BGS DIGITAL

# User guide: BGS Permeability version 8

Open report OR/20/054

British Geological Survey

BRITISH GEOLOGICAL SURVEY

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OPEN REPORT OR/20/054

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Keyworth, Nottingham British Geological Survey 2021

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# Foreword

The British Geological Survey (BGS) is a world-leading geological survey, focusing on public-good science for government, and research to understand earth and environmental processes.

We are the UK's premier provider of objective and authoritative geoscientific data, information and knowledge to help society to:

- use its natural resources responsibly
- manage environmental change
- be resilient to environmental hazards

We provide expert services and impartial advice in all areas of geoscience. As a public sector organisation, we are responsible for advising the UK Government on all aspects of geoscience as well as providing impartial geological advice to industry, academia and the public. Our client base is drawn from the public and private sectors both in the UK and internationally.

The BGS is a component body of the Natural Environment Research Council (NERC), part of UK Research and Innovation (UKRI).

### DATA PRODUCTS

The BGS produces a wide range of data products that align to government policy and stakeholder needs. These include baseline geological data, engineering properties and geohazards datasets. These products are developed using in-house scientific and digital expertise, and are based on the outputs of our research programmes and substantial national data holdings.

Our products are supported by stakeholder focus groups, identification of gaps in current knowledge and policy assessments. They help to improve understanding and communication of the impact of geo-environmental properties and hazards in Great Britain, thereby improving society's resilience and enabling people, businesses, and the government to make better-informed decisions.

# Acknowledgements

This report is the published product of a study by the British Geological Survey (BGS) to produce a digital dataset depicting permeability across Great Britain. The methods used to derive and process the data, and the compilation of this report, were determined by M Lewis, S Bunting, D Daley, C Cartwright, K Lee.

BGS has a long history of investigations related to the permeability of the rocks of Great Britain, hence a large number of colleagues have contributed to the project, past and present. Key staff have helped to review draft chapters of this report. The work has particularly benefited from discussions with, and comments by: Derek Ball, Dr John Bloomfield, Colin Cheney, Dr Anthony Cooper, Brighid Ó Dochartaigh, Dr Andrew Farrant, Prof Alan MacDonald, Andrew McKenzie, Prof Denis Peach, Dr Nick Robins, and Geraldine Wildman.

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# Summary

Permeability data is often used in studies of groundwater such as investigations of aquifer pollution or contamination. BGS has prepared permeability information based on the 1:50 000 Digital Geological Map of Great Britain (BGS Geology 50k).

The Permeability data product is based on geological considerations as follows:

- the Predominant Flow Mechanism: intergranular flow, fracture flow, or a mixture of intergranular and fracture flow
- a Maximum Permeability value
- a Minimum Permeability value

The BGS Permeability data product is a qualitative classification of estimated rates of vertical movement of water from the ground surface through the unsaturated zone (the zone between the land surface and the water table). Permeability is the capacity of a rock to transmit a fluid and hence this dataset provides an indication of the rate of water movement between the ground surface and the water table.

The permeability codes assigned are not actual values, derived from field tests or that have been tested in a groundwater flow model. They are a heuristic assessment based on knowledge of fluid movement through rocks of differing lithologies based on their dissolution potential, age, degree of cementation, and fracturing (see Appendix 3 for more details). They indicate where rapid infiltration through the unsaturated zone could occur, potentially causing pollution of groundwater or where water could pond on the ground surface due to slow drainage rates through poorly permeable material.

The data product covers Great Britain, and is presented as a map at a scale of 1:50 000, based on the geological data at the same scale. It is for use at the regional scale and is not recommended for use at the site-specific scale.

The information provided in this User Guide is intended to provide a quick guide to using and understanding this BGS data product.

# 1 Introduction

The term permeability refers to the capacity of a rock to transmit water. The BGS Permeability data product (Figure 1) is a derived data product that provides a qualitative classification of estimated rates of vertical movement of water through the unsaturated zone of sediments and rocks (i.e. the zone between the land surface and the water table). The dataset is based on an attribution of the 1:50 000 scale BGS digital geological mapping (BGS Geology 50k).

The data can be used to compare the relative permeability of deposits at the regional scale, indicating where highly permeable rocks could allow rapid infiltration to occur, or where less permeable rocks are present and water could pond on the ground surface. The dataset can be used as a component in a wide range of geo-environmental assessments such as natural flood management, SuDS, engineering desk studies, slope stability and aquifer vulnerability.

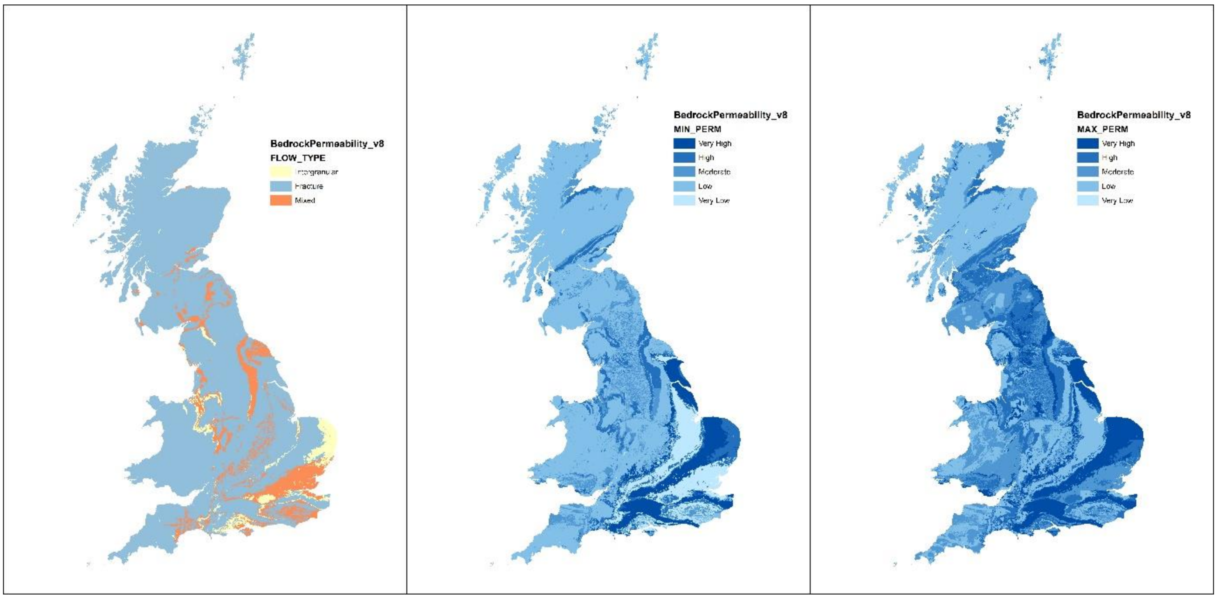


Figure 1: An overview image of the BGS Permeability data product (Bedrock: Flow Type, Min-Perm, and Max-Perm)

# 2 Use Cases

## 2.1 PERMEABILITY USE CASE 1: DRAINAGE POTENTIAL

### 2.1.1 The Challenge

Building Regulations dictate an order of priority of methods for the disposal of rain water collected from buildings, and an adequate soakaway or filtration system must always be the first choice if the design criteria can be met. Discharging the water into a water course, drain or sewer will only be allowed if soakaways or other infiltration methods are not suitable.

Therefore, understanding the nature of the rocks below the surface, and how quickly water will drain away or can be dispersed into the ground evenly and quickly, is required.

### 2.1.2 The Solution

The design of 'Sustainable Drainage Systems' or SuDS to collect rainwater and infiltrate it into the ground, requires several datasets, of which permeability of the unsaturated zone is the most important factor. Differences in permeability control whether water will pond on the ground surface or infiltrate into it, and the rate of infiltration.

Combined with information on the depth to the water table and the shallow geology (including shallow geohazards such as soluble rocks, landslides, shallow mining, presence of made ground, running sands, swelling clays, compressible ground and collapsible ground), engineers can select appropriate drainage solutions. While detailed local conditions will be considered during the design process (and may require field investigation) permeability data can be used to screen sites and select the appropriate initial design.

### 2.1.3 The Outcome

The Permeability data product forms part (in combination with the thickness of the unsaturated zone and geohazard data) of the BGS infiltration SuDS dataset in assessing the suitability of the subsurface for the construction of different types of SuDS schemes such as wetlands, soakaways, infiltration basins, infiltration trenches and permeable pavements (Dearden, 2016a;b). The Maximum and Minimum Permeability ratings are used as part of the drainage potential assessment and the Predominant Flow Mechanism within the groundwater protection zone one.

Permeability information can also guide decisions on other land uses that require information on drainage potential and the likelihood of the presence of saturated ground, such as methods of cultivation and trafficability for construction projects.

## 2.2 PERMEABILITY USE CASE 2: ASSESSING CLIFF STABILITY

### 2.2.1 The Challenge

The variability of the Great Britain's c.11,000 miles of coastline, especially cliff geology and lithology, are all too often under-represented in coastal modelling and coastal management planning. This creates an oversight in potential critical factors such as cliff complexity (e.g. multiple lithologies, jointing and bedding structures, permeability), cliff profiles, marine and coastal deposits, etc. which can all influence the resilience of the coast. Addressing gaps in the information pertaining to these attributes is vital as coastal erosion (and flooding) is an increasing issue in Great Britain and poses a significant threat to people living and working in this environment, as well as the associated infrastructure and assets.

### 2.2.2 The Solution

Permeability is an important factor in assessing the stability of cliffs and coastlines. Differences in permeability between adjacent rock types in cliffs, can influence the infiltration and flow of water, and consequently, contribute to the stability of a coastline. The deposits above the mean high water mark (i.e. cliff or low-lying), but not including the beach, were classified to formation level using the BGS LEX-RCS system (Lexicon – Rock Classification Scheme). These formations were then analysed according to their properties and in particular, the differences between adjacent formations.

This rock property information helps identify where potential instability within the cliff might be present. For example:

- Where a highly permeable sandstone overlies low permeability mudstone, in-cliff slip planes might develop.
- Where a permeable or unconsolidated lithology forms the base of a cliff or low permeability mudstones, wave erosion might be prevalent.

The Permeability data product has contributed to these assessments to develop a coastal stability dataset, which grades the potential for cliff erosion based on 3D geology. Along with permeability, other factors incorporated include rock discontinuities (e.g. fractures, bedding, jointing), and rock/lithology strength. Together, these properties can provide important information on the susceptibility of a coastal zone to potential instability such as erosion, rockfall or landslide.

### 2.2.3 The Outcome

Permeability data has been an important factor in the creation of new coastal morphological units based on multiple variables including coastal transect morphology through to geology type and coastline orientation. Data and information relating to the natural characteristics and properties of coastal environments can then provide a toolkit for the assessment of coastal resilience and coastal change in Great Britain. This novel approach to data provision has been used to provide end users with the data that they require for system understanding and resilience planning and preparation.

# 3 Methodology

## 3.1 BACKGROUND

Considerable effort has been devoted by the BGS to gather, collate and integrate physical properties data for aquifers (porosity, permeability, hydraulic conductivity, transmissivity, storage coefficient, etc.) and to produce publications that are of value to the hydrogeological community (Allen *et al.,* 1997, Jones *et al.,* 2000, Graham *et al*., 2006). These physical properties are characteristics of the saturated zone of the various aquifers that occur in Great Britain. Considerably less attention has been devoted to potential rates of liquid movement from the ground surface, through the unsaturated (or vadose) zone above the water table which has variable water content. Such measurements are rare and even then have only been carried out at a relatively small number of specific sites, almost invariably located on the major aquifers in England (such as the Sherwood Sandstone Group and the Chalk) and usually specifically designed to determine aquifer recharge rates or for diffuse pollution studies. Little or no information on rates of liquid movement in the unsaturated zone is available for the other aquifers in Great Britain.

In view of the scarcity of this data it can be difficult to provide a meaningful account of vertical travel times that could be applied to the entire outcrop areas of the major aquifers, let alone to the much wider range of rock types that occur at outcrop across Great Britain. There is, nevertheless, a need for an assessment of the relative rate at which liquids may be expected to migrate vertically through the various rock types, to provide at least a qualitative classification of vertical movement rates that can be applied to the various mapped rock units and their lithologies.

As the classification needed to be applied to all of the rock units that occur in England, Wales and Scotland, BGS Geology 50k was used as the basis, since this was already available in digital form and was linked to the BGS Lexicon (dictionary), a BGS directory that provides detailed information for every named rock unit that has been mapped in Great Britain. This report provides information on the permeability classification of the rock units and lithologies, together with details regarding concepts and assumptions that were inherent in drawing up the classification.

## 3.2 OVERVIEW

The methodology used to create the BGS Permeability data product is based upon known physical characteristics derived from flow in the saturated zone and on expert judgement of estimated rates of vertical movement of water from the ground surface through the unsaturated zone. The data attributes a permeability rating to each distinct combination of rock unit and lithology mapped by BGS Geology 50k, with the permeability attribution added to the LEX-RCS code.

The permeability codes are qualitative and ascribed solely on the known hydrogeological characteristics of the various lithologies, considering their age, dissolution potential, degree of cementation/induration and fracturing. In unconsolidated deposits, intergranular flow is the Predominant Flow Mechanism. In most consolidated sedimentary rocks, and igneous and metamorphic rocks, fracture flow will occur and hence a wide range of permeability values can occur for any one lithology. The potential for dissolution and degree of cementation, lithological variation and induration are also factors that affect actual measured values.

The BGS Permeability data product consists of a three-part code representing: Predominant Flow Mechanism, Maximum Permeability and Minimum Permeability.

The Predominant Flow Mechanism code indicates how fluid will migrate from the ground surface through the unsaturated zone of each rock unit and lithology combination and has three classes: Intergranular, Fracture or Mixed (intergranular and fracture).

The Maximum Permeability and Minimum Permeability values indicate the range of flow rates likely to be encountered in the unsaturated zone for each rock unit and lithology combination. Five classes are used: very high, high, moderate, low and very low. The Maximum and Minimum Permeability values represent a likely permeability range for the specified rock unit and lithology combination at, and immediately below, its outcrop or subcrop (rather than at any significant depth).

The Maximum Permeability represents the fastest potential vertical rate of migration through the unsaturated zone likely to be encountered in the specified rock unit-lithology combination. The Minimum Permeability represents the minimum, and in some cases more normal, bulk rate of vertical movement likely to be encountered. Where a widely variable combination of lithologies occurs within a rock unit this Minimum Permeability value reflects the probable movement rate likely to be encountered in the least permeable horizons.

Generally, for any given lithology of a specific age, the Maximum and Minimum Permeability values will be the same or similar (just one class different), indicating that the range of probable flow rates for that rock unit and lithology combination is relatively narrow. However, for the same lithology of different ages (e.g. sandstones of Jurassic and Devonian ages), the permeability code allocated may vary, as the degree of dissolution, fracturing and consolidation can vary widely with age. Where a wide range of lithologies are covered by a rock unit and lithology combination, the Maximum Permeability would represent the most permeable lithology (e.g. gravel) and the Minimum Permeability the least permeable (e.g. clay). Therefore, where the amount of secondary permeability caused by dissolution and karst, fracturing (both degree and size of fractures) or the lithology (e.g. glacial deposits or alternating beds of limestones and mudstones) is very variable, there could be two, three or even four class differences between the Maximum and Minimum Permeability values, with the Minimum Permeability value reflecting the more likely rate of movement through the least permeable horizon.

Additional explanation and information about permeability is provided in Appendix 1.

### 3.3 SOURCE DATASETS

- BGS Geology 50k (formally known as DiGMapGB-50) version 8.24
- BGS GeoSure v8: Soluble Rocks
- Academic literature

# 4 Technical Information

This section provides more detailed information on the data product, its content, and advice on best use as well as highlighting some important considerations.

### 4.1 SCALE

The BGS Permeability data product is intended for use at 1:50 000 scale. All spatial searches of the maps should be undertaken using a minimum 50 m buffer. This is because the smallest detectable feature at this scale is 50 m.

The BGS Permeability data product may be used as a guide to permeability in the shallow unsaturated zone, (e.g. for desk studies) and should only be used for regional planning purposes. The data product should not be used at larger scales, where individual site-specific site investigations will be necessary.

## 4.2 COVERAGE

Data coverage is provided for Great Britain (Figure 1).

## 4.3 ATTRIBUTE DESCRIPTION

The BGS Permeability data product contains the following attributes:

| FIELD NAME | FIELD DESCRIPTION |
|---|---|
| FLOW_TYPE | Classification of the type of flow expected within lithology, either intergranular, fracture or mixed |
| MAX_PERM | Description of the highest permeability within the lithology ranging from very low to very high |
| MIN_PERM | Description of the highest permeability within the lithology ranging from very low to very high |
| VERSION | Dataset name and version number |

Table 1: BGS Permeability attributes

## 4.4 DATA FORMAT

The Permeability data product has been created as vector polygons and are available in a range of GIS formats, including ArcGIS (.shp) and imply we provide MapInfo (.tab) as standard on request. Additional GIS formats may be available but may incur additional processing costs.

## 4.5 DATASET HISTORY

The BGS is continually surveying and resurveying areas of Great Britain, improving and updating the geological maps. These updates are added to the BGS Geology 50k dataset regularly. This document refers to version 8 of the Permeability data product, which is based on the latest geological mapping, BGS Geology 50k v8 and the latest dissolution data (BGS GeoSure v8: Soluble Rocks). This incorporates both new mapping and also updates to Formation classifications/nomenclature (e.g. the Nottingham Castle and Hawksmoor formations (Sherwood Sandstone Group) have been reclassified as the Chester Formation in BGS Geology 50k, which in some cases has meant a change in the Permeability codes).

In addition, development in research can also feed into updates, for example, the latest version has incorporated more detailed data on soluble rock (dissolution) properties, which has improved the analyses. BGS is committed to improving the Permeability data product as more information becomes available. Additional enhancements are made to the datasets for each new version.

Below is an outline of the data history of the BGS Permeability data product:

- Version 1 (released 2005): Derived from DiGMapGB-50 version 1.10
- Version 2 (released 2005): Derived from DiGMapGB-50 version 2.11
- Version 3 (released 2006): Derived from DiGMapGB-50 version 3.14
- Version 4 (released 2007): Derived from DiGMapGB-50 version 4.16
- Version 5 (uncompleted): Derived from DiGMapGB-50 version 5.18
- Version 6 (released 2010): Derived from DiGMapGB-50 version 6.20
- Version 7 (released 2015): Derived from DiGMapGB-50 version 7.22
- Version 8 (released 2021): Derived from BGS Geology 50k (formally known as DiGMapGB-50) version 8.24, incorporating BGS GeoSure v8: Soluble Rocks.

## 4.6 DISPLAYING THE DATA

All four data layers can be visualised using any of the ‘MIN_PERM’, ‘MAX_PERM’ or the ‘FLOW_TYPE’ attributes. This provides a straightforward visualisation of each attribute, for all layers, that can be used to sort data or select certain class ratings depending on user need. A legend file is supplied with the dataset. A colour look-up table (Table 2 to

| MAX_PERM | RED | GREEN | BLUE | HEX | LOOKS LIKE |
|---|---|---|---|---|---|
| CLASS | This is the equivalent red channel colour | This is the equivalent green channel colour | This is the equivalent blue channel colour | This is the equivalent HEXadecimal value | This cell shows the colour as intended |
| Very High | 0 | 77 | 168 | 004DA8 | |
| High | 35 | 113 | 190 | 2371BE | |
| Moderate | 79 | 152 | 212 | 4F98D4 | |
| Low | 130 | 192 | 233 | 82C0E9 | |
| Very Low | 190 | 232 | 255 | BEE8FF | |

Table 4) is also provided for each attribute in the datasets for users of non-ESRI software to be able to correctly symbolise the data. (See Table 2 to

| MAX_PERM | RED | GREEN | BLUE | HEX | LOOKS LIKE |
|---|---|---|---|---|---|
| CLASS | This is the equivalent red channel colour | This is the equivalent green channel colour | This is the equivalent blue channel colour | This is the equivalent HEXadecimal value | This cell shows the colour as intended |
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| Low | 130 | 192 | 233 | 82C0E9 | |
| Very Low | 190 | 232 | 255 | BEE8FF | |

Table 4).

| FLOW_TYPE | RED | GREEN | BLUE | HEX | LOOKS LIKE |
|---|---|---|---|---|---|
| CLASS | This is the equivalent red channel colour | This is the equivalent green channel colour | This is the equivalent blue channel colour | This is the equivalent HEXadecimal value | This cell shows the colour as intended |
| Intergranular | 255 | 255 | 191 | FFFFBF | |
| Fracture | 145 | 191 | 219 | 91BFDB | |
| Mixed | 252 | 141 | 89 | FC8D59 | |

Table 2: Colour symbology for Permeability attribute FLOW_TYPE

| MIN_PERM | RED | GREEN | BLUE | HEX | LOOKS LIKE |
|---|---|---|---|---|---|
| CLASS | This is the equivalent red channel colour | This is the equivalent green channel colour | This is the equivalent blue channel colour | This is the equivalent HEXadecimal value | This cell shows the colour as intended |
| Very High | 0 | 77 | 168 | 004DA8 | |
| High | 35 | 113 | 190 | 2371BE | |
| Moderate | 79 | 152 | 212 | 4F98D4 | |
| Low | 130 | 192 | 233 | 82C0E9 | |

| | | | | | |
|---|---|---|---|---|---|
| Very Low | 190 | 232 | 255 | BEE8FF | |

Table 3: Colour symbology for Permeability attribute MIN_PERM

| MAX_PERM | RED | GREEN | BLUE | HEX | LOOKS LIKE |
|---|---|---|---|---|---|
| CLASS | This is the equivalent red channel colour | This is the equivalent green channel colour | This is the equivalent blue channel colour | This is the equivalent HEXadecimal value | This cell shows the colour as intended |
| Very High | 0 | 77 | 168 | 004DA8 | |
| High | 35 | 113 | 190 | 2371BE | |
| Moderate | 79 | 152 | 212 | 4F98D4 | |
| Low | 130 | 192 | 233 | 82C0E9 | |
| Very Low | 190 | 232 | 255 | BEE8FF | |

Table 4: Colour symbology for Permeability attribute MAX_PERM

# 5 Limitations

## 5.1 DATA CONTENT

The BGS Permeability data product has been constructed based on BGS Geology 50k and the BGS GeoSure v8: Soluble Rocks datasets.

The BGS Geology 50k dataset is a compilation of digital tiles derived from previously published and unpublished maps and archive information. The mapping, description and classification of rocks **are based upon the interpretations and evidence available at the time of survey**, or **time of re-evaluation for modifications/correction**.

All data layers are derived from the most up-to-date version of the 1:50 000 scale geological maps and best available associated input layers.

The digital 1:50 000 scale geological maps hold information for four layers or themes representing four different types of deposits. At any one location, bedrock will always be present, but the other three (artificial ground, mass movement deposits and superficial deposits) may be absent. For areas where no 1:50 000 scale digital data are available; the next best scale will be used.

## 5.2 SCALE

The BGS Permeability data product has been developed at 1:50 000 scale (where 1 map unit equates to 50,000 equivalent units on the ground) and must not be used at larger/finer scales, and all spatial searches against the data should be done with a minimum 50 m buffer.

## 5.3 ACCURACY AND UNCERTAINTY

The mapping accuracy associated with the BGS Permeability data product is based on that of the BGS Geology 50k dataset. This is nominally 1 mm which equates to 50 m on the ground at 1:50 000 map scale (see 5.2).

The creation of the data relies upon a number of assumptions regarding the procedure and technical methodology. The procedures for the assessment of these methodologies were largely based upon the expert judgement of hydrogeologists and extensive discussion with district geologists. Further technical assumptions were also made:

1. BGS Permeability data producer is based on, and limited to, an interpretation of the records in the possession of the BGS at the time the dataset was created.
2. The classification provides a permeability code for every mapped rock unit-lithology combination for each of the four layers or themes (artificial deposits, mass movement deposits, superficial deposits and bedrock) in BGS Geology 50k. No attempt has been made to combine the separate layers to produce a single permeability value that could be applied to the subsurface below any given point. This would not be possible without information regarding the physical and chemical characteristics of the soil, the thickness of the different geological units present, and the depth to water, as well as details of any changes in lithology with depth. In particular, without information on the thickness of superficial deposits, and whether other unmapped deposits are present within the sequence, it is impossible to derive a combined permeability value for the different BGS Geology 50k layers present. Any interpretation of the three-dimensional nature of the geology made using the BGS Permeability data product need to incorporate this, using site-specific data.
3. The permeability codes were allocated to every unique rock unit and lithology combination (LEX-RCS code) in BGS Geology 50k. Therefore, all polygons having the same LEX-RCS code have the same permeability code. However, although there are known to be lithological variations spatially within rock units, these variations are not included in the dataset, unless the lithological code itself has changed.
4. The permeability codes refer to water movement through the unsaturated zone only.
5. Horizontal permeability values (generally representing flow in the saturated zone) are generally greater than vertical ones (as occur through the unsaturated zone to the water table), due to the layering of the predominantly sedimentary rock sequence observed in Great Britain.
6. Only the uppermost deposit present within each layer is portrayed and other superficial deposits, with differing permeability characteristics, may be present between those mapped and the bedrock.
7. The lithological component(s) for a particular rock unit mapped within BGS Geology 50k was assumed to be correct, whether or not this was expected or normal for the given formation.
8. The order of the deposits in a lithological ‘string’ was assumed to be relevant, and that the dominant lithology was placed first, with the other lithologies in order of their occurrence, e.g. gravel, sand, silt and clay was different to, and more permeable than, clay, silt, sand and gravel.
9. It was assumed that there was a difference between gravel, clayey and gravel and clay; the former comprising gravel with a clay matrix, and the latter could comprise gravel, clay or a mixture of gravel and clay at a given location.
10. Where a given rock unit was described as possessing a range of lithologies the coding took account of the probability that each of these lithologies would be at outcrop at some location across the whole extent of the rock unit outcrop and codes were applied accordingly. The permeability codes for many unconsolidated deposits (Appendix 4), where intergranular flow is the main flow mechanism, could be equated to an approximate range of hydraulic conductivity values. However, permeability codes should not be used to imply that any particular numerical flow rate could be applied to any particular lithology under unsaturated conditions. A competent hydrogeologist should be consulted before attempting to apply the permeability codes to flow conditions in the unsaturated zone.

11. It is assumed that all of the possible geological layers (artificial ground, mass movement deposits, superficial deposits and bedrock) that could be present at a site were mapped/included, however, this is not always the case where the maps are old and the presence of superficial deposits was not always recorded. Similarly, the presence of anthropogenic artificial deposits was not systematically mapped by the BGS until the 1980s. Artificial deposits are constantly changing and only those present at the time of survey were recorded.
12. The dual porosity nature of the Chalk aquifer has not been incorporated in the permeability coding. The Maximum and Minimum Permeability codes for the Chalk indicate the speed of movement through the fractures that provide the response at the water table to rainfall recharge. It does not consider the rate of slower downwards movement via piston displacement of fluid that has diffused into the small saturated pores of the unsaturated zone Chalk that are too small ($<1 \mu m$) to drain under gravity with the water held by capillary forces. Therefore, using the Minimum Permeability value to estimate rates of movement for water and any soluble ions (e.g. nitrate) that have diffused into the Chalk matrix is not appropriate.

### 5.4 ARTEFACTS

The BGS Permeability data product is based on the BGS Geology 50k dataset therefore represents data from different times and origins. Mapping practice, and the lithostratigraphic and lithological coding used in mapping at this scale has been progressively revised. Consequently, adjacent geological sheets/tiles (of different survey dates) may not seamlessly fit together spatially, or in terms of lithological description. This can result in some map-sheet 'edges' that exhibit contrasting colours/attribution. This in turn can affect the representation of the Permeability layers.

### 5.5 DISCLAIMER

The use of any information provided by the British Geological Survey ('BGS') is at your own risk. Neither BGS nor the Natural Environment Research Council (NERC) or UK Research and Innovation (UKRI) gives any warranty, condition or representation as to the quality, accuracy or completeness of the information or its suitability for any use or purpose. All implied conditions relating to the quality or suitability of the information, and all liabilities arising from the supply of the information (including any liability arising in negligence) are excluded to the fullest extent permitted by law. No advice or information given by BGS, NERC, UKRI or their respective employees or authorised agents shall create a warranty, condition or representation as to the quality, accuracy or completeness of the information or its suitability for any use or purpose.

# 6 Frequently asked questions

**Q: What does this dataset show?**

**A:** The BGS Permeability data product is a derived dataset that provides a flow mechanism and a qualitative classification of estimated rates of vertical movement of water through the unsaturated zone of sediments and rocks (i.e. the zone between the land surface and the water table).

**Q: Can I use this dataset as part of a commercial application?**

**A:** This dataset is licenced from BGS, please refer to the terms of your licence or contact iprdigital@bgs.ac.uk for further information

**Q: Are the dataset values real world observations or predictions?**

**A:** The permeability codes assigned are not actual values, derived from field tests or that have been tested in a groundwater flow model. The codes are heuristic and were ascribed using expert interpretation of the estimated rates of vertical movement of water from the ground surface through the unsaturated zone of the various lithologies, considering their dissolution potential, age, degree of cementation/induration and fracturing.

**Q: How accurate is this dataset?**
**A:** The permeability codes were allocated to every unique rock unit and lithology combination (LEX-RCS code) in BGS Geology 50k (hence based on 1:50 000 geological mapping). Therefore, all polygons having the same LEX-RCS code have the same permeability value. However, there are known to be lithological variations spatially within rock units, these variations are not included in the dataset, except where the lithological code itself changes. The estimated permeability values are just for the unsaturated zone.

**Q: How often will this dataset be updated?**
**A:** The current version (version 8) was released in 2021. The dataset is revised on an ad-hoc basis when its source data is updated.

# Appendix 1 Explanation of the permeability codes

The term permeability refers to the capacity of a rock to transmit water. The permeability codes assigned are not an actual hydraulic conductivity value, derived from field tests, or necessarily a value that has been tested in a groundwater flow model. However, for many unconsolidated deposits where intergranular flow is the main flow mechanism, the assigned permeability code could be converted to an approximate range of hydraulic conductivity values, with each of the permeability classes representing about two or three orders of magnitude difference in hydraulic conductivity, as values can vary from $10^{-8}$ to $10^{4}$ m/day. In consolidated sedimentary rocks, igneous and metamorphic rocks, fracture flow may occur, which can lead to a wide range of permeability and hydraulic conductivity values in any one lithology, depending on both the degree of the fracturing and the size and connectivity of the fractures.

It should be noted that values of intrinsic permeability measured on core samples in a laboratory generally represent the matrix permeabilities of a small plug sample. Whilst values of hydraulic conductivity obtained from pumping tests represent significantly larger rock volumes than laboratory tests, they are a measure of the predominantly horizontal flow in the saturated zone to boreholes, rather than the often-vertical flow through the unsaturated zone to the water table. Generally horizontal values are greater than vertical ones, due to layering of the predominantly sedimentary rock sequence of Great Britain.

**Definitions of permeability and hydraulic conductivity**

*Permeability:* the property or capacity of a porous rock, sediment or soil for transmitting a fluid without impairment of the medium; it is a measure of the relative ease of flow under unequal pressure (adapted from American Geological Institute, 1972).

*Intrinsic permeability*: The permeability of rock independent of fluid properties. The SI unit of measurement is $m^2$ (for saturated flow).

*Hydraulic conductivity* (cf. permeability coefficient); the rate of flow of water through a cross sectional area under a unit hydraulic gradient at the prevailing temperature (adapted from American Geological Institute, 1972). The customary unit of measurement is m/day or m/sec.

*Intrinsic permeability* [$L^2$] is related to *hydraulic conductivity* [$LT^{-1}$] by:

**$K = k\rho g/\mu$**

where K = hydraulic conductivity
k = intrinsic permeability
ρ = density of the liquid
g = acceleration due to gravity
μ = dynamic viscosity of the liquid

The *hydraulic conductivity* of a material can be derived experimentally by Darcy's Law:

**$Q = KiA$**

where Q = flow rate through the material
K = hydraulic conductivity (in the direction of flow)
i = hydraulic gradient (in the direction of flow)
A = cross-sectional area of the material

These parameters are relevant for granular aquifers that are homogeneous, isotropic and of infinite extent. This ideal case rarely occurs and often fracture flow is also present.

Box 1 Definitions of permeability and hydraulic conductivity.

# Appendix 2 Unsaturated zone flow

Measured flow in the saturated zone is used in this methodology as an approximation of flow in the unsaturated zone to inform the qualitative classification as permeability. Vertical fluid movement through the unsaturated zone is in many ways analogous to fluid movement through the saturated zone. High travel rates occur in the saturated zone of highly permeable deposits (such as clean well sorted gravels) or rocks that possess high hydraulic conductivity values (such as karstic limestones). Rapid movement of fluid through the unsaturated zone may also be expected to occur in these strata, although this is predominantly vertically oriented rather than horizontally oriented, as would generally be the case for flow in the saturated zone. Conversely, saturated flow rates will be slow in strata that possess low permeability or hydraulic conductivity values and this will also generally be the case for flow through the unsaturated zone in the same rocks.

Table 1.1 Typical ranges in hydraulic conductivity of common rock types (after Lewis, 1989)

| Lithology | Hydraulic conductivity (m/day) |
|---|---|
| Clay* | $5 \times 10^{-7}$ to $10^{-3}$ |
| Loess | $10^{-2}$ to 1 |
| Silt | $10^{-3}$ to $10^{-1}$ |
| Sand | $10^{-1}$ to $5 \times 10^{2}$ |
| Gravel | $5 \times 10^{1}$ to $5 \times 10^{4}$ |
| Sand and gravel | 5 to $10^{2}$ |
| Till | $10^{-7}$ to $5 \times 10^{-1}$ |
| Halite | $5 \times 10^{-6}$ to $5 \times 10^{-3}$ |
| Limestone, dolomite | $5 \times 10^{-6}$ to 1 |
| Karstic limestone | $10^{-1}$ to $10^{3}$ |
| Chalk | Up to 5 |
| Sandstone | $5 \times 10^{-5}$ to $2 \times 10^{1}$ |
| Shale | $5 \times 10^{-8}$ to $10^{-4}$ |
| Lignite | $10^{-1}$ to 10 |
| Friable tuff | $2 \times 10^{-2}$ to 2 |
| Welded tuff, ignimbrite | $5 \times 10^{-5}$ to $2 \times 10^{-1}$ |
| Dense basalt | $10^{-6}$ to $10^{-3}$ |
| Fractured basalt | $10^{-4}$ to 1 |
| Vesicular lava | $10^{-4}$ to $10^{-3}$ |
| Lava | Less than $5 \times 10^{-9}$ to $10^{3}$ |
| Slate | $5 \times 10^{-9}$ to $5 \times 10^{-6}$ |
| Schist | $10^{-7}$ to $10^{-4}$ |
| Dense crystalline rock | $5 \times 10^{-8}$ to $10^{-5}$ |
| Fractured crystalline rock | $10^{-3}$ to 10 |

*montmorillonite clays are generally about two orders of magnitude less permeable than kaolinite clays.

The flow of liquids through saturated and unsaturated strata is not however completely analogous, since vertical flow under unsaturated conditions will be slower than under similar saturated conditions (often considerably so) and is proportional to the degree of saturation, and any horizontal anisotropy will reduce vertical flow with respect to horizontal flow.

Permeability of the unsaturated zone is complex even when dealing with an idealised aquifer, where the infiltration of water through the unsaturated zone depends on the gravity potential (head) and the soil potential. At moisture potentials close to the specific retention, gravity potential predominates, whereas when the material is dry, the moisture potential controls water movement.

The ‘unsaturated hydraulic conductivity’ is not a constant but rather a function of the volumetric water content. Hence at low volumetric water contents (e.g. late summer and early autumn) the hydraulic characteristics and behaviour of contrasting lithologies in the unsaturated zone may be quite different to their behaviour in the saturated zone. For example, the case of a sand layer within a finer-grained medium illustrates this point, as paradoxically the unsaturated hydraulic conductivity of the clay may be greater than that of a sand, as the clay may have retained much of its volumetric water content whereas this will have drained from the coarser-grained sand horizon. Great care should therefore be taken before applying permeability values to the unsaturated zone, particularly if this zone is at a seasonal dry state. Further information is provided in Fetter (1994).

In most fractured aquifers (limestones, other highly indurated sediments, igneous and metamorphic rocks) the orientation of these fractures could control recharge. In the Chalk where conditions are close to saturation at depth in the vadose zone, the above comments on seasonal variations will not apply. Even in the Sherwood Sandstone (a mixed intergranular and fractured aquifer) recharge can take several years to reach the water table.

# Appendix 3 The conceptual model

The permeability codes are a qualitative classification based on expert judgement of estimated rates of vertical movement of water from the ground surface through the unsaturated zone. This water is regarded as having identical properties to the rainwater that would act as natural recharge to the aquifer.

Permeability codes were attributed to every lithology or combination of lithologies ascribed to each named rock unit that has been mapped and is in BGS Geology 50k. The derivation of each of the three Permeability codes is detailed below (Section 3). The thickness of the rock unit and the unsaturated zone at any particular location have a significant effect on the total travel time between the ground surface and the water table, and these may vary considerably across the geographical extent of a single rock unit. However, the variation in rock unit thickness and unsaturated zone thickness is often not known. It was therefore not possible to account for these factors when ascribing Permeability codes. The codes were ascribed solely on the known hydrogeological characteristics of the various lithologies, considering their age, dissolution potential, degree of cementation/induration and fracturing. Where a given rock unit was described as possessing a range of lithologies the coding took account of the probability that each of these lithologies would be at outcrop at some location across the whole extent of the rock unit outcrop and codes were applied accordingly. For example, in the case of Alluvium for which the lithology was described as clay, silt, sand and gravel it was necessary to ascribe codes that encompassed the potential properties of this wide range of lithologies, ranging from highly permeable to effectively impermeable.

In some areas, the presence of structural features (such as faults or folds) is known to have a significant effect on the hydraulic properties of the rock. However, no account was taken of structural features, principally because only a limited portion of the areal extent of a given rock unit is likely to have been influenced by any particular structural effect and it was necessary to ascribe codes that are applicable to the bulk of the unit. The lack of a structural control on the Permeability codes is not thought to be a significant issue since it is probable that in the majority of cases the range ascribed to a given rock unit is sufficiently broad to encompass the majority of these effects.

Permeability and dissolution/karst potential or susceptibility to dissolution are not the same thing. However, knowing where there may be dissolution/karst is relevant as it indicates where there may be rapid movement from the ground surface to the water table; Hence the latest dissolution weighting score from the BGS GeoSure v8: Soluble Rocks dataset was used in deriving the Maximum Permeability value. Karst is very heterogeneous, but any score over 10 could have very high potential karstic permeability, and anything less than 5 may be a carbonate (e.g. some of the limestone bands in the Kimmeridge Clay) but is unlikely to be karstic, although could have a high permeability. Similarly, some of the Jurassic limestones are permeable but not very karstic. Calcareous rocks such as some of the Devonian calcretes, thin limestones in the Upper Carboniferous and some of the Scottish meta-limestones have very little evidence of karst development, but this cannot be ruled out.

### OTHER FACTORS AFFECTING PERMEABILITY

As only the age and lithology were used to attribute the BGS Permeability data product, the following important factors were not considered, but could be incorporated at a later date.

#### SOIL

Soil commonly constitutes the upper 0.5 to 2.0 metres of the subsurface but is almost invariably derived from the underlying strata and consequently has similar lithological constituents to those strata. A scoping study to assess the potential effects of soils concluded that in almost all cases the soils were a product of weathering of the underlying deposits and that the resulting soils were of a similar permeability to the deposits from which they were derived. Although in the case of a few soils, their permeability was likely to be significantly less than the underlying deposits. However, these soils have a very limited extent (<1% of the total area occupied by soil cover) and only form in isolated upland areas. The study concluded that since the permeability of the vast majority of soils did not differ significantly from the underlying deposits, there was little need for the creation of an additional ‘permeability’ layer for the soils. However, soils also contain organic material which can affect the overall permeability and also the soil leaching potential, which may be very different to that of the underlying rock units. As BGS does not own soil data, it was not taken into account in this classification. If available it could be considered as an additional layer above the uppermost geological layer of BGS Geology 50k.

#### WEATHERING AND VARIABILITY WITH DEPTH

For the purpose of attributing the codes it was assumed that the rock fabric was not highly weathered, but where the material at the ground surface is highly weathered, this would generally increase the permeability. The only exception was the granites of SW England, where the coding reflects the fact that kaolinisation of the alkali feldspars has increased the permeability. The variability with depth due to greater amounts of compaction could possibly be included if a dataset containing details for such parameters were to become available for at least a significant part of Great Britain.

#### TOPOGRAPHIC POSITION

Topographic position affects the transmissivity of some aquifers such as the Chalk, where the greatest values correlate to increased dissolution in the zone of water level fluctuation, and hence interfluve localities are less permeable, even if occasional fractures are present. Integration of such information with the current dataset would, however, require a departure from the relatively straightforward use of the BGS Geology 50k digital mapping since every unit of the Chalk covers a wide range of topographic positions. It could be possible to integrate an additional dataset based on topographic variations into the assessment of permeability values.

#### THICKNESS OF SUPERFICIAL DEPOSITS AND UNSATURATED ZONE

Other factors affecting the rate of movement of recharge from the ground surface to the water table in the bedrock are the total thickness and overall lithology of the overlying superficial deposits and the thickness of the unsaturated zone. The current classification only assesses the mapped, and hence uppermost superficial deposits present at the ground surface and the uppermost bedrock deposits: there could be several different types of superficial deposits present between these horizons, with widely varying lithologies. If all these factors are considered, it would be possible to produce travel time maps for the main British aquifers; however, there is insufficient information to provide national coverage of all the formations.

# Appendix 4 Permeability coding

## SUPERFICIAL AND UNCONSOLIDATED DEPOSITS

Table 5 shows the classification that was applied to both superficial and unconsolidated bedrock deposits. In some cases, it was possible to narrow down the Predominant Flow Mechanism or permeability range for the superficial deposits, from knowledge of the depositional environment of the material provided by the Lexicon code.

### Artificial ground and Mass movement deposits

All artificial ground deposits with ‘unknown’ as the lithology, were coded with ‘mixed’ Predominant Flow Mechanism and Maximum and Minimum Permeability codes of ‘very high’ and ‘low’. Voids were removed from the dataset. Where the lithology was specified, unconsolidated artificial deposits were coded in the same way as for similar lithology superficial deposits, but the Minimum Permeability for clay was ‘low’. Consolidated lithologies (e.g. rock) were assumed to mainly comprise broken bedrock with ‘intergranular’ Predominant Flow Mechanism and Maximum and Minimum Permeability codes of ‘very high’ and ‘high’.

Mass movement deposits include foundered strata and landslide deposits. Foundered strata are considered to have similar properties to in situ superficial deposits or bedrock. For unconsolidated landslide rock types, the Predominant Flow Mechanism and Maximum and Minimum Permeability codes were similar to those for the same lithology superficial deposits, but the Minimum Permeability for clay was ‘low’. However, landslide deposits comprising consolidated strata are assumed to mainly comprise broken bedrock with ‘intergranular’ Predominant Flow Mechanism, and with Maximum and Minimum Permeability codes generally of ‘very high’ and ‘high’, unless the lithology contained mudstone.

### Superficial and Unconsolidated Deposits

Not all the following lithological combinations have been used to describe bedrock formations.

Clay is generally used in the lithological description to refer to the grainsize (clay-grade material) rather than implying the presence of clay minerals. The permeability value for clay depends on whether the deposits are saturated. For Recent deposits this typically reflects the genesis and topographic position. Where the clay is likely to be effectively saturated (e.g. tidal flat deposits, alluvium or beach deposits), the Predominant Flow Mechanism was coded as ‘intergranular’ (as the clay is unlikely to drain and dry out and crack/fracture) and both Maximum and Minimum Permeability codes were ‘very low’. Where the clay could be unsaturated (and hence could dry out and crack/fracture) the Predominant Flow Mechanism was coded as ‘mixed’ and the Maximum and Minimum Permeability ranged from ‘low’ to ‘very low’. Mixed lithologies including a significant proportion of clay, were coded in a similar manner with the Predominant Flow Mechanism incorporating whether the clay was likely to be saturated or not. In these cases, the other lithologies present provided the Maximum Permeability (as this was always coarser grained and hence more permeable, e.g. sand) and hence the clay has no effect on the Maximum Permeability. Areas where no superficial deposits are present/mapped have no data, and deposits below all mapped water bodies (including reservoirs) were not included in the dataset. Neogene and Palaeogene age clays were coded as having ‘fracture’ as the Predominant Flow Mechanism and ‘low’ and ‘very low’ Maximum and Minimum Permeability codes.

Where the lithology was unknown the Predominant Flow Mechanism was coded as ‘mixed’, unless the genesis was known and hence it was possible to infer that the deposits were likely to be effectively saturated (e.g. Intertidal deposits) when it was coded as ‘intergranular’. The Maximum and Minimum Permeability range was ‘very high’ to ‘very low’, unless this could be narrowed down from knowledge of the depositional environment of a deposit.

The Maximum and Minimum Permeability codes for gravel, clayey were ‘moderate’ and ‘low’ for clay-with-flints and ‘high’ and ‘low’ for Till and all other deposits, with ‘mixed’ as the Predominant Flow Mechanism.

It was assumed that there was a difference between gravel, clayey and gravel and clay; the former comprising gravel with a clay matrix, and the latter could comprise gravel, clay or a mixture of gravel and clay at a given location.

Clay, (silt,) sand and gravel are coded with ‘mixed’ or ‘intergranular’ Predominant Flow Mechanism depending on whether they are likely to be effectively saturated or not. Hummocky (moundy) glacial deposits are coded as having Maximum and Minimum Permeability codes of ‘high’ and ‘low’, all other deposits had ‘high’ Maximum Permeability and either ‘low’ or ‘very low’ Minimum Permeability codes.

The Maximum Permeability code for diamicton was reduced from ‘high’ to ‘moderate’, when it was known that sand and gravel lenses were likely to be absent (e.g. some of **Oadby Member**, **Coddington Till Member**).

Table 5: Typical Permeability codes for unconsolidated deposits.

| Lithology | Predominant flow Mechanism | Maximum Permeability | Minimum Permeability |
|---|---|---|---|
| Gravel | Intergranular | Very high | Very high |
| Sand | Intergranular | High | High |
| Silt | Intergranular | Moderate | Low |
| Clay | Fracture/Mixed/ Intergranular | Low/Very low | Very low |
| Sand and clay with gravel | Intergranular | High | Low |
| Gravel, clayey | Mixed | High/Moderate | Low |
| Sand and Gravel/ Gravel and Sand (with boulders) | Intergranular | Very high | High |
| Gravel, sand and silt/sand, gravel and silt | Intergranular | Very high | Moderate |
| Sand and silt | Intergranular | High | Moderate |
| Silt and sand | Intergranular | High | Low |
| Silty sand | Intergranular | High | Moderate |
| Silt and gravel/silt, sand and gravel | Intergranular | High | Moderate |
| Sandy silt | Intergranular | Moderate | Low |
| Silty clay | Intergranular/Mixed | Low | Very low |
| Clay and silt | Intergranular/Mixed | Low | Very low |
| Silt and clay | Intergranular/Mixed | Moderate | Low/Very low |
| Clay and sand | Intergranular/Mixed | Moderate | Very low |
| Sand and clay | Intergranular | High | Low |
| Clay, silt, sand and gravel/clay, sand and gravel | Intergranular/Mixed | High | Low/Very low |
| Gravel, sand, silt and clay | Intergranular | Very high | Low |
| Sand, silt and clay | Intergranular | High | Low |
| Clay, silt and sand | Intergranular/Mixed | Moderate | Very low |
| Unknown/undifferentiated | Intergranular/Mixed | Very high | Very low |
| Peat | Mixed | Low | Very low |
| Peat and silt | Mixed | Moderate | Low |
| Peaty silt and clay | Mixed | Low | Very low |
| Diamicton | Mixed | High/Moderate | Low |
| Clay, gravelly | Mixed | Low | Low |
| Shells | Intergranular | Very high | High |
| Regolith | Mixed | Very high | Low |

## BEDROCK

### General principles

- Where the age range fell across a boundary between two different codes, the minimum age (period) was used rather than the maximum.
- For all non-oolitic limestones, mudstones, metamorphic and igneous rocks, the Predominant Flow Mechanism is ‘fracture’.
- All sediments, Devonian and older, have ‘fracture’ as the Predominant Flow Mechanism.

- For any rock unit and lithology combination (LEX_RCS code) with a dissolution weighting score in the BGS GeoSure v8: Soluble Rocks dataset of 5 or more, it was assumed that a 'very high' Maximum Permeability code was possible. This included the four main lithostratigraphic rocks that can exhibit dissolution and karst (Palaeozoic and older limestones, Permian dolostones and Mercia Mudstone Marginal Facies, Jurassic limestones and Chalk).

### Limestones

- The Predominant Flow Mechanism for all limestones is 'fracture', except for the Middle Jurassic, mainly ooidal limestones, which were coded as 'mixed'.
- The Maximum Permeability allocated to limestones was generally 'very high' or 'high', depending on whether the limestones are known to develop dissolution features (with a BGS GeoSure v8: Soluble Rocks dissolution weighting score of 5 or more) or not. However, the range of scores (from 5-40) that are allocated the same Maximum Permeability value means that the possibility of solution features or karst occurring will vary considerably.
- Jurassic and Cretaceous limestones (e.g. Chalk, Cotswolds and Yorkshire Corallian, Great Oolite/Blisworth Limestone, Lincolnshire Limestone/Inferior Oolite) are generally subject to dissolution and can potentially develop karst features and often have both Maximum and Minimum Permeability codes as 'very high'. All other limestones aged Carboniferous or younger that are known to be soluble and can exhibit karstic features, were coded with 'very high' and 'high' Maximum and Minimum Permeability codes.
- Limestones that do not develop significant solution features (BGS GeoSure v8: Soluble Rocks dissolution weighting score less than 5) have been allocated 'high' Maximum and Minimum Permeability codes. Limestones with no dissolution weighting score have also generally been coded with 'high' Maximum and Minimum Permeability codes. There were a few exceptions for Carboniferous and older limestones that were coded with Maximum and Minimum Permeability as 'high' and 'moderate', 'moderate' and 'moderate' or 'moderate' and 'low'.
- When limestone occurs interbedded with other lithologies, the Maximum Permeability for the limestone depends on the BGS GeoSure v8: Soluble Rocks dissolution weighting score ('very high' or 'high') and the Minimum Permeability value reflects the permeability of the other lithology present (commonly mudstone).

### Dolomites

- Carboniferous and younger age dolostone, dolomitised limestone and dolomite, and dolomite-mudstone known to have potential for the development of solution features (BGS GeoSure v8: Soluble Rocks dissolution weighting score of 5 or more) have been coded with 'very high' and 'high' Maximum and Minimum Permeability codes. Devonian and older Palaeozoic dolostone with dissolution potential (weighting score of 5 or more) have been coded with 'very high' and 'moderate' Maximum and Minimum Permeability codes. Neoproterozoic dolostone (with no dissolution weighting score) was coded with Maximum and Minimum Permeability codes of 'moderate' and 'low'.
- Other dolomitised rocks were given Maximum Permeability values of 'very high' (if the BGS GeoSure v8: Soluble Rocks dissolution weighting score was 5 or more), otherwise 'high' to 'low', with Minimum Permeability values ranging from 'high' to 'low'; depending on associated lithologies.

### Sandstones

- The age and degree of cementation were both considered, with all three flow types ('intergranular', 'mixed' or 'fracture') being possible as the Predominant Flow Mechanism, and Maximum Permeability codes ranging between 'high' and 'moderate' and Minimum Permeability codes between 'high' and 'low'. In general, the older sandstones are better cemented and indurated, and therefore fracture flow is more likely to predominate, with lower Maximum and Minimum Permeability codes.

- Wacke is coded with ‘fracture’ Predominant Flow Mechanism and with Maximum and Minimum Permeability codes of ‘moderate’ and ‘low’.

### Siltstones and Mudstones

- Siltstones have generally been coded with ‘moderate’ and ‘low’ Maximum and Minimum Permeability codes and with ‘fracture’ Predominant Flow Mechanism.
- Most Devonian or younger siltstone and mudstone, or siltstone, mudstone and sandstone lithologies have been allocated Maximum and Minimum Permeability codes of ‘moderate’ and ‘low’, with most Silurian and older rocks having both Maximum and Minimum Permeability codes as ‘low’. The Predominant Flow Mechanism is generally ‘fracture’, apart from those of Cretaceous age that are ‘mixed’ and those of Jurassic age where the Predominant Flow Mechanism is ‘fracture’ or ‘mixed’ depending on the degree of induration.
- Argillaceous rock includes both silt and clay grade particles, and hence is coded with ‘fracture’ Predominant Flow Mechanism and has been allocated ‘low’ Maximum and Minimum Permeability codes.
- Jurassic Liassic age and older mudstone can generally transmit small amounts of water where fractured and has been allocated ‘low’ Maximum and Minimum Permeability codes.
- Mudstone that is younger than Liassic in age is generally less well indurated than older mudstone, hence they are likely to be less fractured, and consequently have been coded with ‘low’ and ‘very low’ Maximum and Minimum Permeability codes. Where mudstone is the primary lithology of a rock unit of variable lithology that is younger than Liassic age, the Minimum Permeability allocated was ‘very low’.
- Mudstone, sandy; it is assumed mudstone is dominant and hence the Predominant Flow Mechanism is always coded as ‘fracture’. For Liassic and older age rocks both Maximum and Minimum Permeability codes are ‘low’, but where younger than Liassic in age the Maximum and Minimum Permeability codes are ‘low’ and ‘very low’.
- Mudstone, dolomitic; siltstone, dolomitic; and argillaceous rocks, dolomitic have a ‘fracture’ Predominant Flow Mechanism and are coded as ‘moderate’ to ‘low’ Maximum and Minimum Permeability; unless they develop solution features and have a BGS GeoSure v8: Soluble Rocks dissolution weighting score.
- Where mudstone is the subordinate rock type in a rock unit of mixed lithology, the Minimum Permeability has been coded as ‘low’, unless the mudstone is unlikely to be hydraulically significant.

### Sedimentary rock cycles

These are Carboniferous in age (of Border Group, Clackmannan Group, Coal Measure, Strathclyde Group or Yoredale types) and are generally coded with ‘fracture’ as the Predominant Flow Mechanism and with Maximum and Minimum Permeability codes of ‘high’ and ‘low’.

### Ironstones

The Predominant Flow Mechanism can be ‘mixed’ or ‘fractured’ and the Maximum and Minimum Permeability codes range between ‘high’ and ‘low’, depending on the age, the specific lithology and degree of cementation of any particular rock unit. For example, the **Frodingham Ironstone Member** has a ‘mixed’ Predominant Flow Mechanism and Maximum and Minimum Permeability codes of ‘high’ and ‘moderate’, whereas for Ordovician ironstones ‘fracture’ is the Predominant Flow Mechanism with both Maximum and Minimum Permeability codes being ‘low’.

### Igneous and metamorphic rocks

The Predominant Flow Mechanism in all igneous and metamorphic rock units is 'fractured', apart from a limited number of Permian or younger volcaniclastic rocks in Scotland.

#### IGNEOUS ROCKS

- Intrusive rocks (e.g. diorite, dolerite, gabbro, granite, granodiorite, lamprophyre, pegmatite, peridotite, syenite, teschenite, tonalite, metabasalt) are all coded with both Maximum and Minimum Permeability codes as 'low'. Intrusive andesite, basalt, felsite, mugearite, rhyolite and trachyte were coded in the same manner. The only exceptions were Caledonian granite (and microgranite) in S W England, where kaolinisation of the alkali feldspars has increased permeability and they were coded with 'moderate' Maximum and 'low' Minimum Permeability codes.
- Extrusive lavas (e.g. andesite, basalt, dacite, basaltic andesite, felsite, hawaiite, mugearite, rhyolite, trachyandesite, trachybasalt, trachyte) were allocated 'moderate' and 'low' Maximum and Minimum Permeability codes if Devonian or younger in age, and 'low' Maximum and Minimum Permeability codes if Silurian or older in age.
- Extrusive tuff, tuffite and pyroclastic rock, and all agglomerate were coded with 'moderate' and 'low' Maximum and Minimum Permeability codes if Carboniferous or younger in age, and both Maximum and Minimum Permeability was 'low' if Devonian or older in age.
- Pyroclastic breccia, volcaniclastic breccia, volcaniclastic rock and tuffisite (including vents and plugs) are coded with 'moderate' and 'low' Maximum and Minimum Permeability codes if Devonian or younger in age, and 'low' Maximum and Minimum Permeability codes if Silurian or older in age.
- Volcaniclastic conglomerate of Devonian or younger age are coded with 'moderate' for both Maximum and Minimum Permeability codes, and for Silurian and older age with both Maximum and Minimum Permeability codes as 'low'
- Both igneous and sedimentary volcaniclastic sandstone and tuffaceous sandstone were generally allocated 'moderate' and 'low' Maximum and Minimum Permeability codes.
- All pitchstone and hyaloclastite were allocated 'low' Maximum and Minimum Permeability codes.

#### METAMORPHIC ROCKS

- Metalimestones; Maximum and Minimum Permeability codes of 'very high' and 'low' were allocated if potentially contain solution features (BGS GeoSure v8: Soluble Rocks dissolution weighting score 5-30), 'high' and 'low' (if dissolution weighting score less than 5) and 'high' or 'moderate' and 'low' if not subject to dissolution (no dissolution weighting score).
- Marbles were allocated 'low' for both Maximum and Minimum Permeability, unless potentially exhibiting solution features, where the Maximum Permeability was 'very high' (BGS GeoSure v8: Soluble Rocks dissolution weighting score 5 or more).
- Schists and gneisses were allocated 'low' Maximum and Minimum Permeability codes.

## CHANGES FROM VERSION 7

All new formation names and lithologies (LEX_RCS codes) were added.

Some minor changes were made as a result of a hydrogeologist's feedback.

Some of the igneous rocks were incorrectly coded, as to whether they were intrusive or extrusive; information from the original geological maps and their environment (data associated with BGS Geology 50k) in combination with the formation name and lithology, was used to correct these.

A few discrepancies in the way sedimentary codes were coded were corrected.

It was checked that the minimum period (rather than the maximum one) had been used, when permeability codes vary with age.

Silt and clay were split into ‘Intergranular’ and ‘Mixed’ Predominant Flow Type, depending on depositional environment, with the Maximum Permeability remaining ‘moderate’ but the Minimum Permeability being either ‘low’ or ‘very low’.

Standardisation of stratigraphic names have led to some changes in codes. This includes in the **Sherwood Sandstone Group**, the **Nottingham Castle Formation** is now part of the **Chester Formation**, and the **Kirklinton Sandstone Formation** now part of the **Helsby Sandstone Formation**, in both cases areas of sandstone that formerly had ‘high’ Maximum and Minimum Permeability codes, are now ‘high’ and ‘moderate’.

The coding of limestones and dolomites with potential for dissolution was formalised, by reference to the value in the BGS GeoSure: Soluble Rocks dissolution weighting scores database. This has led to some changes in the Maximum Permeability code, predominantly leading to an increase to ‘very high’ from ‘high’.

Triassic age halite and gypsum in the **Mercia Mudstone Group** was given a Maximum Permeability of ‘very high’ due to potential for dissolution features although not being scored in BGS GeoSure v8: Soluble Rocks dissolution weighting scores database.

# Glossary

| *Jargon* | Explanation |
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| *Age* | Indicates the geological period as a division of geological time. |
| *Anthropogenic* | Environmental change caused by or resulting from the influence of people or their activities either directly or indirectly. |
| *Aquifer* | A rock formation that is sufficiently porous and permeable to yield a significant quantity of water to a borehole, well or spring. The aquifer may be unconfined beneath a standing water table or confined by an impermeable or weakly permeable horizon. |
| *Artificial ground* | Ground surface has been significantly modified by human activity. Examples include recent anthropogenic or artificially modified ground where the ground surface has been significantly modified by human activity including quarrying, landscaping, land-raise, cuttings and embankments. |
| *BGS Geology 50k* | Generalised digital geological map data based on BGS's New Series 1:50 000 and 1:63 360 scale (one-inch to one-mile) maps with updated nomenclature. |
| *Bailer* | A bailer in hydrogeology is a hollow tube used to retrieve groundwater samples from monitoring wells. |
| *Bedrock* | The main mass of rocks forming the earth, laid down prior to 2.588 million years ago. Present everywhere, whether exposed at the surface in rocky outcrops or concealed beneath superficial deposits, artificial ground or water. Formerly called solid. |
| *Cementation* | Hardening and welding of clastic sediments (those formed from preexisting rock fragments) by the precipitation of mineral matter into the pore spaces. It is the last stage in the formation of a sedimentary rock. The cement forms an integral and important part of the rock, as its precipitation affects the porosity and permeability of the rock. |
| *Chalk* | Chalk is a soft white porous sedimentary rock formed from the tiny calcite and silica rich skeletons of marine microorganisms, which accumulated on the sea floor. |
| *Consolidation* | Compaction and cementation of sediments to the degree that they become coherent, relatively solid rock. Typical consequences of consolidation include an increase in density and a decrease in porosity. |
| *Devonian* | A period of geological time between 354 and 417 million years ago. |
| *Dissolution* | Process of water passing through soluble material such as gypsum, halite (rock salt) or limestone (including chalk). The dissolution process begins with the development of solution-enhanced features (e.g. joints, planes, pipes), and subsequently, allows for more rapid infiltration. The final result of this process can be large dissolved voids such as caves, sinkholes, sinking streams and large springs, creating a landscape known as karst. |
| *Dual porosity aquifer* | A rock characterized by primary porosity from original deposition and secondary porosity from some other mechanism, and in which all flow to the well effectively occurs in one porosity system, and most of the fluid is stored in the other. |

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| *Flow rate* | Rate at which groundwater moves through rock. |
| *Flow type* | This is the predominant flow mechanism for water to travel through the deposit. In this dataset we use ‘intergranular’, ‘mixed’ or ‘fracture’ |
| *Fracture flow* | The preferential flow of groundwater through dilated cracks, joints, bedding planes or other features of secondary porosity within an aquifer. It does not include preferential groundwater flow through a thin high-permeability horizon of an aquifer. |
| *Geohazard* | Geological and environmental conditions, involving long and short-term processes which may lead to widespread damage. There are many different types of geohazard with different natural and artificial processes causing them to occur. All have the potential to create problems for development of the human environment and threats to the safety and well-being of people.<br>Geohazards can develop quickly (seconds or minutes) in response to the processes that drive them, or take tens, hundreds, or thousands of years to develop to a point where they pose a danger. They are found in most parts of the world, including marine and fluvial environments. |
| *Groundwater flow* | The part of streamflow that has infiltrated the ground, has entered the phreatic zone (underground water in the zone of saturation beneath the water table), and has been discharged into a stream channel, or springs and seepage water. |
| *Hydraulic conductivity* | For an isotropic porous medium and homogenous fluid, the volume of water that moves in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Commonly, though imprecisely taken to be synonymous with permeability. |
| *Induration* | The process of hardening rocks through cementation of soil or porous rock. |
| *Infiltration* | The movement of water into a rock formation that has a structure through which water can pass. |
| *Igneous* | Rocks that originated when a molten magma or lava cooled and solidified. |
| *Intergranular flow* | Groundwater flows through bedrock through small interconnected pore spaces. |
| *Intrusive igneous dykes* | Magma which has pushed up towards the surface through cracks in the existing rock. Dykes are vertical or steeply dipping sheets of igneous rock. |
| *Jurassic* | The period of geological time between 142 and 205 million years ago. |
| *Karst* | Limestone terrains produced by dissolution of and attrition by groundwater. Karstic limestone is characterised by the absence of surface drainage and by sinks and rising streams connected underground by flow along major fissures or in cave systems. |
| *LEX-RCS* | A two-part attribute code describing the name of the geological unit(s) or deposit(s) represented and their composition.<br>Lexicon (or LEX) computer code used to identify the rock unit(s) or deposit(s) as listed in the BGS lexicon of Named Rock Units. |

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| | A rock-classification scheme (RCS) code of up to 6 characters (mostly letters forming the second part of the primary LEX-RCS attribute e.g. MDCO. The code can represent a single lithology or multiple lithologies. |
| *Limestone* | Any sedimentary rock consisting mostly of carbonates (calcite and/or *dolomite*). |
| *Lithological units* | A rock identifiable by its general characteristics of appearance colour, texture and composition defined by the distinctive and dominant, easily mapped and recognizable petrographic or lithologic features that characterize it. |
| *Lithology* | Rocks maybe defined in terms of their general characteristics of appearance: colour, texture and composition. Some lithologies may require a microscope or chemical analysis for the latter to be fully determined. |
| *Mass movement deposits* | Primarily superficial deposits or weathered bedrock that have moved downslope under gravity to form landslips. |
| *Metamorphic* | A pre-existing rock is chemically or physically altered by heat, pressure or chemically active fluids so that mineral grains are preferentially orientated or new types of crystals begin to grow. |
| *Permeability* | The term permeability, used in a general sense, refers to the capacity of a rock to transmit water. Such water may move through the rock matrix (intergranular permeability) or through joints, faults, cleavage or other partings (fracture or secondary permeability).<br>A stricter definition of permeability is that it is a measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient. It is a property of the medium only and is independent of the fluid. Commonly, but imprecisely, taken to be synonymous with the term Hydraulic Conductivity which implies the fluid is water. |
| *Piston flow* | When any given water front advances uniformly downwards through the pores of the aquifer, with the same velocity and negligible dispersion and mixing. |
| *Porosity* | The ratio of the volume of the interstices to the total volume of rock expressed as a fraction. Effective porosity includes only the interconnected pore spaces available for groundwater transmission; measurements of porosity in the laboratory usually exclude any void spaces caused by cracks or joints (secondary porosity). |
| *Predominant* | The main, principal, overriding, influential feature. |
| *Qualitative classification* | Qualitative data approximates and characterizes, it can be observed and recorded. This data type is non-numerical in nature. It is collected through methods of observations, allowing the determination of traits and characteristics. |
| *Sedimentary* | Rocks that originated from the broken up or dissolved and re-precipitated particles of other rocks. Examples include clay, mudstone, siltstone, shale, sandstone, limestone and conglomerate. Sedimentary rocks cover more than two-thirds of the Earth's surface. They are formed from the weathering and erosion products of rock material, which have been transported (usually by water, wind or ice), redeposited and later consolidated. |

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| *Sediments* | Silt, sand, rocks, fossils, and other matter carried and deposited by water, wind, or ice. |
| *Slug test* | A slug test is a type of aquifer test where water is quickly added or removed from a groundwater well, and the change in hydraulic head is monitored through time to determine the near-well aquifer characteristics. |
| *SuDS* | Sustainable drainage systems. |
| *Superficial deposits* | The youngest geological deposits formed during the most recent period of geological time, the Quaternary. They date from about 2.6 million years ago to the present. |
| *Unsaturated zone* | The zone between the land surface and the water table. It includes the capillary fringe and may contain water under pressure less than that of the atmosphere (synonymous with vadose zone). |

# 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.


ALLEN, D J, BREWERTON, L J, COLEBY, L M, GIBBS, B R, LEWIS, M A, MACDONALD, A M, WAGSTAFF, S J, AND WILLIAMS, A T. 1997. The physical properties of major aquifers in England and Wales. Eds. Allen D J, Bloomfield J P, and Robinson V K. *British Geological Survey Technical Report,* WD/97/34; Environment Agency R&D Publication 8.

AMERICAN GEOLOGICAL INSTITUTE. 1972. Glossary of Geology. Pub. American Geological Institute.

BALL, D F, MACDONALD, A M, Ó DOCHARTAIGH, B E, AND DEL RIO, M. 2004. Development of a groundwater vulnerability screening methodology for the Water Framework Directive, *British Geological Survey Report*, CR/03/249N to SNIFFER WFD 28.

DEARDEN, R. 2016a. User Guide for the Infiltration SuDS Map: detailed, *British Geological Survey Report,* OR/16/009.

DEARDEN, R. 2016b. User Guide for the Infiltration SuDS Map: summary, *British Geological Survey Report,* OR/16/010.

FETTER, C W. 1994. Applied Hydrogeology. Macmillan College Publishing Company, New York.

GRAHAM, M T, BALL, D F, Ó DOCHARTAIGH, B E, IRVING, K, AND SIMPSON, E. 2006. Scottish Aquifer Properties, 2006 interim report, *British Geological Survey Report,* CR/06/073N.

JONES, H K, MORRIS, B L, CHENEY, C S, BREWERTON, L J, MERRIN, P D, LEWIS, M A, MACDONALD, A M, COLEBY, L M, TALBOT, J C, MCKENZIE, A A, BIRD, M J, CUNNINGHAM, J, AND ROBINSON, V K. 1997. The physical properties of minor aquifers in England and Wales. Morris, B L, Jones, H K, Thomas, J E, Stuart, M E and Robinson, V K. (editors). *British Geological Survey Technical Report,* WD/00/004; Environment Agency R&D Publication 68.

LEE, K A, AND DIAZ DOCE, D. eds. 2017. User Guide for the British Geological Survey GeoSure dataset. Version 8. *British Geological Survey Report*, OR/17/050.

LEWIS, M A. 1989. 'Water' in Earth Science Mapping for planning, development and conservation. McCall, J, and Marker, B; Graham and Trotman (editors).

LEWIS, M A, CHENEY, C S, AND Ó DOCHARTAIGH, B E. 2006. Guide to Permeability Indices. *British Geological Survey Report*, CR/06/160N

MCKENZIE, A A, 2014. User Guide for the British Geological Survey National Depth to Groundwater Dataset. *British Geological Survey Report*, OR/15/006.

Ó DOCHARTAIGH, B, DOCE D D, RUTTER H K, AND MACDONALD A M. 2015. User guide: Aquifer Productivity (Scotland) GIS datasets, Version 2, Revised report, *British Geological Survey Open Report*, OR/15/003.