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Guide to Permeability Indices

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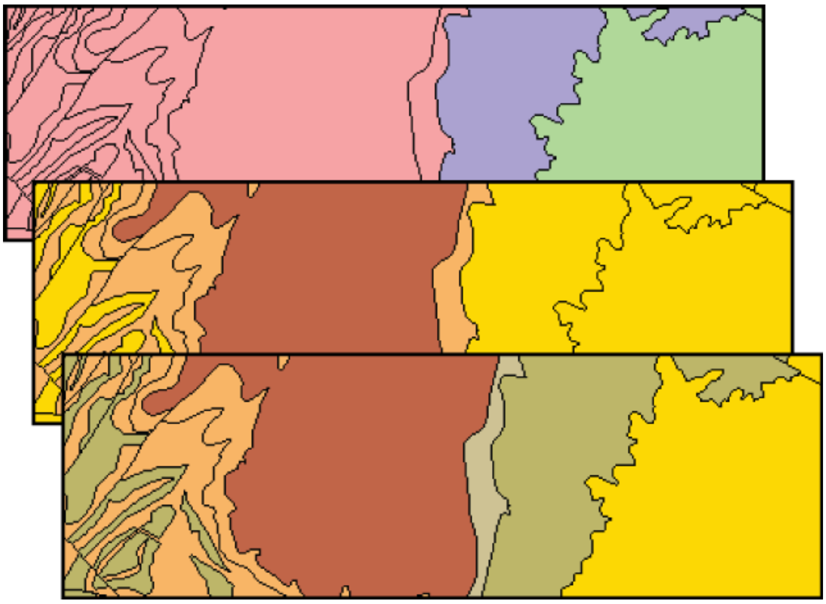

BRITISH GEOLOGICAL SURVEY

INFORMATION PRODUCTS PROGRAMME

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Guide to Permeability Indices

M A Lewis, C S Cheney and B É ÓDochartaigh

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British Geological Survey offices

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA

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Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

☎ 028-9038 8462 Fax 028-9066 2835
e-mail: gsni@detini.gov.uk

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345
e-mail: hydro@bgs.ac.uk

Sophia House, 28 Cathedral Road, Cardiff, CF11 9LJ

☎ 029–2066 0147 Fax 029–2066 0159

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Foreword

This report is a guide to using the BGS Permeability Indices dataset. It discusses what the indices mean and how the data have been derived. It describes the methodology used to classify each geological unit in DiGMapGB-50 (consisting of a unique combination of named stratigraphic rock unit and lithology) according to its predominant flow type and probable permeability.

Acknowledgements

The work described in this report is the product of a long history of investigations that have been undertaken by BGS related to the permeability of the rocks that underlie the United Kingdom and consequently it owes much to the efforts of colleagues in the BGS, past and present. In particular discussions with, and comments by, John Bloomfield, Nick Robins, Denis Peach, Derek Ball and Alan MacDonald have been very helpful and are gratefully acknowledged.

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Summary

This report describes how the BGS Permeability Index dataset has been prepared and includes guidance on how it can be used. It discusses what the indices mean and how the data have been derived. It describes the methodology used to classify each geological unit in the Digital Geological Map of Great Britain at 1:50 000 scale (DiGMapGB-50) according to its predominant flow type and probable permeability.

The Permeability Index 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. The Permeability Index codes have been allocated to every lithology (or combination of lithologies) for each named rock unit that has been mapped in DiGMapGB-50. This has been carried out for all four types of deposit shown as separate layers in the DiGMapGB-50 (artificial ground, mass movement deposits, superficial deposits and bedrock) dataset.

The Permeability Index consists of a three-part code representing:

- Predominant Flow Mechanism
- Maximum Permeability
- 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 second and third codes (Maximum and Minimum Permeability) indicate the range of flow rates likely to be encountered in the unsaturated zone for each rock unit and lithology combination. Five classes have been used for the Maximum and Minimum Permeability codes: very high, high, moderate, low and very low. The Maximum and Minimum Permeability values represent a likely permeability range for the specific named rock unit and lithology combination at, and immediately below, outcrop (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. 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 lithology combination occurs within a rock unit this value reflects the probable movement rate likely to be encountered in the least permeable horizons

The coding was based on expert judgement but with the following assumptions:

- the lithological component(s) for a particular named rock unit mapped within DiGMapGB-50 was correct, whether or not this was expected or normal for the given formation.
- the order of the deposits in a lithological ‘string’ was of relevance; it was assumed 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.
- that all of the possible geological layers (artificial, mass movement, superficial deposits and bedrock) that could be present at a site were mapped. It is, however,

known that this is not the case where the maps are old and the presence of superficial deposits was not always recorded. Similarly the presence of artificial deposits is constantly changing and only those present at the time of survey were recorded.

1 Introduction

1.1 BACKGROUND

Over the last decade, considerable effort has been devoted by 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 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 contamination 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 (if not impossible) 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.

It was decided at an early stage that a classification that can be applied to all of the rock units that occur in England, Wales and Scotland would need to be developed in a format that would permit easy dissemination. In consequence, DiGMapGB-50 was used as the basis for the classification since this was already available in digital form and was linked to the Lexicon, 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.

1.2 PERMEABILITY AND HYDRAULIC CONDUCTIVITY

Both 'permeability' and 'hydraulic conductivity' (Box 1) are usually measured under saturated flow conditions. 'Intrinsic permeability' (Box 1) is normally measured on horizontal or vertical core samples in a laboratory and hence generally represents the matrix permeability of a small plug sample. Where samples are only partially saturated the 'relative permeability' of each phase (e.g. liquid and gas) can theoretically be obtained. Hydraulic conductivity is commonly obtained from pumping tests (including slug and bailer tests) carried out in wells or boreholes and represents significantly larger rock volumes than the permeability values obtained from laboratory tests. Field hydraulic conductivity values are generally a measure of predominantly horizontal flow in the saturated zone to pumped boreholes.

Box 1. Definitions of hydraulic conductivity and permeability.

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.

The hydraulic conductivity of a material is defined 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

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). The SI unit of measurement is m^2 (for saturated flow).

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

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

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.

Generally, hydraulic conductivity values in a horizontal orientation are greater than those in a vertical orientation, due to the layering of the predominantly sedimentary rock sequence of the UK; this is especially the case for sedimentary rocks in England. Table 1.1 indicates the relative hydraulic conductivity values of various deposits under saturated flow conditions. In unconsolidated deposits, intergranular flow is the predominant flow mechanism. In consolidated sedimentary rocks and igneous and metamorphic rocks, fracture flow will almost invariably occur and hence a wide range of values of hydraulic conductivity can occur for any one lithology, depending on both the degree of the fracturing and the size of the fractures. The degree of cementation, lithological variation and induration are also factors that affect measured hydraulic conductivity values.

1.2.1 Unsaturated zone flow

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*	5×10^{-7} to 10^{-3}
Loess	10^{-2} to 1
Silt	10^{-3} to 10^{-1}
Sand	10^{-1} to 5×10^{2}
Gravel	5×10^{1} to 5×10^{4}
Sand and gravel	5 to 10^{2}
Till	10^{-7} to 5×10^{-1}
Halite	5×10^{-6} to 5×10^{-3}
Limestone, dolomite	5×10^{-6} to 10^{0}
Karstic limestone	10^{-1} to 10^{3}
Chalk	Up to 5
Sandstone	5×10^{-5} to 2×10^{1}
Shale	5×10^{-8} to 10^{-4}
Lignite	10^{-1} to 10
Friable tuff	2×10^{-2} to 2
Welded tuff, ignimbrite	5×10^{-5} to 2×10^{-1}
Dense basalt	10^{-6} to 10^{-3}
Fractured basalt	10^{-4} to 1
Vesicular lava	10^{-4} to 10^{-3}
Lava	Less than 5×10^{-9} to 10^{3}
Slate	5×10^{-9} to 5×10^{-6}
Schist	10^{-7} to 10^{-4}
Dense crystalline rock	5×10^{-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.

The permeability of the unsaturated zone is complex even when dealing with an idealised, infinite, homogeneous, isotropic granular aquifer where the infiltration of water in the unsaturated zone depends on the gravity potential (head) and the soil potential. At moisture potentials close to the specific retention, the 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. The unsaturated hydraulic conductivity of a clay may paradoxically be greater than that of a sand, because the sand may retard downwards movement of infiltrating water owing to its low unsaturated hydraulic conductivity in the drained state. The clay, comprising small pore spaces, 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.

However, 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.

1.2.2 Permeability Indices

The term hydraulic conductivity has a very precise definition in terms of flow under saturated conditions, and should not be used in connection with a classification relating to vertical flow rates through the unsaturated zone. The term *Permeability Index* has been developed to provide a qualitative classification by which every named lithostratigraphic rock unit and different lithology (or combination of lithologies) for these rock units that has been mapped, and hence shown on DiGMapGB-50, can be ascribed an index code. The index is based upon known physical characteristics as determined for flow in the saturated zone but with appropriate variations where vertical flow through the unsaturated zone in a specific rock or lithology is known to depart from these characteristics. The index codes for many unconsolidated deposits, where intergranular flow is the main flow mechanism, could be equated to an **approximate** range of hydraulic conductivity values. However, Permeability Index codes **should not** be used to imply that any particular numerical flow rate could be applied to any particular lithology under unsaturated conditions. Moreover, the use of the term ‘permeability’ within this report should be interpreted with the widest possible meaning, and does not imply any specific value or range of values. A competent hydrogeologist should be consulted before attempting to apply the Permeability Indices to flow conditions in the unsaturated zone.

The derivation of the Permeability Index codes is described below (Section 2). Integration with DiGMapGB-50 has allowed complete coverage of Great Britain to be achieved.

1.3 DIGMAPGB-50

DiGMapGB-50 (Digital Geological Map of Great Britain), provides 1:50,000 scale digital data for England, Wales and Scotland. The current versions of all the existing paper maps were digitised, with the nomenclature, particularly of older maps, updated to current usage. A complete listing of the lithostratigraphic rock unit names used within DiGMapGB-50 is contained within the BGS Lexicon, which also provides extensive details regarding lithology, geographical occurrence, former nomenclature and age. Every polygon has been attributed with both a lithostratigraphic rock unit name, based on lithostratigraphical, or chronostratigraphical nomenclature (Lex) and a lithological (Rock) description, to provide a Lex_Rock combination. For example, 'Dyrham Formation-silty clays'.

The above Lex_Rock attribution has been applied to all four of the different mapped layers in DiGMapGB-50, namely:

- Artificial ground
- Mass movement deposits
- Superficial deposits
- Bedrock

At any given location, bedrock will always be present in the subsurface and could be overlain by one or more of the other types of deposit, but these other three younger deposits may be (and frequently are) absent.

1.4 CONCEPTUAL MODEL

The Permeability Index is 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 Index codes were attributed to every lithology or combination of lithologies ascribed to each named rock unit that has been mapped and is in DiGMapGB-50. The derivation of each of the three Permeability Index codes is detailed below (Section 2). 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 Index codes. The codes were ascribed solely on the known hydrogeological characteristics of the various lithologies, taking into account their age, 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 Index 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.

1.5 LIMITATIONS ON THE CONCEPTUAL MODEL AND POSSIBLE FUTURE IMPROVEMENTS

The Permeability Indices can be used to give a qualitative indication of the degree of variability of permeability on the catchment scale. The Permeability Indices are based on 1:50 000 scale geological mapping data and hence should only be used for regional scale planning purposes. These indices only give an indication of permeability and should not be used at the site-specific scale, when site investigations should be carried out. Neither should they be converted to saturated hydraulic conductivity values or used to provide quantitative values for rates of movement of pollutants to the water table.

1.5.1 Other factors affecting permeability

As only the age and lithology were used to attribute the Permeability Indices, the following important factors were not taken into account, 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. Soil data was not taken into account in this classification, but could be considered as an additional layer above the uppermost geological layer of DiGMapGB-50.

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.

GEOLOGICAL STRUCTURE

The effects of geological structure (folding and faults) was not incorporated. This could be done only for the limited areas where relevant information is available.

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 DiGMapGB-50 digital mapping since every unit of the Chalk covers a wide range of topographic positions. However, it would be possible to integrate an additional dataset based on topographic variation into the assessment of Permeability Indices.

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 taken into account, it would be possible to produce travel time maps for the main UK aquifers; however, there is insufficient information to provide national coverage of all the formations.

2 Permeability Index Codes

The Permeability Index codes have been allocated to each lithology or combination of lithologies for each named rock unit that has been mapped in DiGMapGB-50. This has been carried out for all four types of deposit as defined as separate layers in DiGMapGB-50 (Section 1.3). The Permeability Index codes comprise three parts, representing each of the following parameters:

- Predominant Flow Mechanism
- Maximum Permeability
- Minimum Permeability

The first code denotes the predominant flow mechanism by which fluid will migrate from the ground surface through the unsaturated zone of a specific rock unit and lithology. There are three classes:

- Intergranular
- Fracture
- Mixed (intergranular and fracture)

The second and third codes (Maximum and Minimum Permeability) indicate the range of flow rates likely to be encountered in the unsaturated zone for a particular named rock unit and lithology (Lex_Rock) combination. Five qualitative classes have been used for each code:

- very high
- high
- moderate
- low
- very low

These Maximum and Minimum Permeability values represent a likely permeability range for the specific named rock unit and lithology combination at, and immediately below, outcrop (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 a specific rock unit and 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 value reflects the probable movement rate likely to be encountered in the least permeable horizons.

Generally, for a particular 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 type and lithology combination is relatively narrow. For example the rates of movement are not likely to vary appreciably between different Carboniferous age karstic limestones and they will all have similar codes. The same is true of Jurassic age clays which are likely to all be relatively impermeable. However, for specific lithologies of differing ages the codes allocated will be less similar, as the degree of dissolution, fracturing and consolidation can vary widely with age. For some limestones, the Permeability codes can also be very different, as a karstic limestone will have high values but for unfractured massive limestones that do not contain karstic dissolution features, they may be considerably lower. Where a wide range of lithologies are covered by a rock unit and lithology combination, the maximum would represent the most permeable lithology (e.g. gravel) and the minimum the least permeable (e.g. clay). Therefore, where the amount of secondary permeability caused by fracturing or the lithology (e.g. glacial deposits or alternating beds of limestones and mudstones) can be very variable, there could be two, three or even four class differences between the Maximum and Minimum Permeability values.

Table 2.1 provides a listing of Permeability Indices for typical lithologies. A comparison with Table 1.1 shows that each of the values (very high, high, moderate, low and very low) for the unconsolidated deposits, might be considered approximately equivalent to about two or three orders of magnitude difference in hydraulic conductivity as these values can vary by twelve orders of magnitude from 10^{-13} to 10^{-1} m/sec (10^{-8} to 10^{4} m/d).

Table 2.1 Typical Flow Mechanism and Permeability codes for a range of lithologies.

Lithology	**Predominant Flow Mechanism**	**Maximum Permeability**	**Minimum Permeability**
Gravel	Intergranular	Very high	Very high
Sand	Intergranular	High	High
Silt	Intergranular	Moderate	Moderate
Clay	Mixed	Low	Very low
Limestone	Fracture	Very high	Moderate
Sandstone	Mixed	High	Low
Mudstone	Fracture	Low	Very low
Granite	Fracture	Moderate	Low
Trachyte	Fracture	Moderate	Low
Gneiss	Fracture	Low	Low

There is generally a greater variability between the Maximum and Minimum Permeability where the Predominant Flow Mechanism is fractured than where it is intergranular. This is shown by the potential for extreme fracturing (karst) where some blocks of rock could be virtually impermeable whilst others contain large open conduits.

Neither of the assigned values takes into account the thickness of either the unsaturated or saturated part of the lithostratigraphical unit or the thickness of overlying units. Hence interpretations, using the indices, need to incorporate this, using site specific data. Without this thickness information, it is impossible to derive a ‘combined Permeability Index’ of the different layers present. Individual sites will always require more detailed assessments to determine the specific impact of potential contamination on groundwater resources. For example, the physical and chemical characteristics of the soil, the thickness of, and depth to water in, the different lithostratigraphic layers as well as factors such as weathering, geological structure and topographic position (see section 1.5.1) all need to be taken into consideration when assessing the overall vulnerability of groundwater to pollution from the ground surface at a particular location.

2.1 METHODOLOGY

The coding was carried out in several phases. Initially all the possible lithological codes (rock type descriptions) occurring in DiGMapGB-50 (about 1000) for the four different types of deposits (artificial, mass movement, superficial and bedrock) were allocated Permeability Index codes. Generally, a lithological code is unique to one, or possibly two, of the four different types of deposits (e.g. sandstone and granite are confined to bedrock and boulders to superficial and mass movement deposits). Where a lithology occurs in more than one type of deposit, the lithology was given the same Permeability Index code, unless the type of deposit (mode of occurrence) could widen the likely range of values. For example, artificial and naturally occurring deposits of similar lithologies may have undergone different amounts of compaction, causing differences in permeability. Mass movement deposits will tend to be more broken up and hence be more permeable, whilst superficial deposits tend to be less well indurated (and again more permeable), than bedrock.

The next phase was to attribute codes to every lithostratigraphic and lithological (Lex_Rock) code in DiGMapGB-50 (about 10,000). The entries were initially populated using the codes assigned during the coding of the lithological codes, then refined on the basis of expert hydrogeological judgement. Two related methodologies were adopted for England and Wales and for Scotland.

2.1.1 Methodology

For entries where the hydrogeological properties of a particular lithostratigraphy were unknown, the initial generalised Permeability Index was not altered. However, where hydrogeological knowledge of a named rock and lithology combination or the age of the formation could be used as a guide to the anticipated degree of cementation or induration, and the generalised Permeability Index could thus be refined, the initial value was amended accordingly. The latter was true for the vast majority of the entries. In some cases, it was recognised that local variation in lithology (such as thin laterally impersistent mudstones or highly cemented bands) could have an effect on the vertical rates of movement but this was not considered to be particularly significant in terms of the overall rates of movement over the whole areal extent of a particular rock unit.

2.1.2 Quality assurance

The codes were then checked for internal inconsistencies by comparing the codes allocated to all rocks of a similar age and lithology and by removing internal inconsistencies in the coding for a particular age of rocks. For example, it was ensured that the index code allocated to silty sand was at least as permeable as the code allocated for sandy silt for rocks of a similar age.

Once all named rocks and lithology combinations had been coded, the Permeability Indices were integrated with the corresponding DiGMapGB-50 shapefiles. The resulting digital maps for England, Wales and Scotland were checked to ensure that the outline of areas that have high permeabilities coincided with the main aquifers and that the areas of low permeabilities coincided with the aquitards. In addition, the maps were reviewed in detail. This resulted in the identification of a number of mismatches at geological map sheet boundaries. The causes of these mismatches were investigated to ensure that the lithologies mapped on adjacent sheets had been coded correctly. The main cause of mismatches at geological sheet boundaries was a difference in the lithological descriptions for a particular named rock in the geological mapping making up adjacent DiGMapGB-50 map sheets. Since these lithological descriptions were an attribute of the DiGMapGB-50 background dataset and the Permeability Indices were in fact correct for the specific named rock/lithological combinations, no amendment was considered necessary. Such mismatches will disappear automatically when lithological inconsistencies in the DiGMapGB-50 dataset are resolved. Elsewhere they correctly represent the fact that the lithology of a given rock unit changes progressively from one area to another (e.g. the London Clay Formation contains more sand in the Hampshire

Basin than in the London Basin). Comparisons were made between the English, Welsh and Scottish data and where appropriate amendments were made to ensure consistency across Great Britain.

3 Permeability Index Coding

The following sections describe the assumptions made and the rationale behind the coding of each of the main types of deposit.

3.1 ASSUMPTIONS

The following basic assumptions were applied whilst allocating Permeability Index codes;

- the lithological component(s) for a particular named rock unit mapped within DiGMapGB-50 was correct, whether or not this was expected or normal for the given formation.
- the order of the deposits in a lithological 'string' was of relevance; it was assumed 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.
- that all of the possible geological layers (artificial, mass movement, superficial deposits and bedrock) that could be present at a site were mapped. It is however known that this is not the case where the maps are old and the presence of superficial deposits was not always recorded. Similarly the presence of artificial deposits is constantly changing and only those present at the time of survey were recorded.

3.2 SUPERFICIAL AND UNCONSOLIDATED DEPOSITS

Table 3.1 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. Not all the following lithological combinations have been used to describe bedrock formations.

Clay is generally used in the lithological description to refer to grainsize (clay-grade material) rather than implying the presence of clay minerals. The Permeability Index 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 flow type 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 Type was coded as 'mixed' and the Permeability Index 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. 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 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 (for example **Intertidal deposits**) and then 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 **clayey gravel** were 'moderate' and 'low' for clay-with-flints and the South West England river terrace deposits and were 'high' and 'low' for Till and all other deposits.

Clay, (silt,) sand and gravel Hummocky (moundy) glacial deposits were coded as 'high' to 'low', all other geneses were coded as 'high' to 'very low'.

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.

Table 3.1 Permeability Index codes for unconsolidated deposits.

Lithology	**Predominant Flow Mechanism**	**Maximum. Permeability**	**Minimum Permeability**
Gravel	Intergranular	Very high	Very high
Sand and gravel	Intergranular	Very high	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
Clayey gravel	Mixed	High/moderate	Low
Sand and Gravel or Gravel and Sand	Intergranular	Very high	High
Sand and silt	Intergranular	High	Moderate
Silt and sand	Intergranular	High	Low
Silty sand	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	Moderate	Low
Clay and sand	Intergranular/Mixed	Moderate	Low
Sand and clay	Intergranular	High	Low
Clay, silt, sand and gravel or 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 or 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
Boulder clay/pebbly clay	Mixed	Low	Low

3.3 BEDROCK

3.3.1 General principles

- For all non-oolitic limestones, mudstones, metamorphic and igneous rocks the Predominant Flow Mechanism is ‘fracture’.
- All sediments Devonian and older, have ‘fracture flow’ as the Predominant Flow Mechanism.
- For the four main lithostratigraphic types of karst (Palaeozoic and older limestones, Mercia Mudstone Marginal Facies, Jurassic Limestones and Chalk) it was assumed that a ‘very high’ Maximum Permeability code was possible in all cases.

3.3.2 Limestones

- The Predominant Flow Mechanism for all limestones is ‘fracture’, except for the Middle Jurassic oolitic 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 karstic features or not.
- Jurassic and Cretaceous limestones (e.g. Chalk, Lulworth Formation, Cotswolds and Yorkshire Corallian, Great Oolite/Blisworth Limestone, Lincolnshire Limestone) are potentially karstic and have both Maximum and Minimum Permeability codes as ‘very high’. All other limestones aged Carboniferous or younger that are known to develop karstic features, were coded with ‘very high’ and ‘high’ Maximum and Minimum Permeability codes.
- Generally all limestones that do not develop karstic features have been allocated ‘high’ Maximum and Minimum Permeability codes. There were a few exceptions for pre-Carboniferous limestones that were coded as ‘high’ to ‘moderate’ or with both Maximum and Minimum Permeability codes as ‘moderate’.
- When limestone occurs interbedded with other lithologies, the Maximum Permeability for the limestone depended on whether it was karstic (‘very high’) or not (‘high’) and the Minimum Permeability value reflects the permeability of the other lithology present (commonly mudstone).

3.3.3 Dolomites

- Dolomite rock, dolomitised limestone and dolomite-mudstone known to have potential for the development of karstic features have generally been coded with ‘very high’ and ‘high’ Maximum and Minimum Permeability codes.
- where there are no known karstic features these rocks have been coded with both Maximum and Minimum Permeability codes as ‘high’.
- Dolostones have been coded with ‘very high’ and ‘moderate’ Maximum and Minimum Permeability codes.

3.3.4 Sandstones

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

- Greywackes were coded as having Maximum and Minimum Permeability codes of ‘moderate’ and ‘low’.

3.3.5 Siltstones and Mudstones

- Siltstones have generally been coded with ‘moderate’ and ‘low’ Maximum and Minimum Permeability codes and with ‘fracture’ as the Predominant Flow Mechanism.
- Devonian or younger siltstone and mudstone or siltstone, mudstone and sandstone mixed lithologies have been allocated Permeability codes of ‘moderate’ to ‘low’, with Silurian and older rocks having both Maximum and Minimum Permeability codes as ‘low’. In all of these cases the Predominant Flow Mechanism is considered to be ‘fracture’.
- Jurassic rocks with mixed siltstone and mudstone lithologies have ‘moderate’ to ‘low’ Permeability codes with the Predominant Flow Mechanism being ‘fracture’ or ‘mixed’ depending on the degree of induration.
- Jurassic argillaceous rocks (undifferentiated) include both silt and clay grade particles, and hence are coded as predominantly ‘fracture’ flow and have been allocated ‘low’ Maximum and Minimum Permeability codes.
- Jurassic Liassic age or older mudstones can generally contain small amounts of water where fractured and have been allocated ‘low’ Maximum and Minimum Permeability codes.
- Mudstones that are younger than Liassic in age are generally less well indurated than older mudstones, hence they are likely to be less fractured, and consequently have been coded with ‘low’ to ‘very low’ Permeability codes. Where ‘mudstone’, ‘sandy mudstone’ or ‘argillaceous’ were the primary lithology of a rock unit of variable lithology that is younger than Liassic age, the Minimum Permeability allocated was ‘very low’.
- Sandy mudstone: it was assumed that the mudstone is dominant and hence the Predominant Flow Mechanism was always coded as ‘fracture’. For Palaeozoic age rocks both Maximum and Minimum Permeability codes are ‘low’, but where younger than Palaeozoic the Permeability codes are ‘low’ and ‘very low’.
- Dolomitic mudstone (only the Sidmouth Mudstone Formation) has a predominantly ‘fracture’ flow mechanism and has been coded as ‘moderate’ to ‘low’.
- 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.

3.3.6 Undivied cyclic sedimentary rocks

- These were generally Carboniferous in age and are coded with ‘fracture’ as the Predominant Flow Mechanism and with Maximum and Minimum Permeability codes of ‘high’ and ‘low’.

3.3.7 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 has a ‘mixed’ Predominant Flow Mechanism and Maximum and Minimum Permeability codes of ‘high’ and ‘moderate’, whereas in Ordovician ironstones ‘fracture’ flow predominates with both Maximum and Minimum Permeability codes being ‘low’.

3.3.8 Igneous and metamorphic rocks

- The predominant flow mechanism in all igneous and metamorphic rock units is ‘fractured’.

Igneous rocks

- **Intrusive rocks** (diorite, dolerite, felsite, gabbro, granite, granodiorite, lamprophyre, pegmatite, peridotite, syenite, teschenite, tonalite, trachyte, hyaloclastite, metabasalt) are all coded with both Maximum and Minimum Permeability codes as ‘low’. Intrusive basalts and rhyolites and trachytes were coded in the same manner. The only exceptions were Caledonian granites (and microgranites) in S W England, where kaolinisation of the alkali feldspars has increased permeability and they were coded with ‘moderate’ to ‘low’ Permeability codes.
- **Extrusive lavas** (andesite, basalt, dacite, basaltic andesite, hawaiite, mugearite, rhyolite, trachyandesite, trachybasalt, trachyte) were allocated ‘moderate’ to ‘low’ Permeability codes if Devonian or younger in age and ‘low’ Maximum and Minimum Permeability codes if Silurian or older in age.
- **Extrusive ashes, tuffs** and **agglomerates** were coded with ‘moderate’ to ‘low’ Permeability codes if Carboniferous or younger in age and both Maximum and Minimum Permeability as ‘low’ if Devonian or older in age.

Metamorphic rocks

- **Metalimestones**; Permeability codes ranging from ‘very high’ to ‘low’ were allocated if potentially karstic and ‘high’ to ‘low’ if not potentially karstic.
- **Marbles** were allocated ‘low’ for both Maximum and Minimum Permeability, unless potentially karstic.
- **Schists** and **gneisses** were allocated ‘low’ Maximum and Minimum Permeability codes.

3.4 ATTRIBUTION OF DIGMAPGB-50 WITH PERMEABILITY INDEX CODES

Once the hydrogeologists had assigned Permeability Index codes it was necessary to attribute DigMapGB-50 with the codes using a GIS.

4 Limitations on Use of the Permeability Indices

The Permeability Indices can be used to give a qualitative indication of the degree of variability of vertical permeability at the catchment scale. They should not be used at the site-specific scale, when site investigations should be carried out. Neither should they be converted to saturated hydraulic conductivity values and used to provide quantitative values for rates of movement of pollutants to the water table.

In addition to the limitations on the conceptual model of Permeability Indices described in Section 1.5, there are specific limitations imposed by mismatches at geological sheet boundaries and associated with the order of deposits in lithological descriptions. These are briefly described below.

4.1 MISMATCHES

The shapefiles produced by combining DiGMapGB-50 with the table of Permeability Indices have a number of mismatches at geological sheet boundaries. This is caused by a particular formation having different lithological codes for the same named rock unit on adjacent sheets. In some cases this reflects the fact that the formation does change in lithology across the outcrop of a rock unit and this is reflected in the lithological descriptions for that unit on each of the two adjoining map sheets. Howver, in consequence, the junction between the two lithologies appears to occur exactly at the geological sheet boundary. However, in other cases such changes are caused by different interpretations of similar lithologies or a reversal of the order in which the same mixture of lithologies are listed (e.g. sand, silt, and clay reversed to read clay, silt and sand on adjoining sheets). By coding up the ascribed lithologies rather than attempting to produce a seamless map, it highlights areas where there may be lithological inconsistencies and the map will automatically become seamless when these lithological discrepancies are resolved. Mismatches caused by coding anomalies will become fewer with time as DiGMapGB-50 is refined.

Other examples of changes at sheet boundaries relate to whether limestones are thought to be potentially karstic, this depends both on the geomorphology and the presence of overlying superficial deposits (e.g. the Pendleside Limestone Formation is classified as having ‘high’ Maximum and Minimum Permeability codes, whilst the continuation eastwards of this unit as the Chatburn Limestone Formation is classified with ‘very high’ and ‘high’ as the Maximum and Minimum Permeability codes).

4.2 ORDER OF DEPOSITS IN LITHOLOGICAL DESCRIPTIONS

It was assumed that the first named lithology in the lithological description of a deposit is the dominant one. The fact that there are mismatches at 1:50 000 geological sheet boundaries due to the order of the deposits in the lithological description being reversed, means that the assumption that the order is relevant may not always be the case. It was also noted that the lithologies were generally either in increasing or decreasing order of grain size (e.g. clay, silt, sand and gravel or gravel, sand, silt and clay), it was very rare for a deposit to be described as sand and silt with some gravel.

4.3 OVERALL PERMEABILITY INDICES

The current classification has produced a Permeability Index for every mapped rock unit and lithology combination for each of the four different layers (artificial deposits, mass movement deposits, superficial deposits and bedrock) delineated in DiGMapGB-50. No attempt was made to combine the separate layers to produce a single Permeability Index value that could be applied to the subsurface below any given point. Information regarding the thickness of the stratigraphic units and the depth to water would be required, as well as details of any changes of lithology with depth.

5 Confidence

Confidence scores are not yet available for the Permeability Indices dataset. This is because an important factor in the confidence associated with the Permeability Indices is the confidence of the underlying DiGMapGB-50 database and the latter is not yet available. However, when using the Permeability Index, the difference between the Maximum and Minimum Permeability codes gives an indication of the confidence with which either the Maximum or Minimum Permeability codes can be regarded as being representative and whether there is likely to be a significant variation in permeability.

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