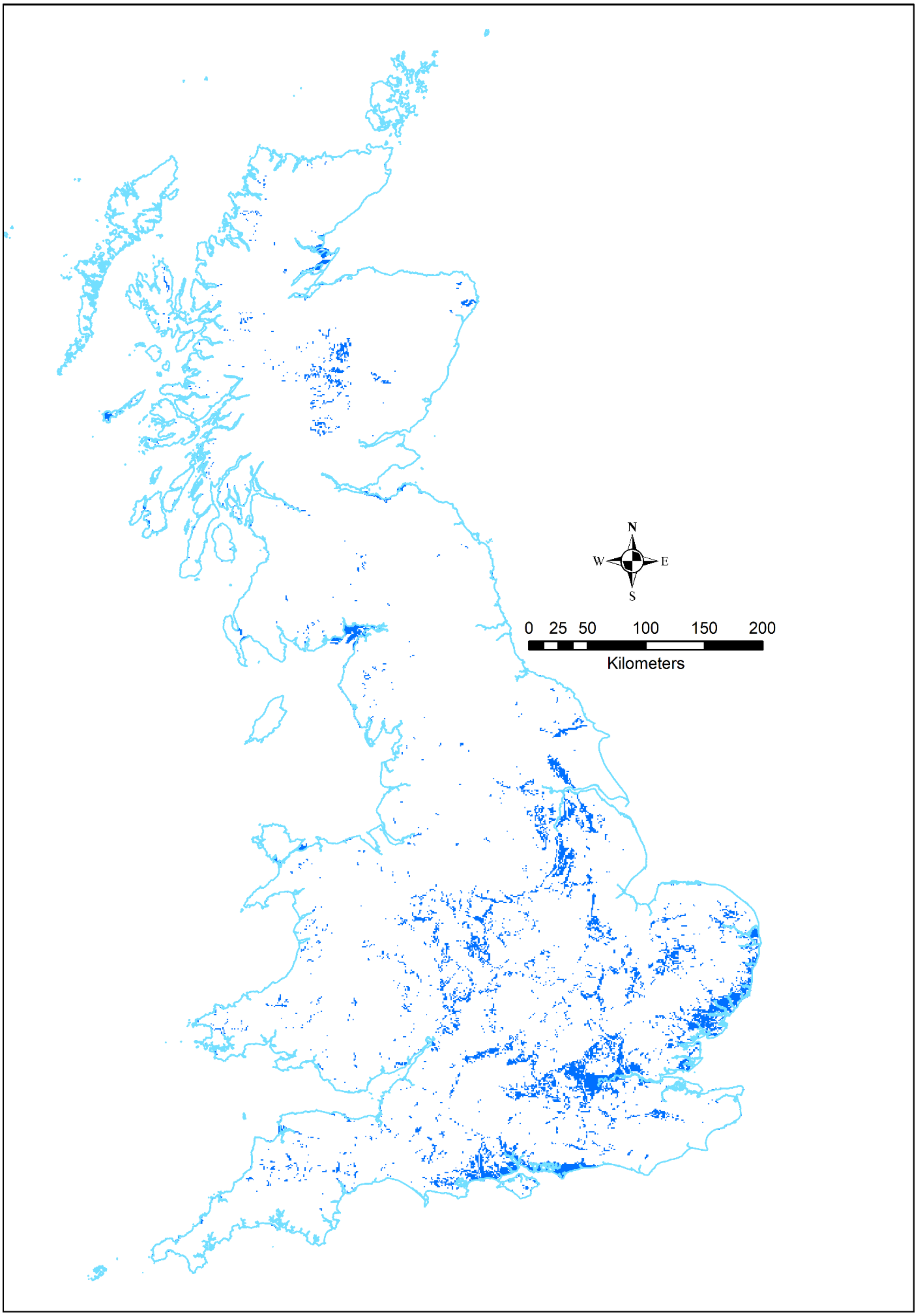
- This report provides an overview of a permeability dataset developed for the UK natural superficial deposits as part of the Hydro-JULES project. It focusses on providing a brief explanation of how the dataset was generated, underpinning geological assumptions and inherent areas of uncertainty. The output data which comprise the final UK dataset is also presented.
- The dataset is gridded at 1 km scale and covers mainland UK (England, Scotland and Wales) and islands where sufficient data was available to undertake the characterisation. This dataset can be translated into numerical hydrogeological values and used to underpin a numerical hydrogeological model – one of the requirements of the NERC-funded Hydro-JULES project, that will couple the ground surface, the natural superficial geology and bedrock geology.
- The dataset was developed using a hybrid approach that aims to characterise the natural superficial geology between the ground and bedrock (rockhead) surface. It utilises published geological maps to help characterise the natural superficial geology. This is supplemented by supporting data (e.g. borehole records, a digital terrain model, aerial photographs, superficial thickness model) and tacit knowledge of geological processes and events in recent UK Earth History to interpret and / or predict the superficial geology profile in areas of thick superficial geology and / or where published geological map data does not effectively characterise the geology.

Appendix 1



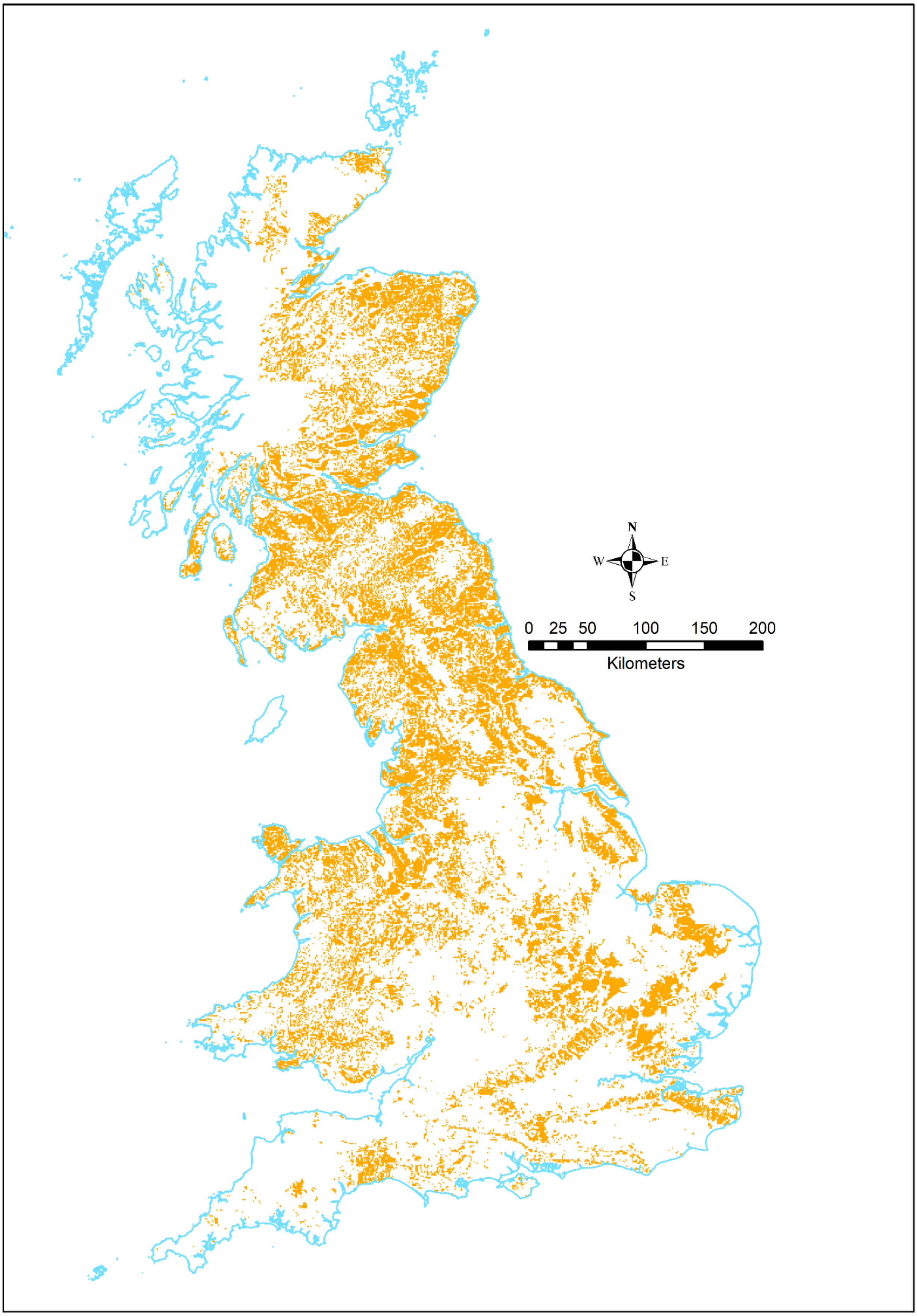
UK-wide distribution of Class A (rock at surface) natural superficial geology.

Appendix 2



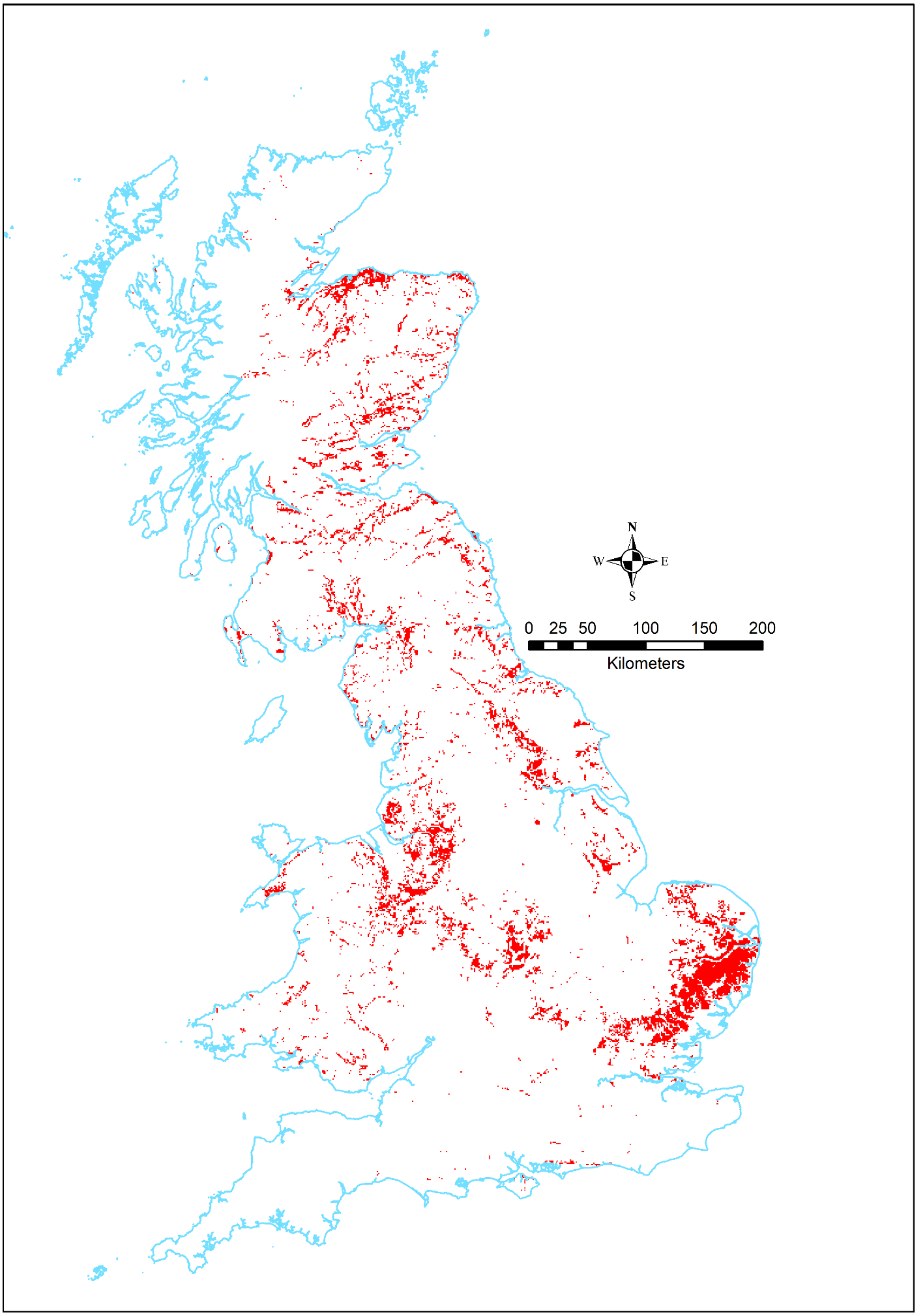
UK-wide distribution of Class B (higher permeability geology over bedrock) natural superficial geology.

Appendix 3



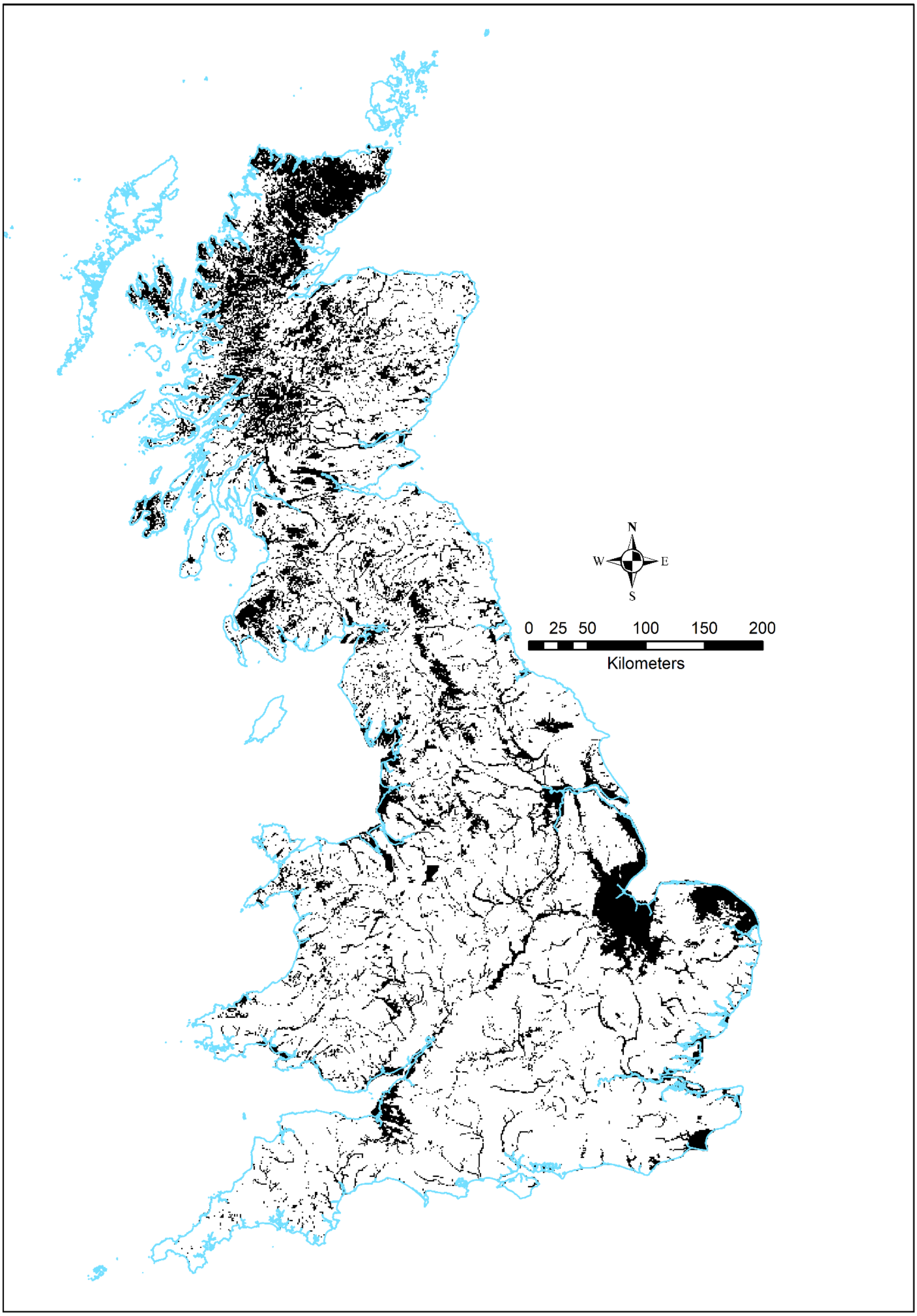
UK-wide distribution of Class C (lower permeability geology over bedrock) natural superficial geology.

Appendix 4



UK-wide distribution of Class D (higher and lower permeability geology over bedrock) natural superficial geology.

Appendix 5



UK-wide distribution of Class E (higher heterogeneous geology over bedrock) natural superficial geology.

References

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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