Final Report **Project WFD 34**

An approach to hydrogeological assessment of Quaternary deposits in the UK
Part 2 Methodology and Testing

October 2006

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EXECUTIVE SUMMARY

WFD 34 An approach to hydrogeological assessment of Quaternary deposits in the UK (October 2006)

Project funders/partners: SNIFFER, Environment Agency, Scottish Environment Protection Agency, Environment & Heritage Service.

Background to research

Superficial (Quaternary) deposits are an important moderator of potential recharge to a bedrock aquifer and they form a key component to the vulnerability of that aquifer to pollution. Understanding the processes by which superficial deposits transmit recharging water to the water table and how the deposits attenuate pollutants as the water passes through them is a vital component of the characterisation of groundwater bodies as required by the Water Framework Directive (WFD).

Superficial deposits may modify both storage and vertical transport in a hydrogeological system, in particular:

- the quantity of recharge (and/or its spatial distribution) to the underlying aquifer;
- the vulnerability of the aquifer to pollution (absorption potential of the deposits, i.e. presence of clay minerals and/or organic material such as peat);
- the aquifer characteristics of the groundwater system (especially aquifer storativity);
- groundwater quality (infiltration moving downwards through these deposits to the underlying aquifer, may mobilise solutes).

Objectives of research

The project aims to improve the understanding and analysis of the hydrogeological processes pertaining to recharge and attenuation that occur in the Quaternary superficial deposits in the UK. The objectives are:

- To develop a fit-for-purpose method for improving the current hydrogeological understanding of Quaternary deposits.
- To provide a longer-term strategy to develop this method to satisfy the increased hydrogeological understanding of superficial deposits that will be required for many elements of the Water Framework Directive including further characterisation, monitoring site selection and programme of measures.

This report describes the main components of the developed project methodology and future application and development opportunities. The background to the issues and summary of current knowledge are described in the accompanying Part 1 report.

The Part 1 report describes two initial components of the overall study:

- A review of approaches taken to Quaternary hydrogeological interpretation both within the UK and elsewhere; and.
- It identifies and describes the key factors for Quaternary hydrogeological understanding, relevant for the assessment of groundwater bodies, as required by the WFD.

The Part 2 report (this report) describes:

- A review of the current status of Quaternary mapping in the UK.
- A description of the development of a methodology to assess the superficial strata in terms of recharge potential and attenuation potential.

- Trialling of the methodology.
- Consideration of the methodology limitations, data scarcity, a route map for future work and data Intellectual Property Rights (IPR) issues.

Key findings and recommendations

A scale independent methodology has been trialled for the whole of the UK and compared against existing assessments of groundwater recharge and groundwater vulnerability. These comparisons show that the methodology is producing plausible results. The methodology follows a rigid and defensible protocol which can be applied at various scales. It is recommended that the methodology be used to populate a new database derived from 1: 50 000 scale input data in order that a useable assessment tool can be developed to assist in the further characterisation of groundwater bodies.

One of the principal strengths of the methodology is that it is designed to capture primary geological and hydrogeological expert knowledge in a systematic manner. Future development of the methodology could allow, for a particular study area, multiple input of knowledge and experience over time, building, in an iterative way, an improved conceptual understanding of hydrogeological processes within a unique archive.

Key words: recharge, attenuation, GIS, Quaternary

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1. INTRODUCTION

Superficial deposits cover approximately 90% of the UK landmass (see Figure 1). The project WFD 34 *An approach to hydrogeological assessment of Quaternary Deposits in the UK* aims to improve the understanding and assessment of the influence that Quaternary deposits in the UK have on hydrogeological processes pertaining to recharge and attenuation of pollutants. The work has been carried out by the British Geological Survey on behalf of SNIFFER.

Knowledge of the influence that different Quaternary deposits have is key to understanding recharge and attenuation processes. This knowledge will assist in the further characterisation of quantitative and chemical status and implementation of suitable programmes of measures. The project aims to develop a methodology for assessing these deposits and to provide recommendations on data gathering and assimilation such as domains mapping. The scope of the project is constrained by the pace of implementation of the Water Framework Directive (WFD) and a cost effective and achievable output is essential. The objectives are:

- To develop a fit-for-purpose method for improving our hydrogeological understanding of Quaternary deposits.
- To provide a longer-term strategy to improve this method to satisfy the increased understanding that will be required for the long-term management and protection of groundwater resources.

Part 1 of the project report describes two components of the background of the overall study:

- A review of approaches taken to Quaternary hydrogeological interpretation both within the UK and elsewhere.
- Identification and description of the key factors for Quaternary hydrogeological assessment of groundwater bodies implicitly required by the WFD.

Part 2, the current report, describes the assessment methodology, and its validation and testing and provides guidelines for the use and constraints of the methodology. It includes;

- A review of the current status of Quaternary mapping in the UK.
- Development and trialling of a methodology to assess the superficial strata in terms of recharge potential and attenuation potential.
- Consideration of the methodology limitations, data scarcity, and identification of a route map for future work
- Identification of copyright (IPR) issues which may influence future application of the methodology.

The methodology uses available Quaternary geological mapping at the domain level (QMT, 2004) but not the sub-domain level data, modified by 1: 625 000 scale geolines. It is intended that the value of the methodology will be proven with the incorporation of smaller scale (more detailed) data at a later date, whilst the current project addresses only the proof of method, which is scale independent. The method is focussed on the characterisation of the superficial deposits in terms of their potential to accept and transmit recharge and potential to attenuate pollutants. The accompanying CD allows trial use of the methodology, albeit at a scale larger than might eventually be available.

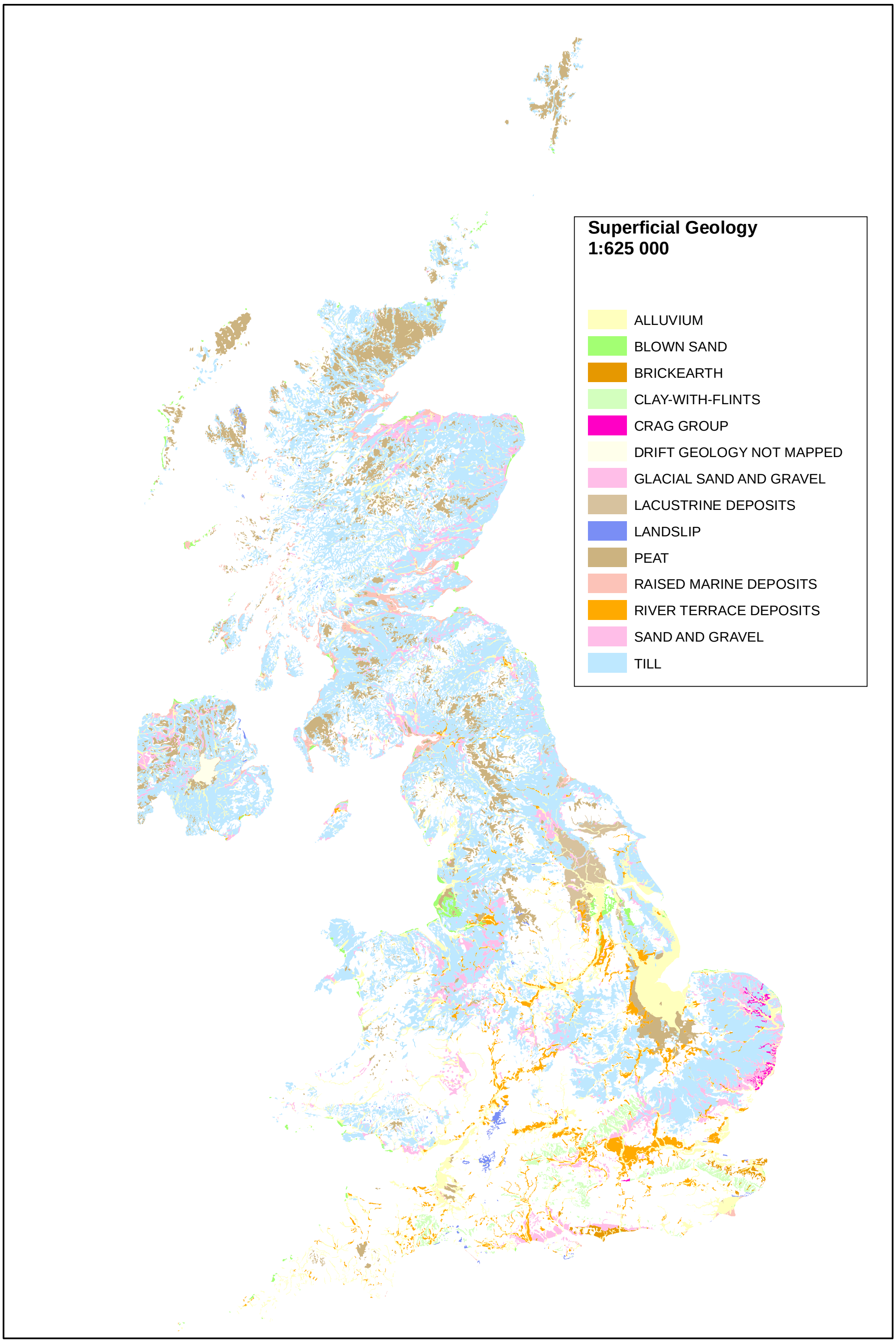


Figure 1 Superficial deposits of the UK at 1:625 000 scale (copyright BGS)

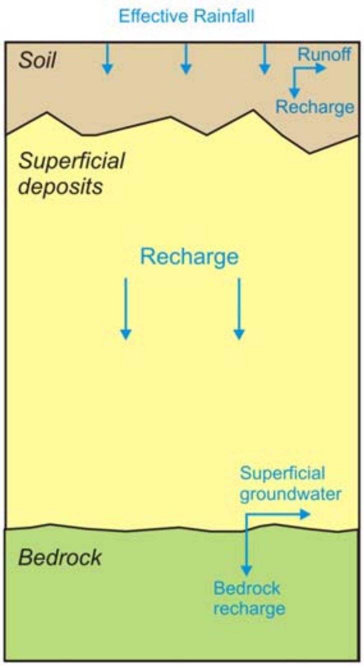
2. CONCEPTS

2.1 Overview

The main emphasis of this project is to assess superficial deposits in terms of their hydrogeological influence on recharge potential and attenuation potential. The following sections describe in more detail the processes at work within the unsaturated zone, see Figure 2 for a summary of the factors affecting recharge and attenuation in the subsurface

- **Recharge potential,** in this instance, is defined as the ability of superficial deposits to accept recharge from the base of the soil zone. Therefore, it is governed by the overall vertical permeability and porosity of the deposit. Fractures and preferential flow paths can also be important mechanisms for increasing flow paths. For most lithotypes (QMT, 2004) the composition is likely to vary and any assessments have to be based on the relative proportions of sediment types present.

- **Attenuation potential,** is defined as the general ability of the superficial deposits to decrease concentrations of contaminants in recharging groundwater. This is necessarily a simplification because different processes govern the attenuation of different contaminants. However, the presence of clay or organic material, and long travel times (thickness of formation) will be significant.



Recharge

The hydraulic properties of the soil first helps to partition the effective rainfall into runoff and potential recharge.

The potential for the superficial deposits to accept recharge from the base of the soil is dependent on the primary permeability and porosity of the superficial deposits. Secondary features, such as the the presence of fractures can also increase recharge potential.

Actual bedrock recharge depends partly on the properties of the bedrock. If the bedrock has low permeability and/or low storage, and cannot physically accept all the recharge, excess recharge may flow horizontally through the superficial deposits.

Attenuation

Much of the attenuation of contaminants occurs within the soil. In this biologically active zone contaminants can be subject to a range of chemical reactions, sorbed onto clays, or taken up by organic material.

Contaminants can be attenuated in the superficial deposits, by the presence of clay or organic material. The travel time is also important as this will give more time for attenuation to occur.

Some attenuation of contaminants can occur, but within the bedrock, dilution is generally the most significant factor.

Figure 2 Factors influencing recharge and attenuation in the sub-surface. This project is concerned only with the processes in the superficial deposits.

2.2 Recharge Potential

The nature of transport in the unsaturated or vadose zone may either be intergranular flow through the pore spaces within the solid medium or flow through discrete fractures. It may also be a combination of the two flow types. There are three phases within the vadose zone: solid, liquid and vapour. Recharge to an unconfined aquifer depends on a number of interacting factors. These are:

1. The texture of the solid phase, both soil texture and the unsaturated rock beneath (both superficial strata and bedrock), which influences the impacts of the forces of gravity and surface tension.
2. Soil moisture that is contained within the rooting depth of available vegetation.
3. Field capacity which is the point at which surface tension equals gravity so that gravity drainage can begin to take place. It is a function of specific retention, evaporation depth and the unsaturated permeability curve of the material (see below).
4. The vapour pressure that, in the unsaturated pores, is atmospheric i.e. the pores are in contact with the air. Adjacent to the water table is a capillary fringe whereby water can be drawn upwards by capillary tension by an amount that balances the weight of the column of water.
5. Unsaturated permeability.

The permeability of the unsaturated zone is a problematic concept. Darcy's law is still valid in the unsaturated zone but 'unsaturated hydraulic conductivity' is not a constant but rather a function of the volumetric water content. The relationship between hydraulic conductivity and volumetric water content can be determined experimentally.

Fine-grained superficial deposits tend to reduce the volume of recharge to underlying aquifers because of their low infiltration capacity (the maximum rate of infiltration which is influenced by the physical properties of the deposit and its moisture content)) although in some cases the excess potential (or rejected) recharge may be rerouted to areas of more permeable superficial deposits or where the bedrock aquifer is exposed at the surface. The amount of recharge and its distribution has obvious and important implications for water resources. (It is recognised that permeable superficial deposits may form aquifers in their own right, but the term aquifer is used in this context to describe only bedrock aquifers.) Thickness in itself does not affect the recharge potential although it provides for greater attenuation potential given longer travel times.

The complex interaction of forces that allow downward gravity flow in an intergranular system can be reduced to a number of key indicators that can be used to assign degrees of recharge potential within a given domain or area. The delicate balance between capillary forces and gravity and the influence of vegetation on evapotranspiration can largely be ignored when addressing the physical properties of the unsaturated zone itself. These forces are common to all systems and disregarding them as well as the overall rainfall for a given area allows a reduction from recharge *calculation* to determination of a recharge *potential*, a potential that indicates relative differences in likely recharge according to the superficial strata characteristics. In addition the relative recharge potential relates entirely to the superficial deposits and does not reflect at all whether the underlying aquifer (in particular bedrock) could physically accept a high, moderate or even low amount of recharge (poorly productive fractured bedrock aquifers underlie a significant proportion of the UK and their ability to accept recharge due to low storage and transmissivity can be significantly restricted).

The main physical characteristic of the geological deposit influencing recharge is unsaturated permeability. However, as unsaturated permeability can only be measured experimentally, resorting to porosity as an indicator of unsaturated permeability is, therefore, not uncommon.

Porosity in turn depends on three key factors: grain size, degree of cementation inhibiting size and interconnection of pores and the degree of compaction, if any.

Consideration must also be given to the likelihood of gravity by-pass flow through fractures in certain superficial deposits. This could, for example, be a dominant flow mechanism in a fractured till. Although the physics of gravity flow in narrow fractures is complicated, the likely presence or otherwise of vertical fracture fields is a second important strand to assigning recharge potential, and the methodology incorporates this on a subjective basis. Fracturing in superficial deposits is most common in the upper few metres, and is rarely significant beneath 10 m.

The thickness of the superficial deposits can also be significant in affected recharge potential. Thin superficial deposits can be discontinuous, or affected by farm practices and excavation. Therefore, where the superficial deposits are only 1 or 2 metres thick, the recharge to the underlying aquifer may remain high.

The subjective nature of recharge potential requires its careful application. It is neither possible nor sensible to attempt to quantify these classes in terms of recharge volume, as they do not account for the other important factors controlling recharge, i.e. prevailing rainfall events, field capacity and vegetation. Further background to the principles of recharge and estimation of recharge volume can be found in previous SNIFFER reports (SNIFFER WFD12, 2003; SNIFFER WFD31, 2004)

2.3 Attenuation Potential

Attenuation of pollutants in the vadose zone is controlled by a number of factors:

1. Interception, sorption and elimination of pathogenic bacteria and viruses.
2. Attenuation of heavy metals, and other inorganic chemicals, through precipitation (as carbonates or hydroxides), sorption or cation exchange.
3. Sorption and biodegradation of many hydrocarbon and synthetic organic compounds.

The processes promoting contaminant attenuation in the vadose zone and, by way of comparison, also in the saturated zone, are listed in Table 1. They depend on the type of soil and rock, the types of contaminant and the associated activity. Attenuation is generally most active in the soil, where bacterial activity is greatest. At deeper layers in the unsaturated zone attenuation still occurs, although the processes tend to be less effective as biological activity decreases. Once the saturated zone is reached, biochemical attenuation processes usually become more limited and natural die-off and dilution predominate.

The unsaturated zone, is nevertheless, of special importance as it represents the most widespread line of defence against pollution of groundwater. It is essential that it is properly considered in the evaluation of risk to underlying groundwater, but the processes that occur in the unsaturated zone are complex and its ability to attenuate contaminants difficult to predict.

It is feasible to assume that the processes that take place in the soil and superficial cover are reasonably uniform from one soil type to another. Clearly there are some soils that need special consideration, gley soils and peat for example, offer significantly different attenuation processes to those that occur in ordinary podsols. It is, therefore, feasible to take key indicators for the unsaturated zone that can be used to create classes of relative attenuation potential. The key indicators relate to the process of sorption, ion exchange, filtration and precipitation. Of these, ion exchange is the main overall process, the others being dependent on the nature of the pollutant as much as the nature of the unsaturated zone medium. In this way a single value describing the potential for the medium to attract cations, the cation exchange capacity (CEC), is the most useful parameter in assigning its attenuation potential. Thus CEC can be used as a meaningful surrogate for the overall attenuation processes that are likely to occur in the vadose zone.

CEC describes the process of attracting cations to a negatively charged surface – usually clay minerals. However, CEC values are commonly not available for the vadose zone and not universally available for the soil zone. It is useful, therefore, to use clay mineral content of the vadose zone as a surrogate for CEC. A second part of the attenuation process is controlled by the availability of carbon as a catalyst for adsorption and precipitation in the medium. Thus the two key indicators used to derive the attenuation potential of the superficial material making up the vadose zone are clay mineral and organic content.

As with recharge potential, this assessment of attenuation potential is subjective and cannot sensibly or usefully be given numerical values, especially given the regional scale of assessment being considered in this project.

Table 1 Processes promoting contaminant attenuation in groundwater systems (after Morris et al., 2003)

	Dilution	**Retardation**				**Elimination**			
		Sorption	Ion exchange	Filtration	Precipitation	Hydrolisis	Complexation	Volatization	Biodegradation
Soil	Minor	Major	Significant	Major	Minor-significant	Significant-major	Major	Major	Major
Unsaturated (vadose) zone	Minor	Minor-significant	Significant	Significant	Significant	Significant	?	Minor	Minor-significant
Saturated Zone	Major	Minor-significant	Minor-significant	Significant	Minor-significant	Significant	?	Minor	Minor-major

3. SCALE INDEPENDENT METHODOLOGY

3.1 Methodology overview

The issue at the centre of this project was how best to use available national geological datasets to create two national overview maps for use by UK hydrogeologists: (1) ***recharge potential*** – the potential of the superficial deposits to allow available recharge to move through vertically; and (2) **attenuation potential** – the ability of superficial deposits to retard and attenuate contaminants. Figure 3 below outlines the main issues surrounding development of these maps.

- At present there are only isolated case studies in the UK and Ireland of groundwater movement or attenuation through superficial deposits.
- The only available national map portraying the superficial deposits is the geological map (available at both 1:625 000 and 1:50 000 scale). These generally show lithologies: e.g. glacial till, alluvium or peat etc.
- There are however other resources that are available that could be used to help reinterpret the national geological map of superficial deposits in terms of recharge and attenuation potential.
    - Conceptual models of the superficial deposits, such as Quaternary domains, or quaternary lithostratigraphy. These subdivide the UK into various ‘areas’ or domains where similar depositional processes were at work to create the superficial deposits.
    - Regional Geologists have much information about the nature of the superficial deposits across the UK – much more than is recorded in maps. Hydrogeologists, engineers and soil scientists also hold additional knowledge and understanding of the properties of the superficial deposits.
    - Other national datasets and maps exist which are potentially helpful. For example, GeoSure (BGS’s national dataset with information on strata permeability, drift thickness, etc), HOST (a dataset with information on the hydraulic properties of soil – back calculated from the base flow index, see Boorman et al. (1995)), GBASE (BGS’s database on the geochemical properties of stream sediments and soil which covers much of the UK).
    - There are also a significant amount of relevant data on superficial deposits held in the BGS/GSNI boreholes and site investigation report archive.

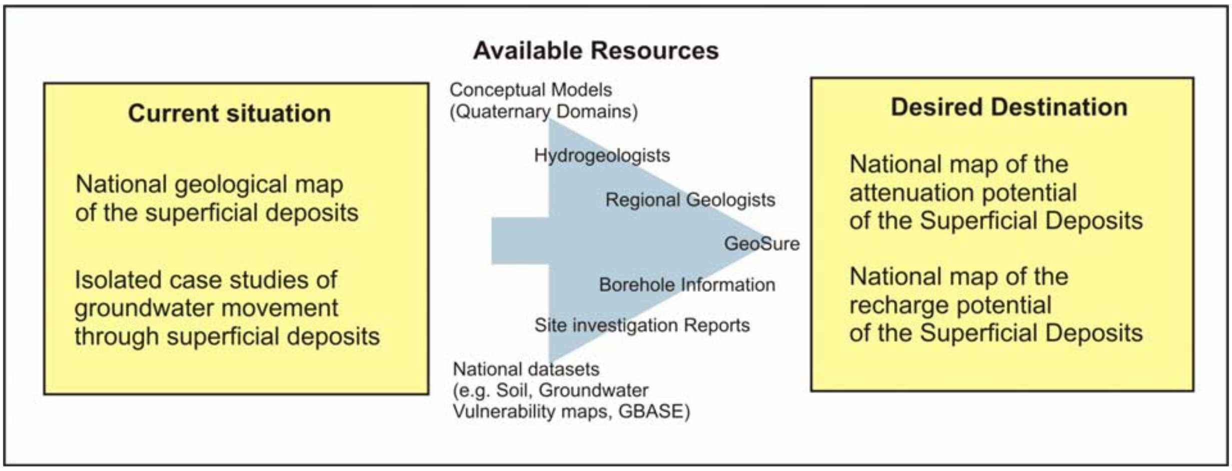


Figure 3 A statement of the aims of the research: to use available resources to create

The method developed in this project was to systemise the additional information and expert knowledge to reinterpret the existing superficial deposits geological map. Figure 4 summarises this approach. Central to the method is the data matrix. Within the matrix, the expert knowledge of the regional geologists is captured and then re-interpreted by hydrogeologists in terms of recharge potential and attenuation. A more detailed description is given below.

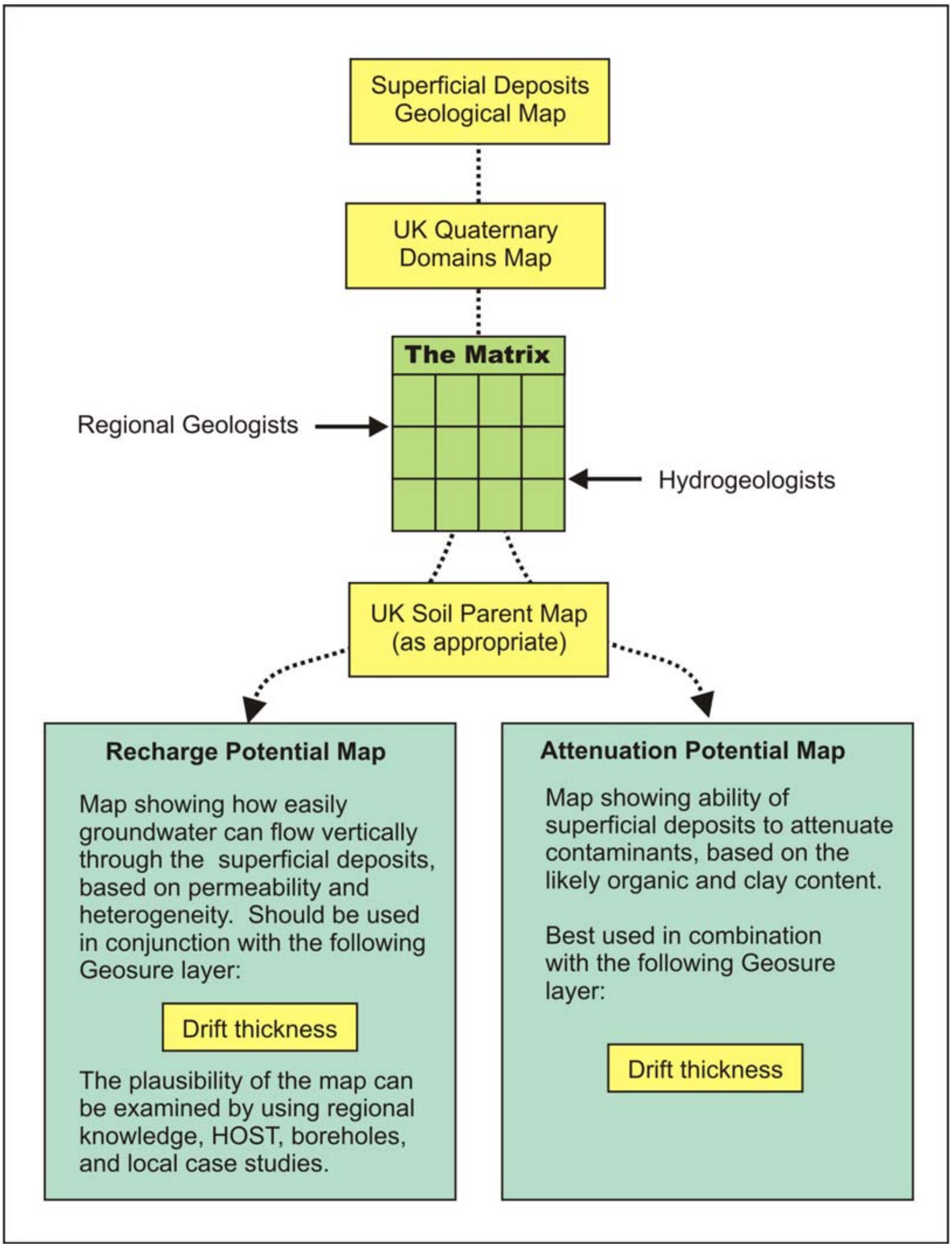


Figure 4 An outline of the methodology developed in this project to develop recharge and attenuation potential maps by using expert knowledge to interpret the superficial geology maps.

1. The first step in the process is to divide the deposits mapped on the Superficial Deposits Geological Map according to the Quaternary Domains (see Figure 5 and Box 1 for a

description of the domains; more detail is given in the supporting report SNIFFER 2006). There are eleven main domains. This allows us to distinguish between the origin and thus possible nature of, for example, what has been mapped as till in the Scottish Highlands, to till in East Anglia.

2. The matrix then describes the recharge and attenuation potential for each geological unit in each domain. This has been done by asking Quaternary geologists a series of questions for the deposits in each domain (see Table 2). The matrix provides a framework for meaningful and systematic discussions between hydrogeologists and Quaternary geologists.

3. Assessment of recharge potential has been made largely on the basis of the composition and grain size of the deposits. For most of the lithotypes the composition is likely to vary and the assessments have been based on the relative proportions of the different grades of material. Recharge potential, in this instance, is defined purely on the expected permeability of the deposits. There is no quantification of the amount of recharge that the deposits could transmit, merely an assessment of their relative ability to transmit infiltrating water (recharge) in general. The method does not take into account other known elements of recharge processes such as the effects of runoff from less permeable deposits with focussed recharge around the periphery and does not consider the thickness of the deposit. Superficial deposit thickness is not directly taken into account at this stage. The separate BGS GeoSure Layer on drift thickness can be incorporated independently as required. Thickness can be important in two main ways: very thin deposits may be discontinuous, and moderately thin deposits may be more fractured.

4. Assessment of the attenuation capacity has been made by estimating the presence of clay minerals and organic material such as peat. The soil cover is not assessed – just the likely clay and organic material within the superficial deposit. The thickness of the deposit is also not taken into account at this stage. Although thickness has a large influence on attenuation capacity, it was not applied during the development of the methodology in order not to compromise IPR. There is a separate BGS dataset (GeoSure) that deals primarily with superficial deposits thickness, and this can be applied independently in the future as required.

5. The lithology of glacial till is governed across much of the UK by the nature of the bedrock. Glaciers scoured material from bedrock and then did not move it far before depositing it again to form till. Therefore, glacial tills developed on sandstones or coarse crystalline rocks tend to be sandy and permeable, while those developed on mudstones are clay rich and have low permeability. The matrix describes whether the lithology of the till within a particular domain largely follows the bedrock. If it does, the soil parent map (a simplified geological map based on bedrock lithology) was used to determine the final recharge potential and attenuation.

6. Other available information, experience and datasets can used to validate the maps. Since there are no similar estimates of recharge or attenuation potential across the UK, the maps cannot be rigorously assessed. However, the plausibility of the maps can be estimated by comparing the Standard Potential Infiltration estimated by the HOST dataset for an area with the recharge potential assigned to the superficial deposits for that area. HOST assigned certain hydraulic characteristics to soils types based on a statistical study of baseflow index and soils (Boorman et al.1995). Where case studies of recharge through superficial deposits exist these can also be used to validate the recharge potential layer. One of the best methods for testing the plausibility of the maps is to compare the assessment of a particular area with the experience and knowledge of local hydrogeologists.

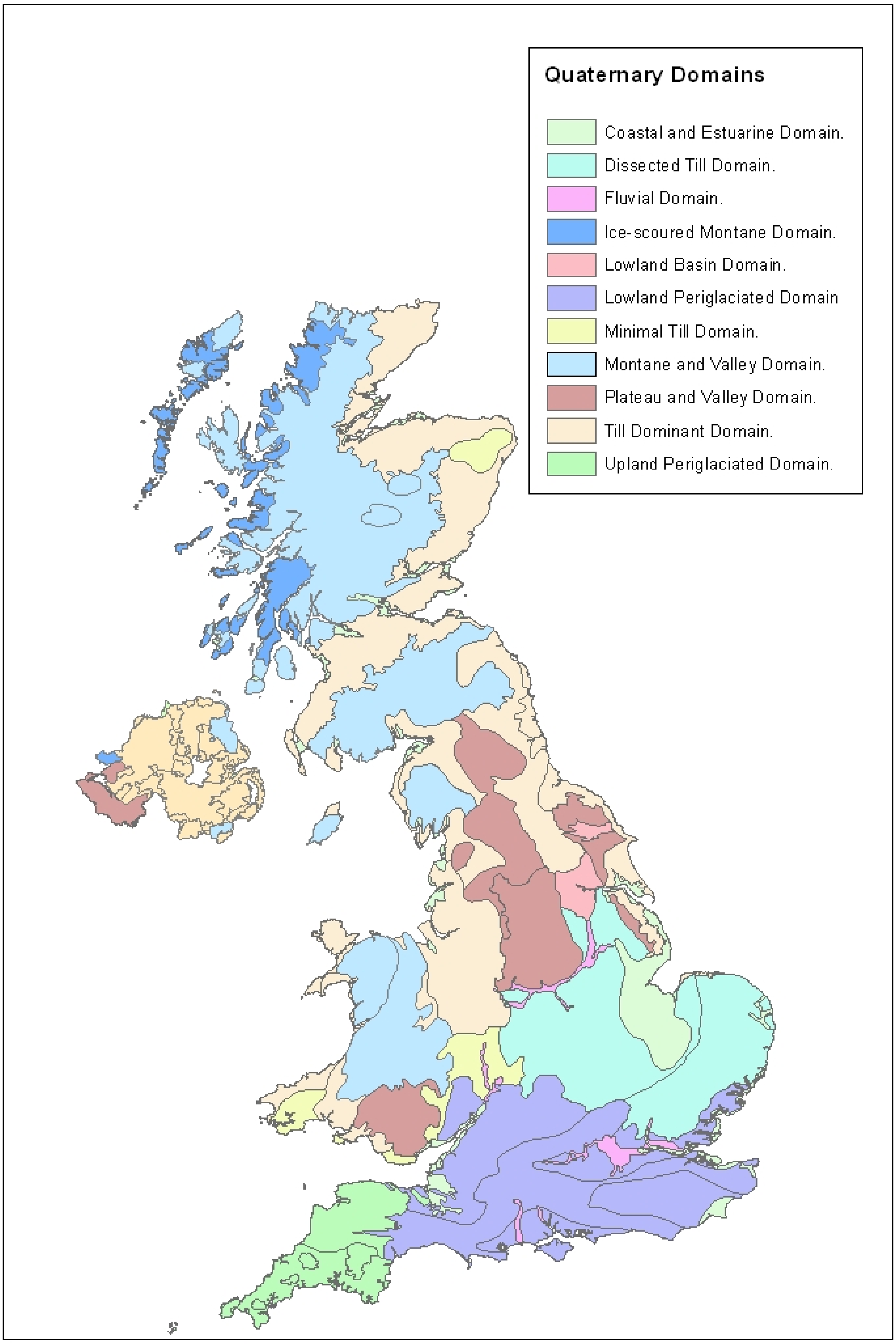


Figure 5 Map of the eleven Quaternary domains (sub domains are also outlined).

Box 1 Quaternary Domains

Quaternary Domains are defined by recurring patterns in geomorphology and lithology, and on the surface processes that formed them. A number of Domains have been subdivided into sub-Domains (40 in total) in order to take into account local variations, which are largely related to the gross characteristics of the bedrock. The domains descriptions are appended digitally in the attached CD. Each description provides graphic representation of the ratio of the superficial cover to bedrock and the subdivision of the superficial material into its component depositional environments. For each domain there follows a description of the associated landforms, lithological deposits and depositional processes. This information is developed into a description of the likely hydrogeological processes pertaining to each domain, and uses case study information where available to support this analysis. Schematic diagrams are used to illustrate the hydrogeological processes

The domains identified for England, Wales and Scotland are:

Glaciated and periglaciated Province: Uplands

- Ice-scoured montane domain
- Montane and valley domain
- Plateau and valley domain

Glaciated and periglaciated province: Lowlands

- Till dominant domain
- Dissected till domain
- Minimal till domain
- Lowland basin domain

Non-glaciated, periglaciated Province

- Upland periglaciated domain
- Lowland periglaciated domain
- Alluvial, estuarine and coastal domain
- Fluvial domain

The situation in Northern Ireland is a little different. Northern Ireland lies exclusively within the Glaciated Province. Six Domains are recognised within Northern Ireland:

- Fluvial
- Alluvial, estuarine and coastal
- Till Dominant
- Montane and valley
- Ice scoured montane
- Plateau and valley

Table 2 Questions used in the matrix to describe each mapped units in each Domain. This allows variations within each mapped units across the UK to be identified. The hydrogeologist uses the information provided by the geologists to make their assessment.

Questions on each mapped superficial deposit within each domain type	Assessor
General Description	Regional Geologist
Map issues	
Sub-domains	
General Thickness	
Architecture	
Lithology	
Clay content	
Organic content	
Horizontal permeability	
Vertical permeability	
Primary adsorption potential	Hydrogeologist
Secondary adsorption potential	
Rationale for adsorption potential	
Primary recharge potential	
Secondary recharge potential	
Rationale for recharge rating	

3.2 Applying the method to the UK at 1:625 000 scale

The present work focuses on proof of method. The national 1:625 000 dataset was used, since this would give national coverage, albeit at a coarse scale. The output is at 1 km grid size. Once the methodology is accepted, larger scale data can be used and a more meaningful output derived, however, at the moment the results are a guide for comparison with existing perceptions of regional recharge and vulnerability of groundwater. The current output cannot, therefore, be applied to support specific environmental judgements.

The use of 1:625 000 geological map data allowed development of the methodology outwith the copyright restraints of more detailed datasets (1:50 000).

3.2.1 The data matrix

A summary hydrogeological description of each of the eleven Quaternary domains was prepared as explanatory background to the domains. Most of the descriptions incorporate either a schematic diagram illustrating the key hydraulic processes or an illustration taken from project work using real data. These descriptions serve two purposes: they are there to inform users of the methodology about the characteristics of the domains, and they provide background information to assist in classifying lithological units within each domain.

The Quaternary Domains data matrix provides the means of classification (see CD attached). It is a series of spreadsheets, one for each of the eleven domains, plus a general one, in which each of the superficial lithotypes within each domain are described and the physical and chemical properties, which control permeability and attenuation, noted. Regional expert mapping geologists from within BGS were asked to assess the properties for each lithological unit within each domain using the questions outlined in Table 2. These descriptions were used to assign attenuation and recharge potential classifications.

For Northern Ireland the characterisation of the Quaternary Domains is still in its early stages and full domains descriptions in the form of a matrix are not yet available. For the purposes of characterising the domains of Northern Ireland and including it in this phase of mapping it was assumed that each of the lithotypes within each domain had similar properties to the English Welsh and Scottish equivalents. Where significant differences occur these have been noted by the NI regional mapping geologist. The maps for Northern Ireland are, therefore, anticipated to change as additional local knowledge is incorporated and the domains assessments evolve.

The *recharge potential* is based largely on the permeability of the deposits. Primary and secondary (see below) recharge potential assessments were made and a rationale for the assessments is provided. These were assessed as <u>H</u>igh, <u>M</u>edium or <u>L</u>ow respectively and tabulated accordingly. This assessment is carried out twice, both for the majority (primary) situation and for a subordinate (secondary) situation; for example, the primary recharge potential through clayey till is <u>L</u>ow but the secondary potential where the till is locally more granular may be <u>M</u>edium. The same primary and secondary classification is also made for *attenuation potential*. Many classes may be the same, peat for example is <u>H</u>igh primary and <u>H</u>igh secondary attenuation potential classification. In this way the primary classification relates to the predominant lithology within each lithotype, for example, an alluvial deposit may be predominantly sand and gravel, however, there may also be minor clay layers within that deposit. In this instance the predominant (primary) attenuation potential would be low, however, where clays are present the (secondary) attenuation potential may be high. Hence it is the interpreted understanding of the nature and variability of the superficial geological deposit which generates the assessment of recharge and attenuation potential.

The rationale for each classification is given in the matrix so that the assessment is reasonably transparent. This not only justifies the assessments but also allows comparisons to be made with existing perceptions. The columns also permit revisions as people with local knowledge use the maps. These comments will enable the classifications and maps to mature and evolve as more detailed maps are used and local knowledge incorporated. This evolution is considered to be a future strength of the methodology.

Bedrock types (see Figure 6) are used as a proxy for superficial deposits lithology within till sheets which are assumed not to have been transported far and, therefore, to be largely derived from the underlying bedrock. For example, till that is developed over granular crystalline rocks comprises sands and gravels and tends to be more permeable than tills developed over mudstones. Table 3 shows the attenuation and recharge potential predicted for superficial material mainly derived from each of 15 generic bedrock types.

A variety of bedrock lithologies fall under the Sedimentary Mixed classification and the attenuation and recharge potential properties will be highly variable within this category. Where the properties of the sedimentary mixed bedrock are known these values have been amended, e.g. the Coal Measures and Ordovician and Silurian rocks in Northern Ireland have been broken down from Mixed Sedimentary to their constituent parts. The crystalline fine classifications were modified after it was identified that many of these rocks weathered to clay materials e.g. the basalts of Northern Ireland and the basalts and andesites of Scotland.

This general rule (of underlying bedrock directly influencing overlying till properties) is not universal, and exceptions are captured in the matrix. For example, the till cover along parts of the north-east coast of England is smeared with low permeability marine clays thus reducing its recharge potential from Medium to Low. Other exceptions occur where two ice sheets converge, e.g. the Irish Sea Ice and the Welsh Ice meet and interdigitate over central Wales, and a similar situation is present over much of East Anglia where one till may overlie another. In these instances, especially where the till is thick, the later deposits in the sequence bear little relationship to the underlying bedrock.

Table 3 Generic bedrock classification (see CD for classification rationale)

Bedrock classification	**Attenuation Potential**		**Recharge Potential**	
	Primary	**Secondary**	**Primary**	**Secondary**
Chalk	H	M	L	L
Crystalline	L	M	H	M
Crystalline Coarse	L	M	H	M
Crystalline Fine	H	M	L	M
Meta	M	H	M	L
Meta Argillaceous	H	L	L	H
Meta Limestone	M	L	M	M
Meta Rudaceous	M	L	M	H
Sedimentary Arenaceous	L	M	H	M
Sedimentary Argillaceous	H	M	L	L
Sedimentary Coal	H	M	L	M
Sedimentary Limestone	M	L	L	M
Sedimentary Mixed	M	M	M	M
Sedimentary Rudaceous	M	M	H	M
Volcanoclastic	L	M	M	M

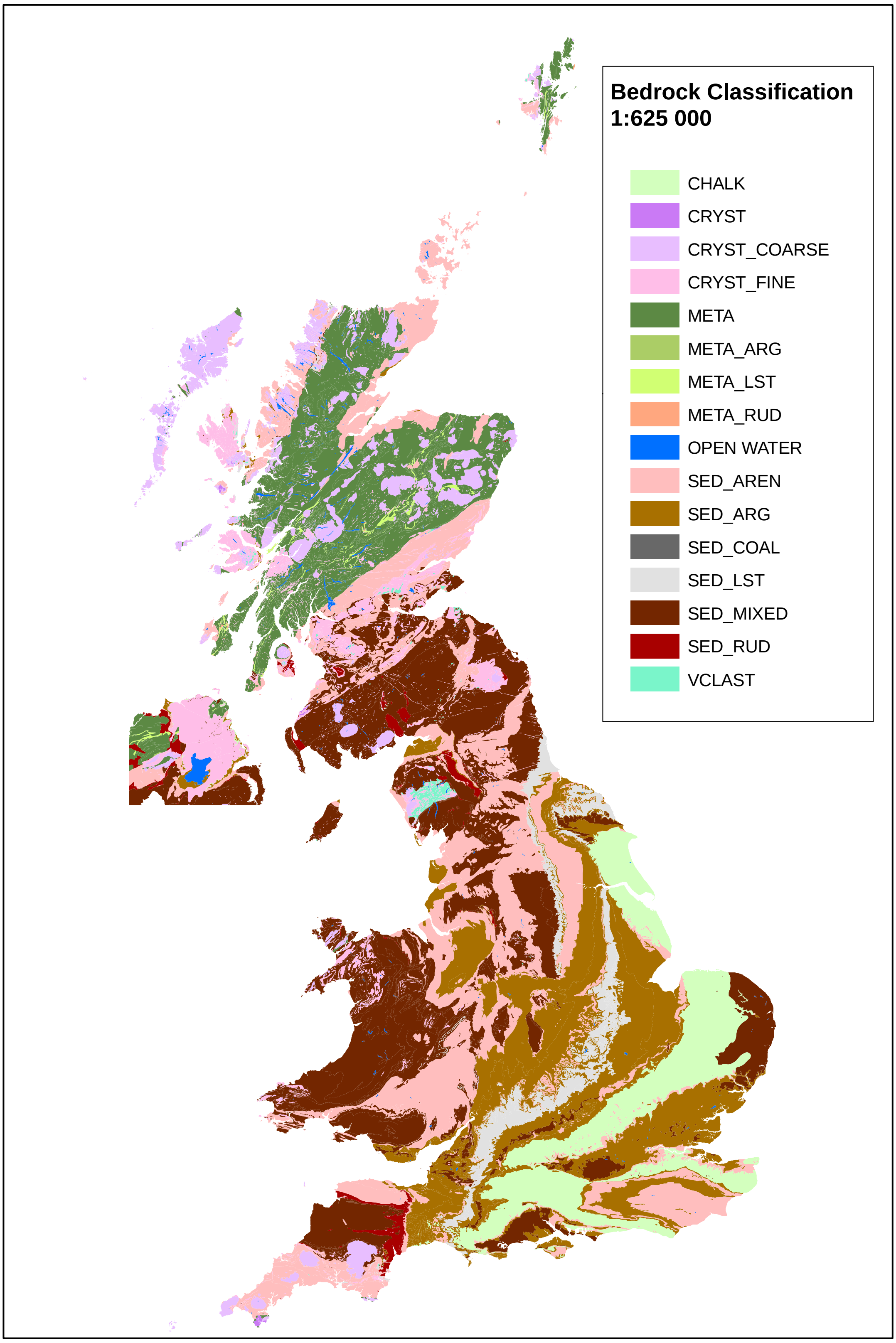


Figure 6 Bedrock classifications at 1:625 000 scale (copyright BGS)

3.2.2 Application to the GIS

To create the 1:625 000 recharge and attenuation potential maps a number of datasets were used and manipulated using Access^{TM} and ArcGIS^{TM} (version 9.1). The shapefile of Superficial deposits at 1:625 000 scale was used as the main layer (Figure 1) Each polygon within this shapefile was attributed with the domain/sub domain into which it falls (Figure 5). Where the superficial polygon intersected more than one domain then it was divided accordingly. The resulting polygons were then attributed according to the bedrock classifications (again splitting them if more than one bedrock type was intercepted) (Figure 6). Figure 7 shows a flow diagram of how the datasets were used.

Once the polygons had been created, recharge and attenuation potential were assigned to each one based on the classifications given in the matrix table for all the lithotypes within each domain (and modified accordingly where local variations had been noted by the geologist in their assessment, e.g. the distinction between carse and more permeable raised beach deposits). The classification for the underlying bedrock type was used (with exceptions, where known) where the lithotype was till.

Initially four maps were produced showing primary recharge, secondary recharge, primary adsorption and secondary adsorption. However, it was felt that this information would be better represented and the natural variability displayed by combining the primary and secondary classifications. This produced nine classes (as primary classification/secondary classification) for both recharge and attenuation potential: HH, HM, HL, MH, MM, ML, LH, LM and LH.

3.3 Data availability and IPR issues for 1:625 000 pilot

In view of the focus on proof of method, data have been incorporated into the pilot model at a coarse scale to avoid IPR issues during methodology development. Consequently the Quaternary domains were used as the basic building block rather than the more detailed sub-domains, and the 1: 625 000 superficial geolines were adopted rather than 1: 50 000 scale data. However, future iterations of the model should concentrate on improving the scale of the input data and, therefore, the clarity of the output data, as data are available at smaller scales to support the analytical process.

The 1 km grids of recharge potential and attenuation potential and the 1:625 000 maps of bedrock classifications and Quaternary domains are provided in a CD and are available freely for use. The background data of the geology of the superficial deposits and bedrock are available only under license from the BGS. In addition, the superficial deposits thickness, which can be used in conjunction with the grid of attenuation potential is only available under licence from BGS.

Non BGS datasets have been used subjectively only, for example the HOST data sets, have only been used for visual comparison with output data during the validation process. More detailed analysis of the dataset using the digital HOST dataset could be carried out by the Environment Agency, EHS and SEPA who all hold licenses for HOST. However, CEH would not permit the validation work to be reported in this study, since SNIFFER do not directly hold a licence for the data.

The GIS also incorporates an assessment of the status of the 1: 50 000 geological maps currently held by BGS (see later). This level of data in the GIS will be valuable when the methodology is applied at 1: 50 000 scale as it provides a degree of confidence on the available geolines.

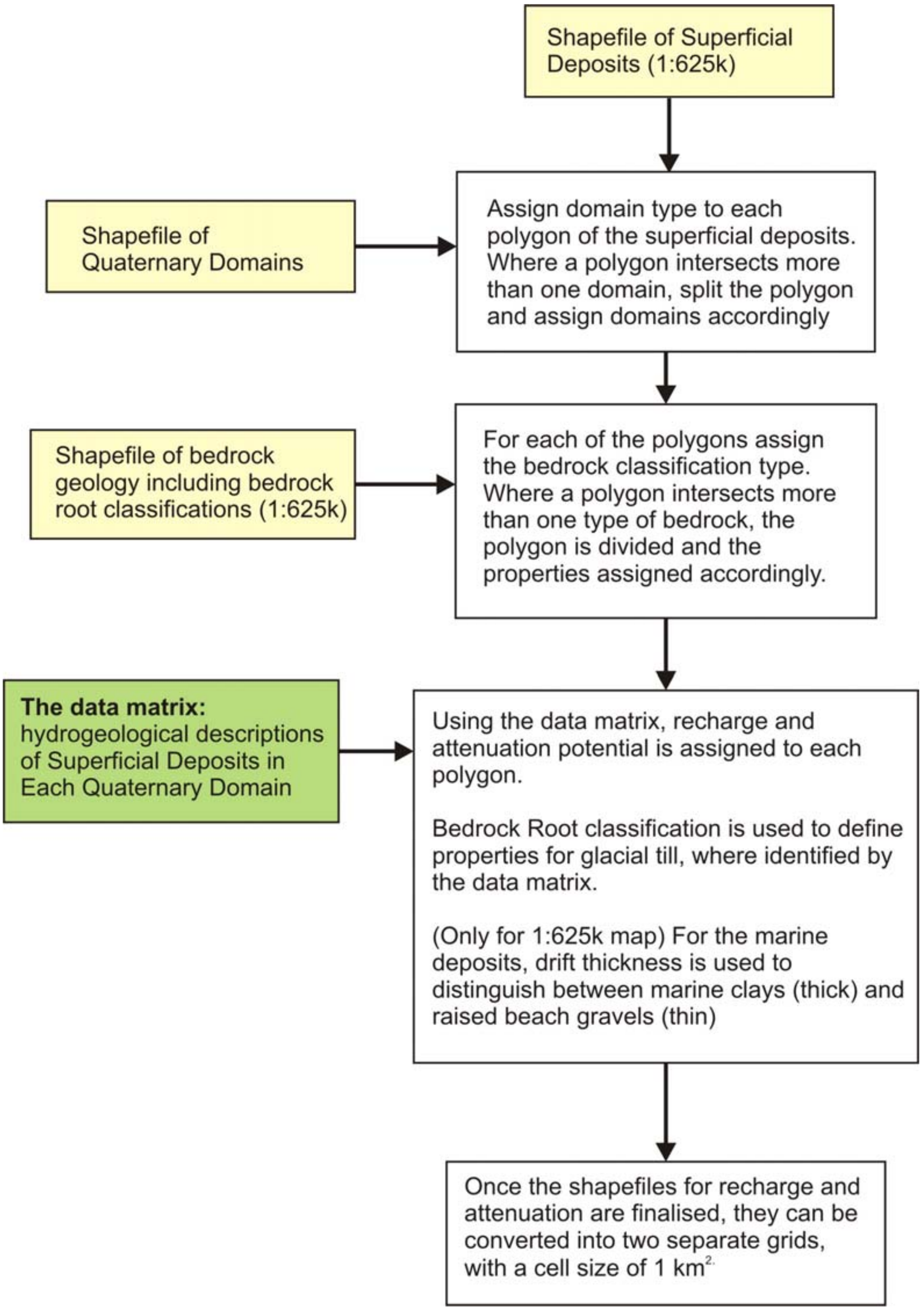


Figure 7 Process diagram of GIS application of the methodology.

4. RESULTS, TESTING AND ISSUES

4.1 Form of output

The initial set of maps which have been produced indicate how the methodology can be applied at 1:625 000 scale. It is intended that, upon acceptance of the methodology, they will form the basic overview after which more detailed data layers and local knowledge will be incorporated, allowing application of methodology at, for example, a catchment or groundwater body scale.

The input maps are available digitally as files which can be used in ArcGIS (9.1).

Once the classifications for each of the superficial deposits within a particular domain were agreed (see Chapter 3) the resultant shape file was then converted into a grid or raster file with 1 km^2 grid size (Figures 8 and 9). Where two or more classifications occurred within the 1 km^2, a majority rule was applied (i.e. the dominant classification was assigned to the whole grid square). At the scale of this map, it was felt that this simplification was acceptable. For more detailed assessments it may be necessary to consult the shape file rather than use a grid. Two grids are available, one for recharge potential and the other for attenuation potential.

A map showing the thickness of the superficial deposits is provided (Figure 10), also on a 1 km^2 grid size. This was based upon data held within the BGS Geosure database. This data layer has not been displayed for NI where assessment of this property is not as advanced as for mainland UK. It can be assumed that if the superficial deposits are thick they are more likely to delay recharge to the underlying bedrock aquifer and that they may have more potential for attenuation.

Five classifications were used for the thickness of superficial deposits;

- Absent, or not sufficiently thick to be mapped.
- 1 – 3 m – superficial deposits can be variable or discontinuous, recharge may occur in holes within the cover.
- 3 - 10 m – tills can fractured within the upper 10 ms, therefore where he till is less than 10 m thick there is a higher potential for bypass flow and therefore higher recharge potential and lower attenuation potential.
- 10 to 30 m – fracture and bypass flow are unlikely to occur.
- more than 30 m thick. At these thicknesses, superficial deposits are likely to be saturated and to be behaving as aquifers in their own right. Also there is a greater chance of heterogeneity.

It can be seen in Figure 4.3 that much of the country has less than 10 m thickness of superficial deposits. However, in some areas, for example East Anglia, The Cheshire Basin and the Fylde, along the Lincolnshire and Yorkshire coast, the Vale of York, Teeside, the Lancashire coast, Carlisle, the northernmost part of the Isle of Man etc there are thick deposits present, predominantly comprised of till. The composition of the superficial deposits in these areas is likely to be heterogenous, particularly vertically. Beds of clay may be interbedded with sands and gravels and the ability of recharge to pass through such deposits will depend on a variety of factors including the lateral extent and connectivity of any more permeable sand and gravels horizons. Where superficial cover is thick it is also more likely that the deposits, particularly in the upper horizons, may bear little relationship to the underlying bedrock parent material.

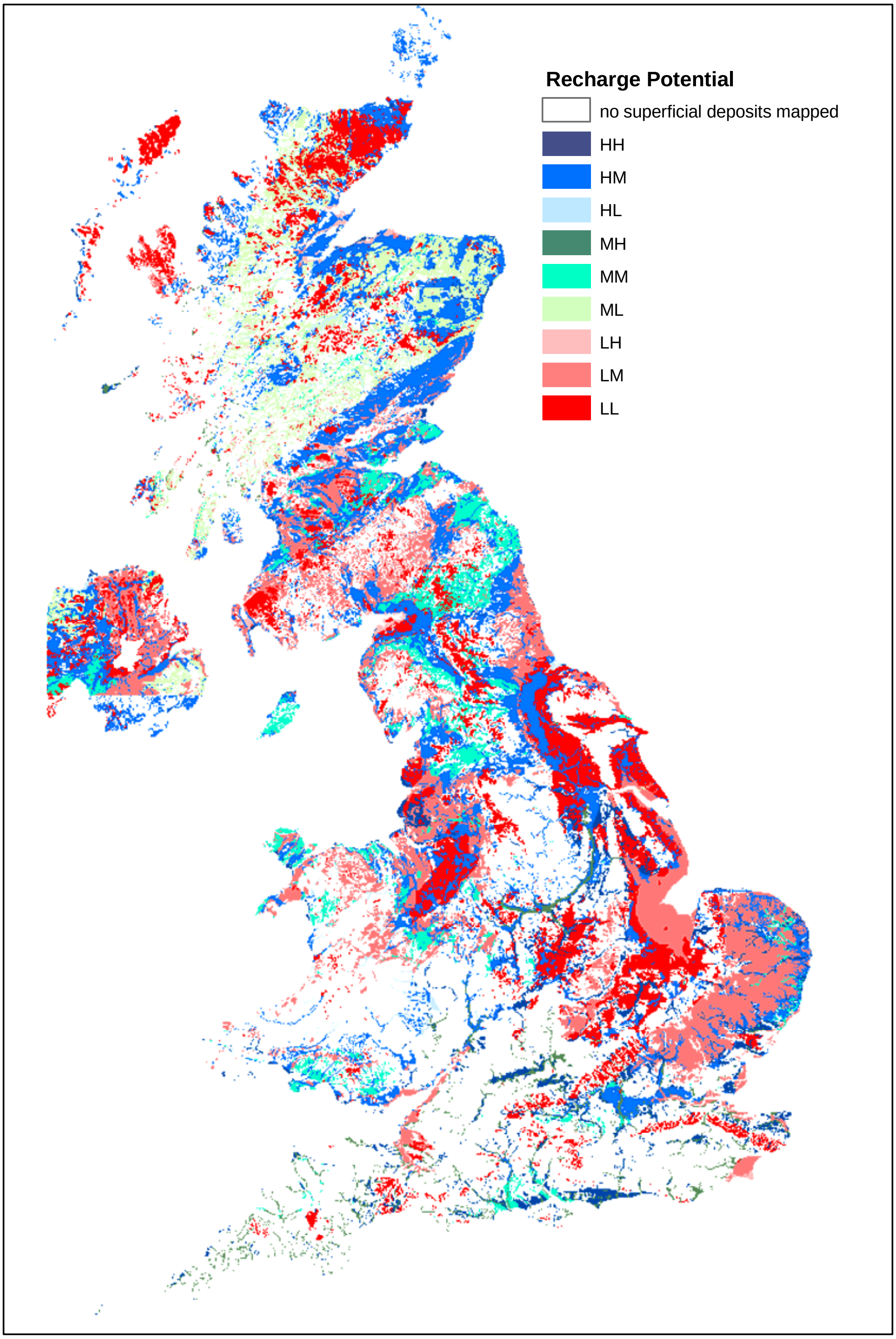


Figure 8 Map of recharge potential at 1:625 000 scale. For high recharge potential, more water would be expected through the superficial deposits. Information on the thickness of the deposits is not incorporated. (Note that data for Northern Ireland are incomplete).

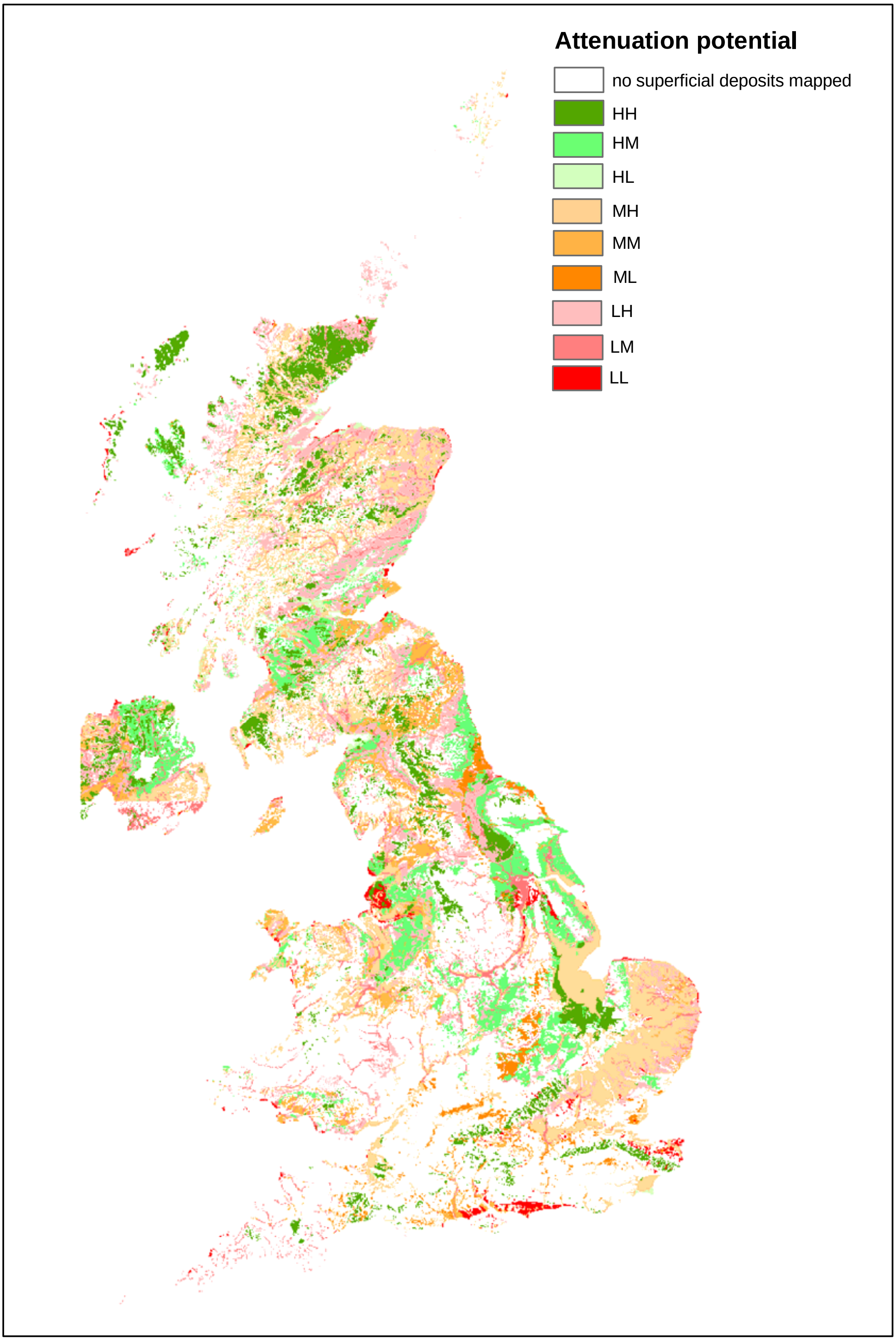


Figure 9 Map of attenuation potential at 1:625 000 scale. For high attenuation, then negligible contamination is expected though the superficial deposits. Information on drift thickness is not incorporated. (note that information on

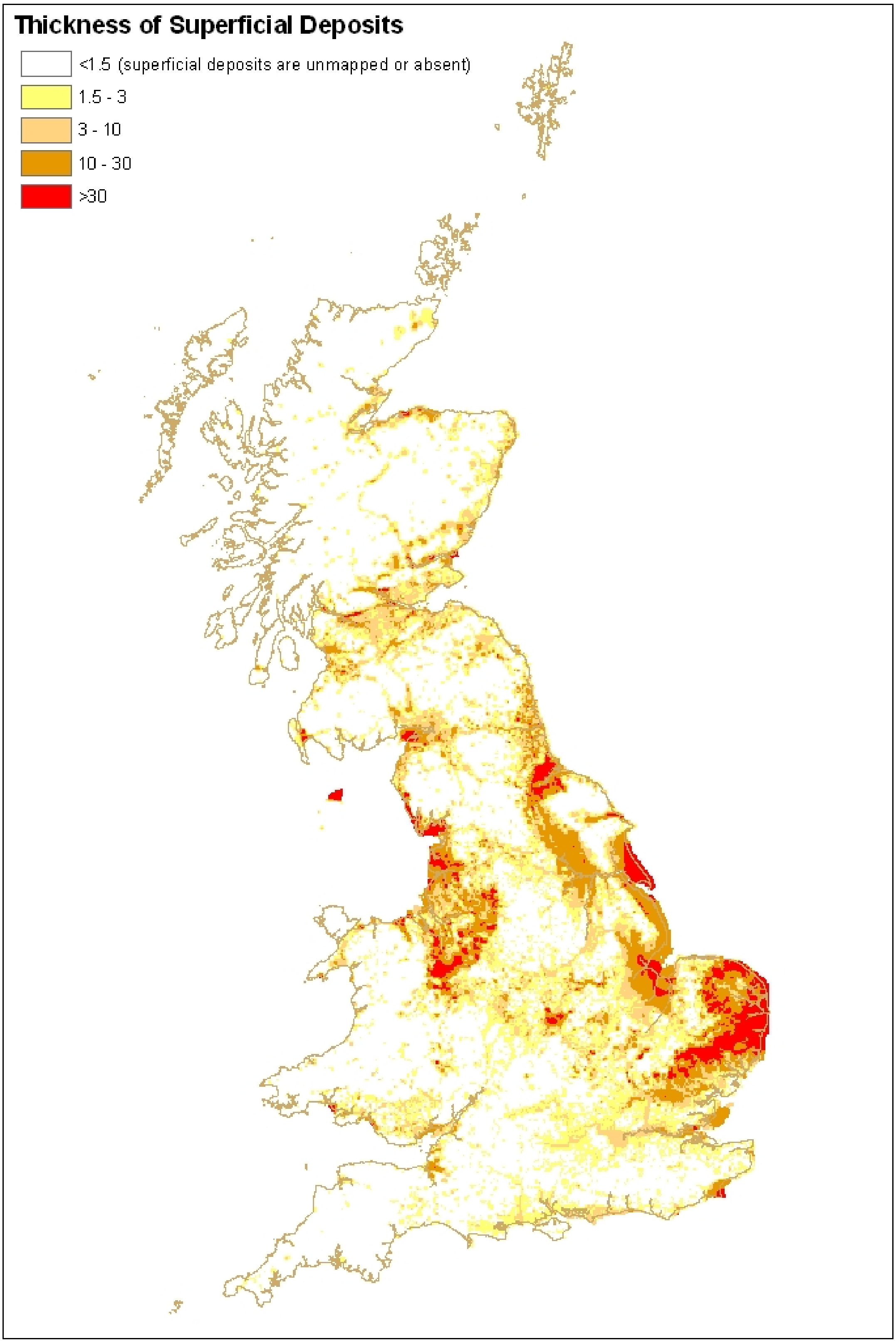


Figure 10 Map of thickness of superficial deposits at 1:625 000 scale

4.2 Comparison with existing assessments and other studies

Although there are datasets which take into account, to different degrees, the nature of superficial deposits in an area such as groundwater vulnerability maps, this study is the first attempt at assessing recharge and attenuation potential of superficial deposits at a national scale. There are, therefore, no other assessments using alternative methodologies with which it can be directly compared. However, to evaluate the success of the method in assessing the recharge and attenuation potential of Quaternary superficial deposits, the map outputs have been compared with a number of other datasets including HOST and the Scottish groundwater vulnerability maps. The maps have also been checked against the results from a number of regional studies on recharge through superficial deposits.

HOST (Hydrology of Soil Types) is a dataset which is based on the 1 x 1 km National Soil map data together with data from the CEH Wallingford (formerly the Institute of Hydrology) on the behaviour of river catchments. There are 29 HOST classes, which describe the dominant pathways of water movement through the soil and substrate. There is a Standard Percentage Runoff (%) associated with each HOST soil class. These percentages were used to calculate an estimate of the Standard Percentage Infiltration (%) for each HOST class (100% - SPR = SPI). In general there is a broad agreement between the datasets, areas where there was less agreement tend to be areas of till which have sedimentary mixed bedrock parent material which suggests that more local knowledge input is required to address the discrepancies. The HOST data cover the whole of the UK whereas the map produced using this methodology is, by its very nature, restricted to the areas covered by superficial deposits.

The calculation of SPR is based on the analysis of flood event data i.e. collated flow and rainfall data for storm events. SPR is the percentage of rainfall that causes the short term increase in flow seen at the catchment outlet and, therefore, the SPI is not directly comparable with recharge potential as derived by this methodology. Nonetheless the SPI map does help provide an indication of the general response of different catchments to rainfall. A more detailed assessment of the anomalies between the two datasets was not possible as part of this project but would be valuable.

The recharge and attenuation potential maps were also compared with the vulnerability screening maps of the superficial deposits which have been determined for Scotland (Ball et al., 2004). (Note: It is not the intention that the derived recharge and attenuation potential layers and associated GIS act as an alternative to groundwater vulnerability maps. Rather the methodology and output, once developed at a more detailed scale, should compliment and enhance the understanding of an area.) However, the attenuation potential map is not directly comparable with the vulnerability map because the vulnerability assessment incorporated a larger number of factors. In addition to permeability and clay content, it took into consideration other elements including the depth to the water table and the thickness of the superficial deposits in a more integrated way than was possible in the time available to develop this method. According to the vulnerability map much of Scotland shows fall into classes 4 and 5 (on a scale where 1 is low risk of groundwater pollution and 5 is high). This reflects the widespread occurrence of igneous and metamorphic rocks where the potential for attenuation of contaminants within these fracture dominated aquifers is limited and where overlying superficial deposits are absent or relatively thin/permeable. The map of attenuation potential using this methodology shows a similar pattern to the vulnerability screening map for the superficial deposits – low and medium values are prevalent over much of Scotland except for where peat or other clay/organic rich materials occur. There is particularly good agreement with the lower vulnerability rating and the methodology-derived higher attenuation potential in the carse areas (low lying flat alluvial; plains developed in the valleys of major rivers as they approach the coast, e.g, the Tay below Perth).

As a first pass the map has been examined against a few of the more detailed recharge studies documented in the literature. For example, the East Anglian Till is known to permit little recharge to the underlying Chalk, particularly in interfluve locations (Marks et al., 2004). It can be seen that the till has a significant impact on recharge quantity and distribution to the underlying Chalk aquifer. Beneath the interfluves recharge appears to be lower than previous estimates of 20 – 40 mm a^{-1} (Klink et al., 1996; Soley and Heathcote, 1998), maybe as low as 5 mm a^{-1} (Marks et al., 2004). It can be seen from the map of recharge potential (Figure 4.1) that the Low Medium recharge potential classification, that the till in this area has been given, is consistent with these studies.

In the Cheshire Basin, recharge to the unconfined Sherwood Sandstone aquifer is estimated to be approximately 350 mm a^{-1}, however, where till cover is present, recharge to the underlying aquifer is considered to be significantly reduced to an estimated 52 mm a^{-1} (Vines, 1984).

Other studies, against which the methodology has not yet been assessed (due to the scale difference), which have looked at hydrogeological domains at area specific scale include work at Sellafield (McMillan et al., 2000), East Shropshire (Bridge et al., 2002) and Manchester as outlined in the Part 1 report. A 3-D model of the superficial deposits between Doncaster and Retford has also been created by BGS.

4.3 Constraints on the methodology at 1:625 000 scale

The aim of this project was to develop a methodology for rapidly assessing hydrogeological properties of superfical deposits on a national/ regional scale. It was always intended that using the 1:625 000 scale datasets would provide a broad overview which would be used to test the success of the methodology. Once the methodology was established it is intended that it would be applied to more detailed data. It is also intended that input of local knowledge will be invaluable for assessing the success of the methodology and improving the resultant maps where anomalies or shortfalls exist.

However, inevitably there are a number of constraints imposed by the methodology which more detailed analysis and incorporation of local knowledge should help to address. These include the following:

Scale issues and lack of detail: By assigning the recharge and attenuation potential classifications at 1:625 000 scale there are inevitably simplifications of what, in many cases, are highly heterogeneous systems. The technique does not permit any account of the relative proportions of the different textures and compositions within a superficial lithotype within a certain Domain. The method also only allows the three dimensional characteristics of the superficial deposits to be incorporated where the information from a Quaternary geologists is available. The heterogeneity is captured in this method by providing a primary and secondary estimated of recharge and attenuation potential. Therefore, a highly variably 3D deposit would be classed as High – Low, while homogenous deposits may be High – High.

At the 1:625 000 scale some of this three dimensional nature was captured in the matrix, for example the areas of thick superficial deposits in the Cheshire Basin. When applying at 1: 50 000 scale, much smaller domains can be mapped (for an example see McMillan et al. 2000) which will characterise the 3 D nature in more detail.

Mapping issues: Some areas of raised beach/ estuarine deposits, e.g. the Wash, have been mapped as alluvium on the 1:625000 superficial geology map. For many areas moraine and till have not been subdivided and variations in the morphology and composition of these deposits will have implications for permeability and attenuation potential. Lower permeability carse deposits are often not differentiated from more permeable raised beach deposits. Within the scope of this project this has been catered for as far as possible by adjusting classifications manually according to local knowledge.

Technique and classification issues: There is also the question of whether the assessment categories are sufficient. For some deposits a highly variable category may be more appropriate. There is also an argument that thickness should be integrated into the classifications rather than be examined as a separate dataset. These issues can readily be addressed in subsequent usage, given that the database can be modified relatively easily.

GIS issues: There a few issues with different boundaries between the different datasets e.g. the superficial and bedrock geology and the domains maps. This means that in some instances, because the geological maps extend slightly beyond the line work of the domains there are a few polygons around the coast which do not have a domain type assigned to them. To rectify this in the future the domains boundaries could be extended slightly. Similarly where two or more polygons intersect there are sometimes ‘slithers’ left behind which may not get coded.

5. MOVING TO THE CATCHMENT SCALE

In the previous sections we have described how the methodology for developing recharge and attenuation potential maps has been applied to the UK at a scale of 1:625 000. This scale does not allow the recharge and attenuation properties of the superficial deposits to be confidently assessed at the local, or small catchment scale. However, the methodology described in Section 3 is essentially scale independent, and can be applied to the most commonly used geological dataset, mapped at 1:50 000 scale. There are also other methods that can be used to help understand the recharge and attenuation processes at work within superficial deposits in a catchment scale.

This chapter describes how the method can be applied at 1:50 000 scale, and also provides a toolbox of some available techniques for understanding recharge and attenuation processes at a local level.

The methodology for creating the maps is shown in Figure 3.2 (the general methodology with the matrix in the middle). The methodology requires three datasets, plus the matrix:

- The superficial deposits geological map.
- A map of the Quaternary domains/sub-domains.
- A derived bedrock geological map divided according to the bedrock types influence on soil parent material.
- The data matrix describing how the properties of the superficial deposits vary between different domains/sub-domains.

Much of this information is available at a scale of 1:50 000.

5.1 Superficial Deposits Geological maps at 1:50 000 scale

Overview: Digital geological maps of the superficial deposits are available at a scale of 1:50 000 over much of the UK. The maps have been produced at different times, to different standards. There is no simple way to undertake a 'quality' assessment of the 1:50K scale geological maps that cover England, Wales and Scotland. Such maps are a complex compilation of empirical observations and measurements that have been made:

- by numbers of different geologists with differing skills and scientific interests
- over a period of 175 years
- mapped at different rates
- initiated/driven by different objectives (e.g. mineral, engineering or hydrogeological).

This inherent complexity applies internally (there are on average 26 1:10K scale tiles per 1:50K sheet) and nationally (there are 530 1:50K tiles times across the UK mainland).

As part of this project a methodology was developed to help gauge the confidence in the superficial geology maps available across Great Britain.

Methodology: To achieve the 'confidence' information provided to the SNIFFER project (Figure 11) a qualitative assessment based on a two-fold approach was undertaken based on:

- A first pass, mechanistic rule-based assessment
- tempered with a second pass subjective appraisal

To visualise the confidence in the mapping, coloured segments within pie charts have been used to indicate the lithological complexity within a 1:50K map tile (green = simple, red = complex) whilst colour density has been used to indicate the stratigraphical confidence (pale colours = high confidence, dark colours = low confidence).

A grade maps
Pie charts dominated by pale green pie-slices indicate maps with a high proportion of simply defined lithological characteristics and a proven stratigraphy. Geological 'understanding' of these maps could be expected to be good and therefore these are unlikely to be significantly improved.

C grade maps
By contrast, pie charts dominated by dark red and dark pink pie-slices are stratigraphically poorly defined units of mixed lithologies. These maps probably require significant resurvey to be fully understood.

B grade maps
Pie charts dominated by pale green, blue and red/pink segments, represent the dominant category (they are maps which require localised attention).

The B grade maps in particular have been re-assessed manually to determine what and if a particular aspect of the geology has unduly influenced the initial classification. A final classification has then been given based on the manual revisions. For example, clay-with-flints has a poor confidence rating in the rule-based scheme because it is lithologically complex; however, stratigraphically it is a very simple deposit to map. Thus, maps covered by clay-with–flints in the first pass appraisal would be dominated by red and pink pie chart segments but in terms of confidence such maps are really 'fit for purpose' and therefore worthy of a better grade.

This is where the subjective appraisal is applied resulting in some B grade maps being promoted to A grade or alternatively some being demoted to C grade to account for such local variations.

There are a number of key points to bear in mind when using these 'confidence' results:

1. The assessment is based upon lithology and stratigraphy data attributes. It is not an assessment of survey linework accuracy, cartographic quality or Surveyor experience/skill, factors that can play a significant role in map 'quality'

2. The assessment is based upon the following assumptions:
   - That simple lithological units are more readily mappable than complex ones
   - That stratigraphically defined units have been fully resolved at field scale
   - That all superficial deposits carry the same importance for the user

3. This approach has produced a basic set of information. It can be improved in detail if required for example, to meet specific user needs such as the 'quality' of the map information relating to tills; this improved resolution would involve additional effort and a refinement of the appraisal strategy.

An assessment of confidence has also been undertaken for the 1: 50 000 scale map tiles in Northern Ireland but the above grading has not been applied at this stage.

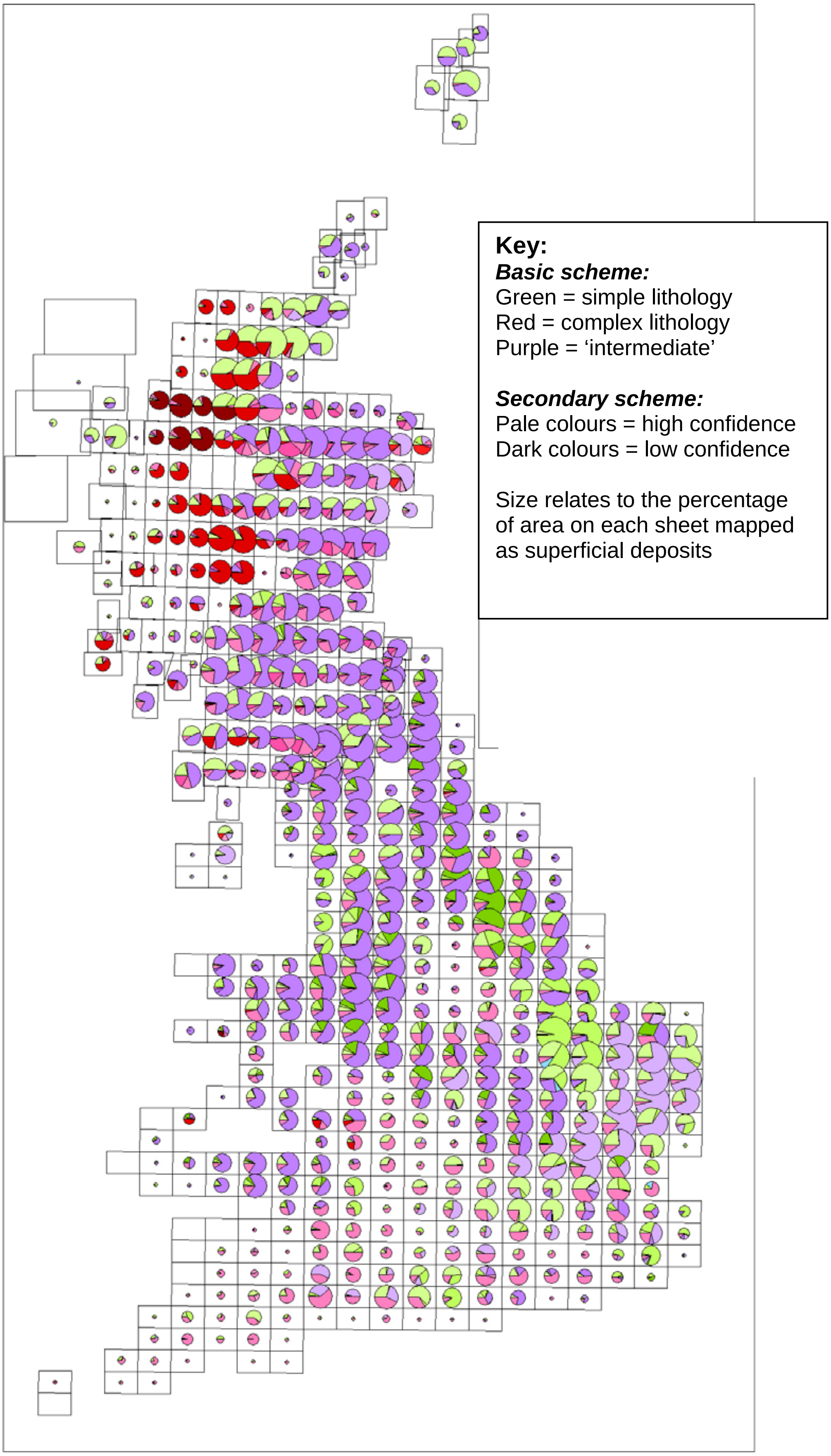


Figure 11 A 'confidence' assessment of the 1:50K geological maps covering the UK mainland

5.2 Quaternary Domains

Quaternary domains for Great Britain are available as an A4 diagram (Figure 5). The eleven main domains were used to make the initial maps based on the 1:625 000 geology. These eleven domains have been subdivided into sub-domains (about 40 in total) which could be used to further refine the outputs. These domains and sub-domains could be used in conjunction with the 1:50 000 scale maps and a revised matrix produced to help describe the properties of the superficial deposits within each sub-domain. Local variations in recharge and attenuation potential would be better identified by having an understanding of the variations in the Quaternary deposits at this more detailed scale.

One possible alternative dataset which may benefit the methodology is the proposed Quaternary lithostratigraphical framework for the UK (McMillan 2004). This is similar to the domains idea, but provides a framework for classifying superficial deposits in the same way that bedrock geology is classified (super group, group subgroup and formation). At present the groups are identified to about the same detail as the domains. However, this structure allows further subdividing to occur based on this framework. Therefore, for each catchment, or area of concern, a regional quaternary geologist could be used to identify further useful subdivisions of the superficial deposits in the area of interest. At present the framework has not been developed for the whole of Great Britain which is why the Quaternary Domains were used for this study.

5.3 Soil parent map

BGS are currently producing a 1:50 000 scale soil parent material map for Great Britain which is based on a variety of sources. The map sub-divides the bedrock into different broad lithological classes and can therefore be used to help characterise the glacial deposits (in particular glacial till) that are derived from it. This 1:50 000 map is directly comparable to the 1:625000 map used in the trial methodology.

DigmapGB50 (digital 1:50 000 geological map of the bedrock) was initially used as a basis for the map but as the dataset does not provide adequate information supplementary spatial layers (‘corrective layers’) and intervening layers have been added. The intervening layers tend to be ‘unpublished’ map data in both digital and analogue form. Aeolian units of cover sand and loess, periglacial head and colluvium, peat and fluvial sheet deposits are deposits which will be added to the map as they are currently not well-represented. The datasets will be supplemented with information from terrain analysis (accumulation zoning, elevation/slope interaction), local knowledge, remote sensing (Hires, Landsat), archive data (fieldslips) and field descriptions of soil samples collected as part of the GBASE programme.

5.4 The data matrix

The matrix can easily be applied at 1:50 000 scale. However its usefulness depends on incorporating local geological understanding and knowledge of variations of the superficial deposits within the area. Commonly this detailed knowledge will reside with the BGS/GSNI regional mapping geologist although there may be other experienced individuals who can make important contributions. It is considered that, at a minimum, the questions set up in the present matrix should be answered for each mapped superficial deposit within the area.

At 1:50 000 scale, borehole information and site investigation reports held by BGS/GSNI and other organisations will be fundamental to understanding and mapping the nature of the various superficial deposits. Therefore, the understanding of the local geologists and hydrogeologists can be enhanced through incorporation of hard data.

5.5 IPR and copyright issues

Moving to a catchment scale, and applying the methodology means incorporating datasets that will require licensing to use.

- Digital1:50 000 superficial deposits geology is available under licence from the BGS as DigMapGB50
- Digitial 1:250000 superficial deposits geology is available for Northern Ireland from GSNI. Digital information at 1:50 000 scale will be available shortly.
- Bedrock lithology classifications are available at 1:50 000 scale under licence from BGS, known as the “soil parent map”.
- The sub domains, or lithostratigraphical map of Great Britain is available from BGS. These are copyright BGS and available digitally under licence
- Superficial deposits thickness is available at 50 m grid over GB. This forms part of the BGS GeoSure dataset available under licence from BGS.
- The HOST dataset is useful for comparing the results of the methodology with. This is available under license from CEH for England and Wales and MLURI for Scotland.

5.6 Toolbox for assessing recharge

Whilst the derived methodology allows relatively rapid incorporation of available datasets and local knowledge to develop an understanding of the general hydrogeological properties of superficial deposits, there are a variety of other techniques which can be applied to enhance our understanding of catchment processes. In this section we describe some of these methods and provide references to follow up the techniques in more detail. Some of these methods could also be used to help validate and improve the recharge and attenuation maps.

5.6.1 Routine site investigation

Fundamental to understanding and quantifying hydrogeological processes in superficial deposits is the undertaking of routine site investigation work to a high standard. The standards set out in the 1999 British Standard BS5930 form a good basis for undertaking site investigation. Some particularly issues are highlighted below:

Geological logs of site investigation boreholes. It is difficult for those logging unconsolidated material to provide a good geological log that helps the conceptual understanding of the superficial deposits in the area. Consultation with a local expert in Quaternary geology will help the site investigation boreholes be sited appropriately, and also may help with interpretation. Often a rapid look at the deposits by an experienced geologist will help to unravel the 3 D quaternary sequence in the area.

Carrying out short pumping test. If the superficial deposits are saturated, short pumping tests, or rising head tests should be carried out to estimate the horizontal permeability. For this, piezometers are best constructed with 50 mm screen and casing. A short test of several hours can give very useful information.

Soil and sub-soil sampling. Although this project is dealing with the superficial deposits, much useful information on recharge can be gathered on infiltration rates by testing the soil. The Geulph permeamater for example will help to define infiltration rates in the soil, and can be used to depths of up to 1 m.

Geological mapping. Catchments can be rapidly mapped by Quaternary geologists by examining landforms and any exposures or quarries in the area. In addition, the many hundreds of thousands of borehole records held by BGS/GSNI can be examined to give a picture of the 3D complexity.

Permeability and porosity measurements. It is essential for permeability and porosity information to be gather from superficial deposits. However, this is difficult to undertake on undisturbed samples. Routinely taking U100 cores and making measurements on these cored samples would give much better data than making measurements from disturbed samples. Undertaking a detailed grain size analysis can also be helpful for estimating permeability using empirical formulas, such as the Hazen formula (Freeze and Cherry 1979).

5.6.2 Recharge assessments using residence time indicators

Identifying the age of groundwater in an aquifer can be a great aid in understanding the rate of recharge through the overlying superficial deposits. For groundwaters, 'age' basically means the time a water has spent underground. There is no single way of dating water: to find the best technique in any particular case, it helps to have some idea, however approximate, of the water's age. For most of the superficial deposits in the UK, the travel time is likely to be less than about 50 years.

These young (less than 50 years old) groundwaters are easiest to date. This is because of certain pollutants vented to the atmosphere during the second half of the 20th Century. These work in two different ways. Firstly there may be a 'spike' of known narrow age range: as for tritium, the radioactive form of hydrogen produced by thermonuclear testing in the late 1950s - early 1960s. Secondly there may have been a gradual build-up: as for the chlorofluorocarbons (CFCs), renowned for their part in thinning the ozone layer. Figure 12 shows this graphically. While the first type is particularly good for determining the rate of downward movement of recharge through the so-called unsaturated (or vadose) zone between ground surface and the aquifer water table, the second type is rather better at providing a reasonably precise value for water residence within the aquifer.

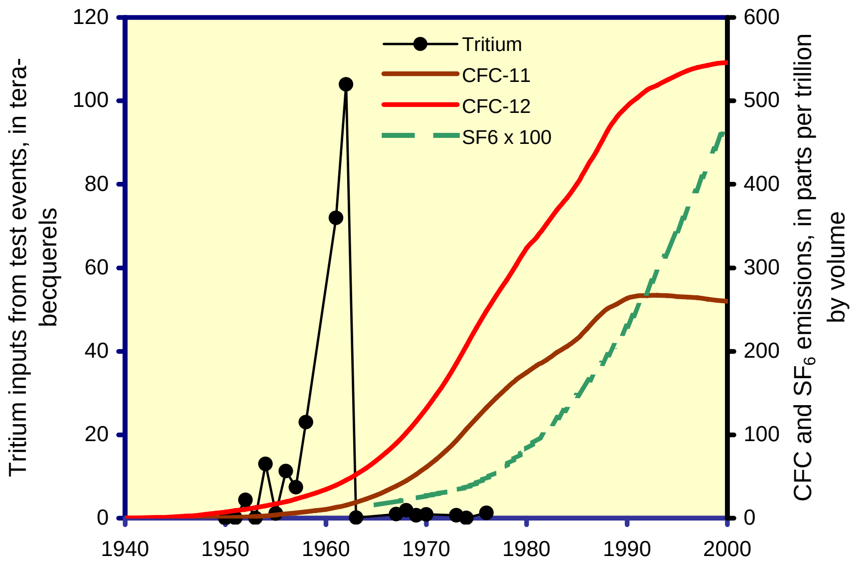


Figure 12 Atmospheric inputs of anthropogenic indicators during the second half of the 20th Century.

5.6.3 Recharge modelling

Distributed recharge models are now often constructed for use with groundwater models. In the UK, there are a number of recharge models used in regional studies; Entec's 4Rs, the Environment Agency's own models and ZOOMQ3D. Distributed recharge models allow the identification and quantification of recharge processes. Both direct recharge processes, i.e. soil based processes and indirect recharge processes such as runoff recharge can be quantified. Other recharge mechanisms such as losses from pressurised water mains and sewers can also be included in the model. The model allows the calculation of potential recharge and consideration of drift deposits is required to determine how much potential recharge becomes actual recharge (i.e how much recharge leaving the soil zone reaches the water table). By including superficial deposits in the recharge model, it is possible to determine the role of the superficial deposits by delaying the recharge, moving water laterally or allowing the superficial deposits to store water.

The main issue with recharge models is the validation of the amount of recharge estimated by the model. Since recharge is difficult to measure directly, then it is necessary to combine the results produced by the recharge model with a water balance, compare time series of recharge with groundwater hydrographs or use the field based methods described below.

5.6.4 Profiling through the unsaturated zone

The use of vertical profiles of nitrate and other solutes has been an important approach to the study of the movement of pollutants from diffuse sources in the unsaturated zone. They offer a great opportunity to actually observe pollutant movement within the superficial deposits. The profiles obtained are interpreted in relation to changes in land use, cropping and fertiliser usage, and the development with time and downward movement of the profile has been studied by repeat profiling at the same sites at intervals of several years.

Boreholes are generally drilled by the dry percussion technique using U100 tubes to recover and retain continuous cores of the unsaturated zone. Where the aquifer material is too hard for percussion drilling air-flush rotary is used. The locations of boreholes must be carefully recorded so that subsequent sampling can take place as close as possible, while still sited on ground undisturbed by previous drilling. The core is preserved, subsampled and porewater extracted by centrifugation. The U100 cores also allows detailed lithological descriptions of the core material.

An example of sequential nitrate profiles in the Yorkshire Chalk is shown in Figure 13. Significantly higher porewater nitrate concentrations were obtained in 1996 than in 1978 and 1979, reflecting the higher nitrogen fertiliser usage demonstrated from the farmer's records. The sharp peaks preserved at 9.5 m and 5 m may reflect high nitrate concentrations in recharging water associated with the growth of oil seed rape at five yearly intervals in the crop rotation. Solute profiles can thus sometimes be interpreted in some detail with respect to cropping histories, although care has to be taken with such interpretation, as leaching from the soil does not necessarily directly represent the immediate cropping.

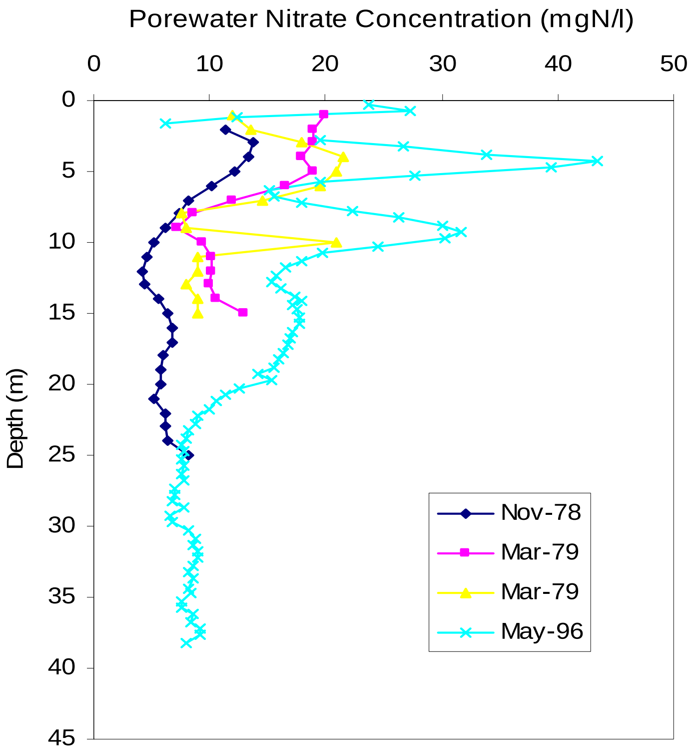


Figure 13 Sequential porewater profiles in the Yorkshire Chalk. Similar profiles can be obtained from superficial deposits.

5.6.5 Additional site investigation measurements

In addition to the methods discussed above, there are several other techniques which could be helpful for understanding the hydrogeological properties of the unsaturated zone.

Direct measurement of CEC. Cation exchange capacity can be directly measured in the laboratory. Samples of superficial material can be removed during normal site investigation and the CEC measured. Alternatively, mineralogical analysis of the samples will identify any clay materials present which may help to predict the CEC. These approaches would be particularly helpful in glacial tills where the CEC may be variable.

Thin sections of the superficial deposits Much detailed information about the nature of flow in unconsolidated material at the pore level can be gathered by taking thin sections. For example, the proportion of intergranular versus fracture flow. The technique, involves taking an undisturbed sample and injecting very slowly with resin, before then taking thin sections. To preserve delicate structures it may take several months for the resin to pervade the sample.

The use of geophysics. The advancement of electrical imaging has meant that detailed images of the electrical resistivity of the superficial deposits are now possible. This can help to identify clay layers within the deposits or variations in thickness.

5.7 Future User needs

The methodology that has been developed represents a means of capturing existing and developing geological knowledge and extracting relevant elements to improve conceptual hydrogeological understanding. Further development of the associated GIS project and incorporation of more detailed data will allow application at local catchment/groundwater body scale. In addition, with appropriate management, the GIS project could act as an ongoing archive of local understanding and knowledge. The layers and datasets developed should compliment and enhance existing vulnerability maps and contribute to local water resource models.

The methodology as described in this report makes use of readily available geological information and local hydrogeological expertise. Initial testing of the output data layers against national nitrate data in England and Wales (Johnson, 2006) shows that the output is able to weakly characterise the expected influence of drift deposits on nitrate fate and transport. This weak performance should be expected because of the scale of the assessment. However, it is also possible that the methodology needs to be extended to incorporate more datasets.

The nitrates work indicated that the key drift properties that are required to predict nitrate concentration in groundwater are drift patchyness (expressed as percentage cover per km^2) and drift depth >10m, both taken from GeoSure. The importance of these parameters varied according to the drift domain under consideration, e.g. drift depth is more important for the till dominant than for the dissected till domain. It is likely that both these parameters need to be incorporated into the matrix if the characterisation of drift is to be improved significantly.

Although there are a number of additional datasets listed below, before these are incorporated into the methodology the outputs need to be tested. The initial testing, which has been done at a large scale using nitrate data, should be refined. This will give a baseline from which to judge the relative improvement in outputs due to the inclusion of any new dataset into the method. The approach also needs to be tested at a local scale to identify the impact of scale on the accuracy of the assessment.

There are a number of additional datasets which could also be considered for inclusion into the methodology or used in conjunction with it. These are described below:

- Soils data: NSRI and MLURI have soil data maps. These maps have been interpreted to give HOST – Hydrology of Soil Types, which has successfully been incorporated in to the Scottish Groundwater Vulnerability Map (Ball et al. 2004).

- Land drainage data: Both ADAS and NSRI have data on land drainage available in a GIS format. The NSRI data identifies soil series which would require under-drainage for commercial agriculture to be practical. The ADAS data identifies where tile drains have been installed.

- Rock head elevation: BGS have a rock head elevation map for the UK as part of GeoSure. This type of information has been used in Denmark with quaternary geologists (Jorgensen *et al*, 2004) to help identify bypass flow due to tension cracking in clay rich drift deposits. Although the current methodology does identify the potential for bypass flow it does not incorporate information on drift tension which may be useful at a finer resolution.

- Monitoring and loading data for England and Wales: There are datasets for surface water nitrate and groundwater nitrate as well as loading maps for agricultural, urban and sewage effluent nitrate. All these data have been combined in a regression model which is able to predict surface water nitrate concentrations given both nitrate source data and some catchment scale characterisation data. The model results are impressive. However, there is some spatial clustering of high and low model residuals. These residuals represent areas where monitored nitrate is not what you would expect given the nitrate loading. This data is ideal for identifying catchments where additional quaternary geological input should be collected.

- Seasonal variability: All the groundwater data have been analysed for variability. For each monitoring point the mean has been compared with the lower 90% confidence interval of the 95%ile. In sites with minimal seasonal variability the difference would be zero. As the difference increases so the seasonality of the nitrate concentrations increases. It is possible that these data may provide some indication on where bypass flow in drift deposits is important.

6. CONCLUSIONS

1. A methodology has been developed which helps to reinterpret the UK superficial deposits geological map in terms of recharge and attenuation potential. The method provides a framework for accessing additional expertise from regional geologists. This methodology has then be trialled across the UK by using 1:625 000 geological data.

2. A qualitative assessment of the results compare favourably with existing recharge studies, and regional hydrogeological knowledge.

3. HOST has been used to provide a more quantitative assessment of the method. Although not directly comparable (since HOST considers soils), HOST was developed partly using the concept of baseflow which should broadly reflect the overall recharge/run-off setting of soil/sub-soil area. The method compares favourably.

4. The methodology excludes direct consideration of the soil zone and other intrinsic processes which are encapsulated in recharge estimation and in the assessment of attenuation potential of the vadose zone. These exclusions do not impact on the assessment for the superficial strata and the output appears to be reasonably robust.

5. As the methodology is scale independent there should be little problem in developing it to 1: 50 000 scale, provided that licensing issues are addressed. Rescaling will also provide an opportunity to add additional components to the methodology as required.

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APPENDIX

DOMAIN DESCRIPTIONS

The domains identified for England, Wales and Scotland are:
Glaciated and periglaciated Province: Uplands

- Ice-scoured montane domain
- Montane and valley domain
- Plateau and valley domain

Glaciated and periglaciated province: Lowlands

- Till dominant domain
- Dissected till domain
- Minimal till domain
- Lowland basin domain

Non-glaciated, periglaciated Province

- Upland periglaciated domain
- Lowland periglaciated domain
- Alluvial, estuarine and coastal domain

Fluvial domain

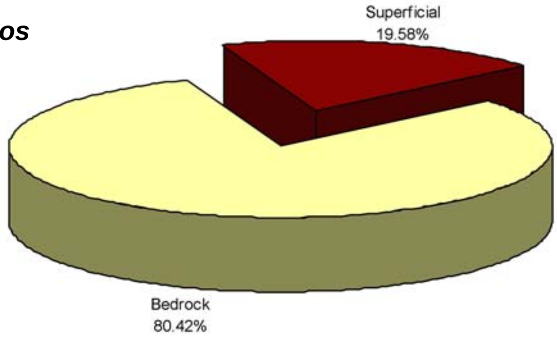
The situation in Northern Ireland is a little different. Northern Ireland lies exclusively within the Glaciated Province.

PROVINCE: GLACIATED AND PERIGLACIATED, UPLANDS

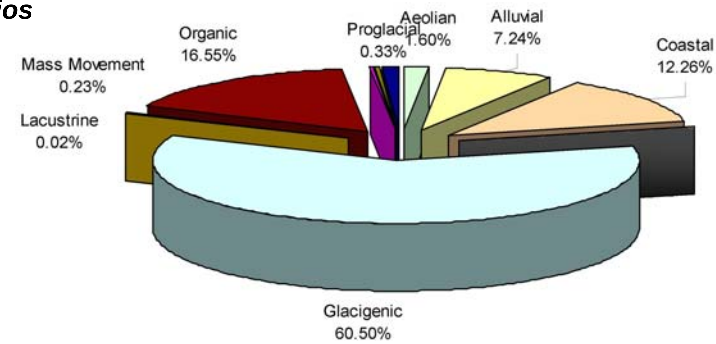
DOMAIN: ICE SCOURED MONTAIN – WEST HIGHLANDS AND AND ISLANDS OF SCOTLAND

Domain: IM **Ice-scoured montane**

Bedrock/Superficial ratios



Superficial component ratios



<u>*Landforms, deposits and processes*</u>

This domain is typically devoid of superficial deposits as it has experienced severe, widespread glacial erosion. Soil is thin or non-existent. The most characteristic landforms are ice-scoured and sculptured knock-and-lochan terrain, fjords and strandflats. Some mountains are included with huge rugged corries and mountaintop blockfields.

Outcrops of till are sparse; the till typically little weathered, extremely bouldery and containing much comminuted rock. Morainic deposits are commonly not distinguished from till on existing maps; they are also typically boulder-rich and form recessional ridges and hummocky ground within valleys. Glaciofluvial deposits are sparse apart from where they merge with raised beaches.

Raised shorelines, beaches and wave-cut platforms are very common along the coasts. They occur as two distinct sets, Late Devensian and Holocene. The older set is locally associated with glaciofluvial deltaic deposits these represent important resources of sand and gravel.

Paraglacial and periglacial processes modified the landscape immediately following deglaciation and marine processes affected the coasts during periods of high sea level. There is minimal occurrence of deeply weathered and decomposed bedrock. Active processes on higher ground include rock topples, debris flow, landslips and other gravitational mass movement processes. Large landslips are uncommon. Fluvial erosion and deposition is confined to narrow alluvial tracts in the valley bottoms. Ice-scoured hollows are ubiquitous on lower ground and are generally filled with highly compressible deposits of peat, silt and clay. A wide range of coastal processes are operational that reflect the diverse nature of the coast, including rugged clifflines with sea stacks, extensive sandy beaches, cobbly storm beaches and tombolos.

<u>*Hydrogeological Processes*</u>

This domain is characterised by only 20% cover of the land area being covered by superficial deposits and the soil cover is thin to absent. The few superficial strata that do exist are mainly granular and include boulder dominated material. This material neither acts to inhibit rainfall recharge nor does it contribute to attenuation of pollutants falling at the surface.

Coastal raised beach deposits are, for the most part, granular, although they do in places contain peat and other lower permeability layers. These act to restrict vertical transport and provide a carbon rich layer in which pollution attenuation may be active. These deposits are, however, of limited extent and by their nature tend to be linear in distribution. In places anaerobic conditions have been found beneath peat layers indicating isolation of some water in the sands and gravels from the atmosphere and from ready access to contemporary recharge.

Peat bog comprises some 17% of the area. This provides largely complete protection to underlying strata as direct rainfall recharge will not penetrate through a peat deposit which is more than a few metres in thickness and attenuation is very active within the peat. Wherever the peat is drained, however, it may become granular and permeability may become enhanced.

Summary

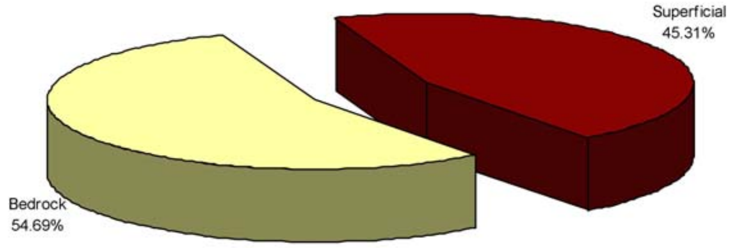
% cover	20
Lithologies	Predominantly coarse grained
Recharge potential	Generally good
Attenuation potential	Very poor except where peat present
Protection of underlying bedrock	Minimal, peat fair

PROVINCE: GLACIATED AND PERIGLACIATED, UPLANDS

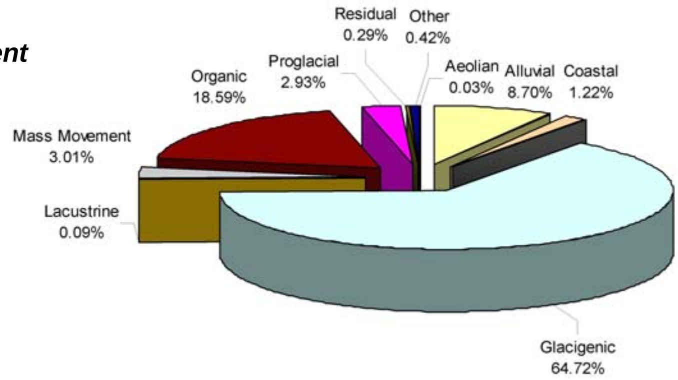
DOMAIN: DISSECTED TILL – THE HIGHLANDS AND SOUTHERN UPLANDS OF SCOTLAND, THE LAKE DISTRICT, SNOWDONIA AND CENTRAL AND NORTH WALES

Domain: MV **Montane and valley**

Bedrock/Superficial ratios



Superficial component ratios



<u>Landforms, deposits and processes</u>

The landscape comprises mountainous terrain with precipitous slopes; craggy glaciated troughs, deep cirques, fjords and numerous lochs residing in ice scoured basins and hollows, or deeply dissected upland plateaux. Seven sub-domains distinguish the locally variable terrain characteristics.

Till, morainic and glaciofluvial deposits are mainly restricted to valleys. Tills are generally of the lodgement type, being little weathered, extremely compact, commonly fissile, stony, massive, matrix-supported diamictons. Morainic deposits are typically gravely and bouldery, forming valley floor mounds and ridges, and chains of mounds rising obliquely up valley sides in the direction of glacial retreat. Glaciofluvial deposits abound locally, being dominated by moundy ice-contact deposits such as kame terraces, plateaux (former fans and deltas) and eskers. Blanket peat is widespread on less rugged mountaintops and across plateaus.

Rubbly gelifractates mantle most summits, but are rarely distinguished from Solid on maps unless they are sufficiently coarse to be recognised as 'Blockfield'. Many mountaintops are covered by up to about 3m of gravely material formed mainly by the cryoturbation of disintegrated bedrock - rarely mapped it is distinguished as 'Blanket Head or Regolith'. Head deposits are ubiquitous on mountainsides and on lower ground, but are rarely mapped. Large landslips are common on the steeper mountainsides. Patterned ground is commonly evident.

Active processes on higher ground include rock topples, severe debris flow activity during flash flood events, landslips and other gravitational mass movement processes. Active periglacial processes operate above about 800 m where they produce a suite of phenomena including small solifluction lobes, turf-backed terracettes and ploughing boulders. Slope modification continues, albeit restricted to colluvial and slow soil creep processes, with localised debris flows and landslips. Fluvial erosion and deposition is confined to narrow alluvial tracts in the valley bottoms.

Hydrogeological Processes

This domain includes a large part of the upland areas of Great Britain. It is characterised by widespread cover of lodgement till over a third of the area with just 45% of the land surface area covered in superficial deposits. The tills vary from almost granular and permeable till in large areas of northern Scotland to clay bound granular tills in the Southern Uplands and central Wales. The remaining deposits comprise a range of alluvial material, from silts to high energy gravels and boulder beds, head deposit, largely scree type material, and peat bog.

The till and peat act to inhibit recharge (Figure A). However, this action is limited in many areas of the till where the granular fraction exceeds any clay minerals or rock flour component as is the case in much of northern Scotland. Clay minerals are in any case subordinate to rock flour throughout this domain and the opportunity for attenuation of pollutants is, for the most part, lower than in a lowland till. Peat often overlays till or forms over impermeable bedrock. In general it provides a good medium for attenuation and has only a limited vertical hydraulic conductivity except where it is drained and desiccated.

Till thickness varies up to a few tens of metres although in many areas of steep relief the till cover may be thin.

Granular superficial deposits also act as shallow aquifers in low-lying areas such as valley bottoms. Although alluvium may be underlain by till in some places, it is also commonly in hydraulic contact with bedrock. In the latter case it affords little if any protection to underlying aquifers and may connect groundwater with surface water in rivers of variable ands occasionally poor quality water. The geometry of the alluvial deposits and the juxtaposition of less permeable material may be complex, but these shallow aquifers act as receivers for overland flow and soil interflow which transport water laterally down the valley sides as well as longitudinally along the valley bottom. The deposits may have a complicated interrelationship with surface waters whereby they gain from rivers in some reaches and lose in others. Resource potential is generally limited. Exceptional yields have, however, been developed for public supply in the Rheidol, Teifi, Dyfi and Tywi catchments in west Wales, notably the Lovesgove boreholes in the Rheidol catchment [SN 638 808] which yield 40 l/s from a formation which has a transmissivity of between 4000 and 6000 m^2/d. Similar high yields are maintained from wells in alluvial deposits to supply some of the towns in the Borders of Scotland.

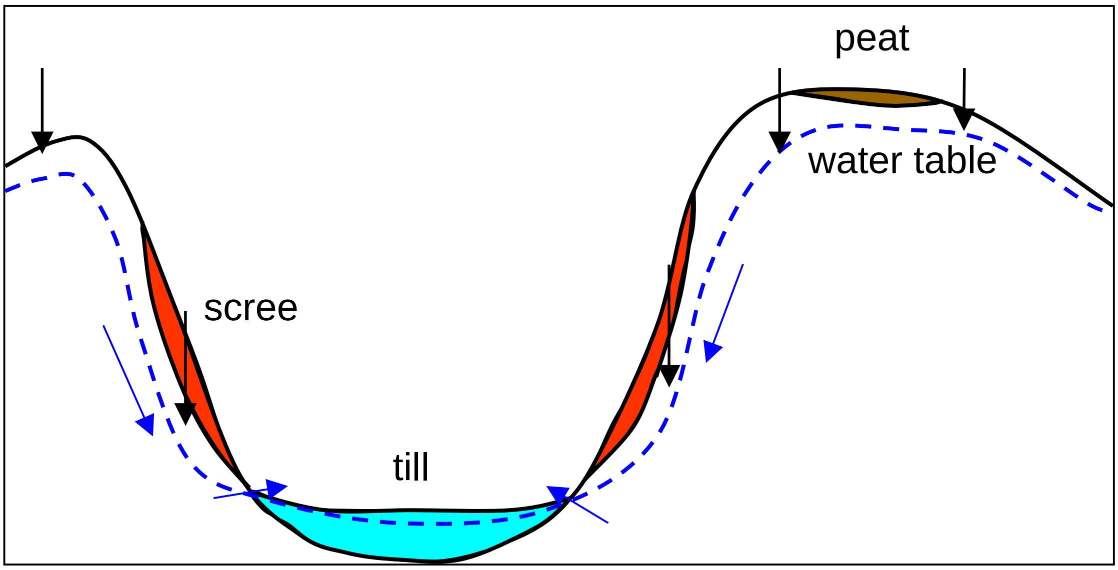


Figure A Schematic cross section showing recharge zones typical of the Montaine and Valley Domain

Summary

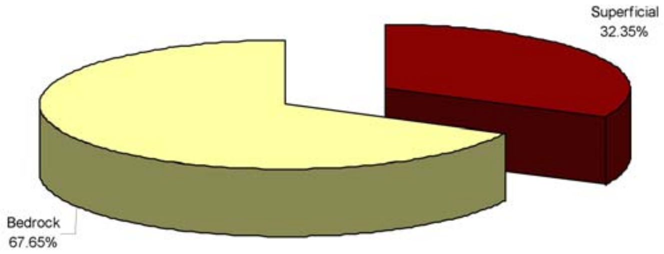
% cover	45
Lithologies	Predominantly till
Recharge potential	Moderate
Attenuation potential	Moderate to poor
Protection of underlying bedrock	Fair

PROVINCE: GLACIATED AND PERIGLACIATED, UPLANDS

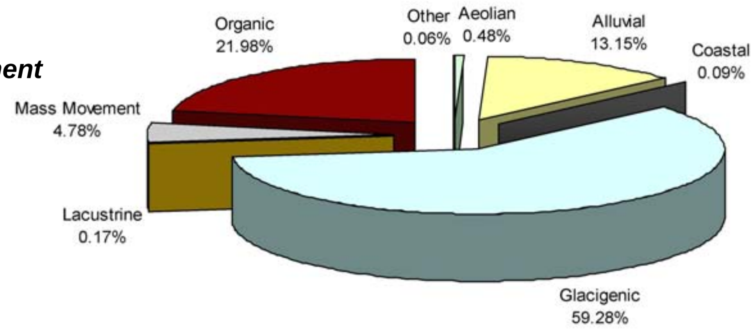
DOMAIN: DISSECTED TILL – THE PENNINES, THE YORKSHIRE AND LINCOLNSHIRE WOLDS AND THE SOUTH WALES COALFIELD AREA

Domain: PV Plateau and valley

Bedrock/Superficial ratios



Superficial component ratios



<u>*Landforms, deposits and processes*</u>

This Domain includes many of the uplands of England and Wales that are underlain by bedrock ranging from unmetamorphosed Carboniferous rocks of the Millstone Grit and Coal Measures (the Dark or High Peak landscape) or Carboniferous Limestone (the White Peak landscape). The North York Moors, although of Jurassic age, have similar bedrock lithologies and character to the Carboniferous strata whilst the Devonian and Carboniferous bedrock in South Wales tends to be softer shales and mudstones. The Yorkshire and Lincolnshire Wolds are dominated by dissected Chalk plateau. Over the Carboniferous and Jurassic strata the landscape is primarily determined by differential erosion of the weaker shales and mudstones and the relatively resistant sandstones and limestones. The latter give rise to scarps and associated 'free faces or edges' which may be fashioned by weathering into tor-like features and surrounded by block debris. This topography was moulded by at least three glacial episodes; evidence for the earlier phases has been mostly obliterated by the Devensian glaciation except perhaps in the Southern Pennines.

Glacial erosion and the occurrence of till, morainic (drumlin fields, and hummocky or moundy ground) and glaciofluvial deposits from late-glacial meltwater channels is mainly restricted to the valleys. Many of the major valleys were originally glacially scoured but are now flat-bottomed, with a partial fill of complex glacigenic deposits overlain by alluvium. Paraglacial and periglacial deposits are both common along valley sides. Blanket peat is widespread on plateau surfaces, where deeply weathered bedrock is common. Landslides and cambering are commonly developed along valley sides and escarpments, with strata in the central parts of valleys typically contorted as a result of complementary 'valley bulging' processes.

<u>*Hydrogeological processes*</u>

Only one third of the land area in the Plateau and Valley domain is covered by superficial material, the majority of which is glaciogenic in origin with subordinate alluvium and peat deposits. The glaciogenic material is largely granular except in South Wales where the till is slightly more clay-bound; it being derived from shales and mudstones rather than grits and sandstones.

Only 20% of the land area is covered in till with glacio-fluvial material above the till or adjacent to it. The till is generally only a few metres thick and weathers to a depth of about 5 m. The weathered zone offers sufficient permeability to promote ingress of rainwater, and even in other areas where the till is thicker, the gritty nature of the till coupled with its limited aerial extent has only a minor effect on potential recharge. Attenuation in the till is poor due to the near absence of clay minerals, although the South Wales area is slightly better with weathered clay minerals derived from bedrock.

The peat deposits are largely restricted to high plateau surface (e.g. Kinder Scout in Derbyshire). Such areas are largely devoid of vertical pathways to bedrock; the Millstone Grit at Kinder is only recharged around the periphery of the plateau.

Alluvial deposits vary from coarse high energy deposits to silty and weakly permeable deposits. For the most part they provide ready access to bedrock and facilitate exchange between groundwater and surface water according to the prevailing head difference in any specific reach.

Summary

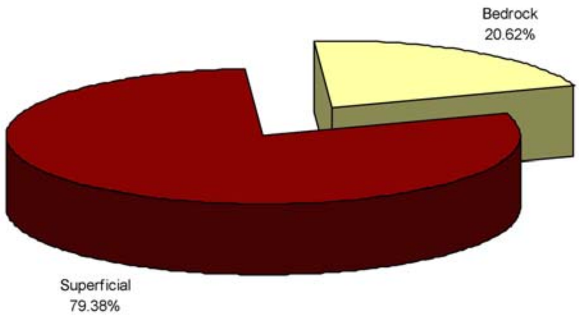
% cover	32
Lithologies	Predominantly till
Recharge potential	Generally good
Attenuation potential	Poor, except for peat areas
Protection of underlying bedrock	Generally poor

PROVINCE: GLACIATED AND PERIGLACIATED, LOWLANDS

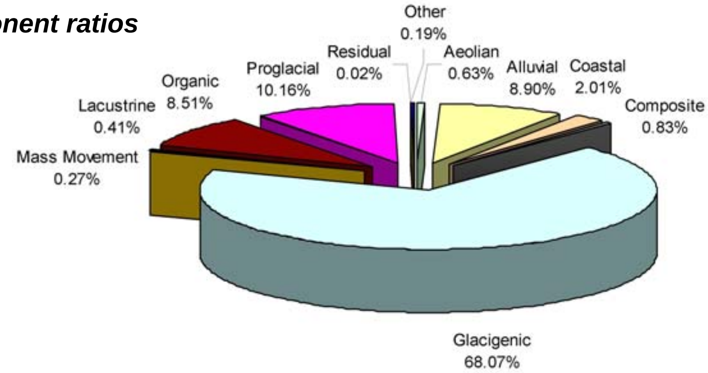
Domain: TILL DOMINANT – EAST SCOTLAND AND MIDLAND VALLEY, NORTH-WEST AND NORTH-EAST ENGLAND, NORTH MIDLANDS, WEST AND SOUTH WALES COASTAL BELT

Domain: TD Till Dominant

Bedrock/Superficial ratios



Superficial component ratios



<u>Landforms, deposits and processes</u>
This very extensive domain includes most of the lowlands of Britain lying to the north of the Devensian glacial limit and the Midland Valley in central Scotland. It is dominated by undulating, subglacially-sculptured spreads of Devensian till that is plastered across hills and valley sides and, importantly, is also generally present beneath younger deposits occurring within valleys and on coastal plains. Till is locally concealed beneath extensive spreads of glaciofluvial sand and gravel and fine-grained glaciolacustrine deposits. The distribution of these deposits is patchy and closely linked to the pattern of deglaciation within an area. For example, many of the more extensive tracts of glaciofluvial ice-contact deposit (eskers, kames, terraces, fans and plateaux) occur where independantly-sourced lobes of the former ice sheet abutted one another. A good example of such an'interlobate' spread is the Carstairs esker system in central Scotland, formed between Southern Uplands and Highland-sourced ice. The distribution of other spreads of glaciofluvial sand and gravel is related to former still-stands and local readvances of ice.

Till composition is generally closely related to the nature of the predominant underlying bedrock. For example, tills are typically clayey across Carboniferous strata and Palaeozoic mudstones whereas they are more sandy across Devonian and Permo-Triassic sandstones, and granites. Very compact, stony lodgement type tills are most common close to mountainous ice sources whereas less compact, deformation type tills with well-dispersed stones within a clayey matrix are more common towards coasts.

Late glacial outwash deposits often obscure tills and glaciolacustrine deposits, which hinders reliable stratigraphical interpretations. The landscape is commonly far more geologically and geomorphologically complex than it might appear from Remote Sensed interpretation, The locally unpredictable, heterogeneous geology is often difficult to depict on a 2D map; stratigraphical models and 3D modelling is problematic especially in the absence of numbers of well-distributed boreholes. Some areas underlain by deposits that predate the last glacial advance often have little or no surface expression.

Hydrogeological Processes

This is one of the more important domains as it acts to conceal and in places confine a number of major aquifers including the Permo-Triassic, the Chalk and a variety of lesser, but nevertheless significant, Palaeozoic aquifers in Scotland. In order to demonstrate a conceptualisation for the Till Dominant domain it is useful to review some of the case study investigations that have taken place:

McMillan et al. (2000) assigned the complex drift sequence of the Sellafield area of the west Cumbrain coast into packages of sediment with common depositional and deformational histories. These were then translated into equivalent hydrogeological domains which included some subdivision of the geological domains and removal of superficial sands, peat and head:

- *Bedrock at or near surface*: Up to 1 m of till but in which recharge acceptance is controlled solely by bedrock characteristics.
- *Thin till (<5 m) and other deposits*: Recharge and interflow largely controlled by bedrock characteristics. The till is characterised by vertical fractures 20 mm wide on a 300 mm spacing allowing ingress of water from the surface and trial pits indicate discrete sub-horizontal flow along discontinuities away from the fissures.
- *Alluvium*: Includes both *alluvial floodplain* and *estuarine* deposits, constituting a minor aquifer recharged from surface water and direct rainfall recharge. It provides direct hydraulic connection with otherwise isolated parts of the Quaternary sequence.
- *Till-sand-till*: Comprises a thin upper till with vertical fissures allowing ingress of water to the sands (and gravels) which may be locally confined. The lower till acts as a barrier to further downward transport.
- *Till and clay*: A network of sub-vertical fissures within a till and clay sequence with variable amounts of silt and very fine sand forms a wekly permeable cover through which limited recharge to bedrock could take place.
- *Lacustrine*: A thick coasening upwards sequence with shallow perching. There one and in places two interbedded tills.
- *Buried channel*: This is a discontinuous lodgement till overlain by granular deposits. The sand and gravel forms a hydraulic continuum with the bedrock aquifer below.

A recent study in East Shropshire by Bridge et al. (2002) uses the same concepts as the Sellafield project gathering Quaternary domains together according to their depositional history. Unlike Sellafield, which developed a 3-D domain model from a 2-D map, this project concentrated on creating 2-D vertical sections through the drift sequence to identify appropriate Quaternary domains. In addition, the domain classifications were more sympathetic to hydrogeological interpretation:

- 100% clay surface to rockhead
- 100% sand and gravel surface to rockhead
- >50% sand and gravel surface to rockhead
- >50% clay surface to rockhead split between sand and gravel at surface and clay at surface
- Undifferentiated fluviatile deposits, split between on bedrock and on other drift
- Peat, split between on bedrock and on other drift
- Bedrock at surface

Another major investigation has been carried out over a 30 square kilometre block of central Manchester including Trafford Park. This project enjoyed data from 3000 site investigation boreholes, which were invaluable to creating the geological framework within the Quaternary deposits. The drift geology has been analysed by creating numerous cross sections through it so that a series of coarse lithologically based domains could be assigned. Transfer of these domains to hydrogeological domains is easy at the generic and subjective level but considerably harder at a more quantitative level. The transfer is further complicated by the presence of considerable areas of perched groundwater. Nevertheless a direct transfer from Quaternary geology domains to Quaternary hydrogeological domains (Table 1) was possible using the same sets of polygons.

Table 1: Lithological/Hydrogeological sub-domains for Manchester

N°	Domain	Characteristic
1	Sandstone	Domain includes sandstone at surface, sandstone overlain by permeable material (alluvium, glacio-fluvial sands and gravel, and peat) and <5 m till. Hydrogeological continuity is assumed between materials
2	Glacio-fluvial sand and gravel (GFDU 1)	Domain consists of GFDU deposit overlying >5 m of impermeable material (lake clay or till). Domain includes overlying permeable material (alluvium, made ground). *Perched groundwater occurs in this domain.*
3	Glacio-fluvial sand and gravel (GFDU 2)	Domain consists of GFDU deposit overlying >5 m of impermeable material (till). This domain is separate from GFDU 1 due to a different depositional environment, however may, in part, be in lateral continuity with GFDU 1
4	Alluvium	Domain comprises of alluvium underlain by >5 m impermeable material (till, lake clay). *Perched groundwater is likely to occur in this domain.*
5	Till	Domain comprises till material greater than 5m thick, and is assumed to be of low permeability. Small, deep Glacio-fluvial sands and gravels are included within this deposit in the east of the project area, as they are assumed to be discontinuous and unlikely to receive major recharge

Although the geological control from borehole data is good, the hydrogeological control is poor. Most groundwater data refer to drillers first water strike data, and it was found that this correlates best with elevation and offers little insight into the location of the water table, perched or otherwise. In addition there are few useable measurements of formation permeability and resort has to be made to the use of generic data. At best the domain mapping indicates where rainfall recharge is likely and where it is not.

These studies all demonstrate that even in the Till Dominant domain other subordinate depositional faces are present without necessarily being underlain by the till sheet. However, areas such as the Cheshire basin and the Fylde are almost universally till covered and it is the characteristics of the till which control recharge and attenuation. For the most part the Till Dominant domain largely inhibits the normal recharge to bedrock processes reducing the potential recharge by a factor commonly quoted as between 60 and 80%, depending on the characteristics of the till. Where clay minerals rather than rock flour are present attenuation is significantly improved.

The conceptual groundwater flow model for the Fylde is based on groundwater flowing from beneath the higher ground adjacent to the Pennines towards the lower ground in the west (Sage & Lloyd, 1978). Piezometric heads fall from 20 to 25 m aOD in the east to only 5 to 10 m aOD as the aquifer passes beneath the Mercia Mudstone Group in the west. No significant groundwater flow occurs beneath the Mercia Mudstone Group and the groundwater rapidly becomes saline in response to this beneath the confining cover. In the till covered part of the aquifer, flow concentrates on baseflow discharge to the River Wyre, with additional discharge towards the north-west into Morecambe Bay and the south-west towards the Ribble estuary. The groundwater flow system is further complicated by faulting and structural constraints as well as local recharge through the granular superficial deposits along the rivers, but it is not influenced by ingress of water through the till cover itself.

Broadly the same pattern is apparent throughout the remaining areas of Till Dominant domain. A generalised schematic conceptual system is shown in Figure A and features little direct recharge or discharge through the till cover wherever it is more than a few metres thick (i.e. unweathered till is present). The dominant recharge and discharge areas are beyond the margins of the till or wherever rivers locally incise through the till.

Figure A shows a schematic cross section of the Fylde area of Lancashire as typical of the Till Dominated hydrogeological domain.

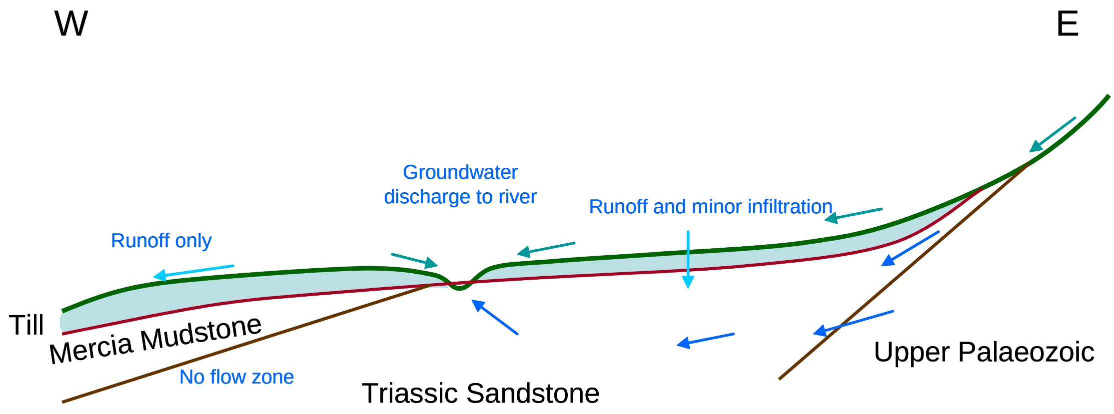


Figure A Schematic cross section showing the recharge and discharge mechanisms to the till covered Fylde aquifer

In Eastern England, for example, north of Northallerton the drift thickness is greater than 40 m, over Sherwood Sandstone. Over the Magnesian Limestone the maximum drift thickness is 84 m. In County Durham, east of the River Skerne, glacial drift is greater than 30 m thick, and west of the Skerne, it is generally less than 30 m and often less than 3 m thick. It nevertheless confines the groundwater in the underlying Magnesian Limestone and Sherwood Sandstone aquifers.

<u>Summary</u>

% cover	79
Lithologies	Mainly till
Recharge potential	Poor
Attenuation potential	Moderate
Protection of underlying bedrock	Generally good

<u>References</u>

Bridge D Mc, Humpage A J, Shepherd H, Lelliot M & Garcio Bajo M 2002. Lowland Catchment Research (LOCAR) geological framework study River Tern catchment, East Shropshire. Technical Report British Geological Survey CR/02/138.

McMillan A A, Heathcote J A, Klinck B A, Shepley M G, Jackson C P & Degnan P J 2000. Hydrogeological characterisation of the onshore Quaternary sediments at Sellafield using the concept of domains. *Quarterly Journal of Engineering Geology & Hydrogeology*, **33**, 301-323.

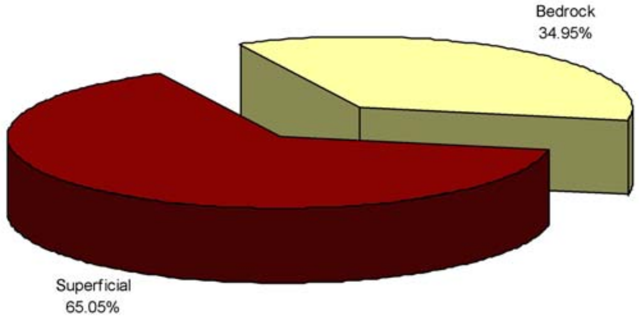
Sage R C & Lloyd J W 1978. Drift deposit influences on the Triassic Sandstone aquifer of NW Lancashire as inferred by hydrochemistry. *Quarterly Journal of Engineering Geology*, **11**, 3, 209-218.

PROVINCE: GLACIATED AND PERIGLACIATED, LOWLANDS

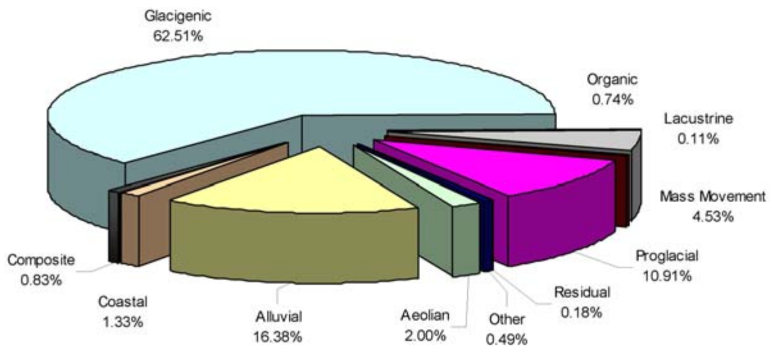
DOMAIN: DISSECTED TILL – EAST ANGLIA AND EAST MIDLANDS

Domain: DT Dissected till

Bedrock/Superficial ratios



Superficial component ratios



<u>*Landforms, deposits and geological processes*</u>
This extensive domain includes the lowlands of the Midlands and East Anglia which occur between the Devensian and Anglian glacial limits. In East Anglia, the landscape is essentially a low-lying, relatively flat dissected till plateau with a universal coverage of superficial deposits that include various glacial lithofacies (till, glaciofluvial and glaciolacustrine) laid-down by successive Middle Pleistocene advances of the British Ice Sheet. These largely exhibit a layer-cake stratigraphic arrangement except for the north of the region where deposits have been highly tectonised and thrust-stacked. Extensive sands and gravels overlie the youngest till in north Norfolk and form positive topographical features such as the Cromer Ridge in northeast Norfolk. Pre-glacial sediments of the Crag and Dunwich groups can frequently be mapped in valley flanks that are cut through the till plateaux. Till locally underlies river terraces and alluvial deposits in the valleys.

In the Midlands, the landscape was profoundly modified during the Anglian (Middle Pleistocene) glaciation, and subsequently by a regime of progressive uplift and incision under climates that oscillated between warm temperate and periglacial. Its topography is characterised by subdued bedrock featuring, locally with ridges and scarps, but the dominant landforms are the extensive till-covered plateaux of the interfluves. Landslips associated with mudflow aprons are prominent features along the steeper slopes, particularly those developed on Jurassic mudrocks, but may also involve the Superficial cappings to the slopes. Head deposits form low-profile sheets on the lower parts of valley slopes and, together with colluvial deposits and alluvium, commonly underlie the flat floors of many small valleys. Palaeovalleys are characterized by layer-cake sequences, up to 80m thick, of glacial, glaciofluvial and glaciolacustrine deposits, which in part overlie Early Pleistocene (pre-Anglian) fluvial deposits. Slope instability features, associated with solifluction sheets and head aprons, are particularly extensive along scarp slopes or valley sides developed on mudstone-rich bedrock.

<u>*Hydrogeological Processes*</u>
This is an important but complex and varied domain which covers a large part of central and eastern England. It overlies large tracts of both the Permo-Triassic and the Chalk aquifer systems. The East

Anglian till is essentially clay bound whereas the tills in the Midlands are slightly more gritty reflecting the predominance of arenaceous bedrock in this area. The domain is characterised by a layer cake of till sheets which remain on the interfluves but which have been incised in valleys where alluvial deposits are found. Steeper and larger valley sides are characterised by head deposits which represent slumping of the till deposits towards the valleys.

Marks et al. (2005) characterise the dissected till as:

- Beneath the interfluves recharge appears to be lower than previous estimates of 20 to 40 mm/a for the Chalk (Klink et al., 1996) and the Permo-Triassic, maybe as low as 5 mm/a.
- Groundwater beneath the interfluves in the Chalk aquifer is old (probably a minimum of several hundreds of years) and has negligible nitrate concentrations. This groundwater makes only a relatively small contribution to the active circulation system in the valleys. CFC analyses suggest that the Chalk fracture waters beneath the interfluves have a small fraction of modern groundwater which varies between about 5 to 15%. This modern component must have effectively 'bypassed' the till matrix (so that diffusion exchange with the till porewaters is minimal); the most likely mechanism is that recharge moves rapidly down fractures which extend through the full thickness of the till sheet. A schematic hydrochemical section is presented in Figure A.

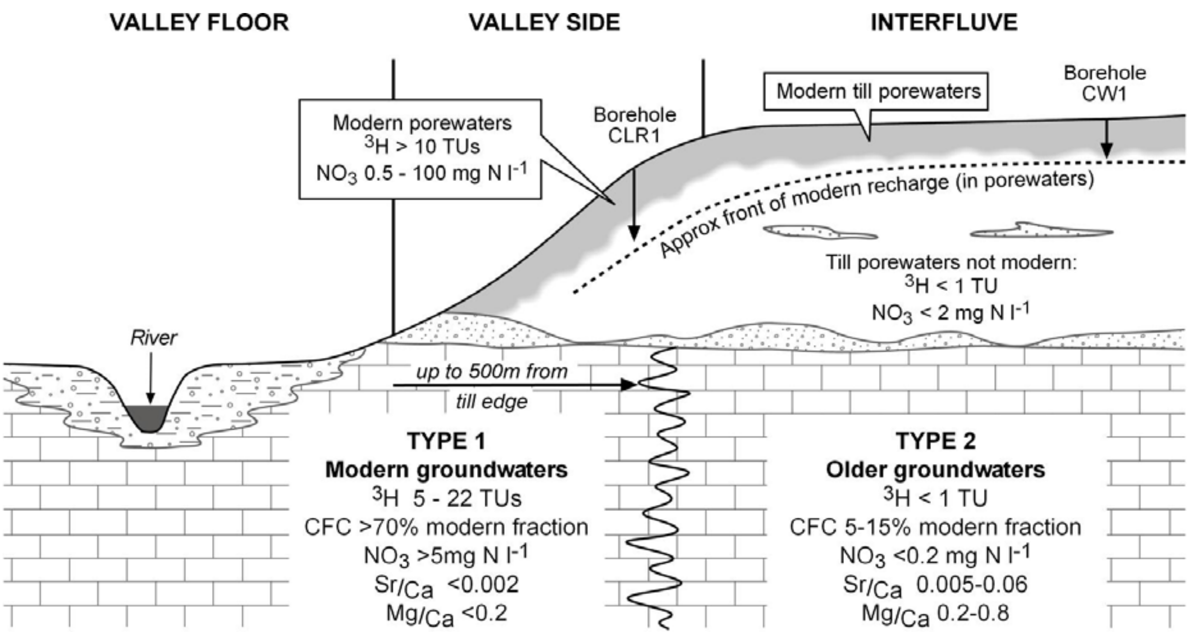


Figure A generalised schematic hydrochemical section across dissected till (from Marks et al, 2005)

- Recharge rates to the Chalk aquifer at the edge of the till are greater than the effective rainfall (rainfall minus actual evapotranspiration) because of the contribution of large volumes of runoff from the till sheet. This water characterises the modern (post-1960s), high-nitrate, groundwaters of the main Chalk valleys with potentially short travel times from recharge to discharge. Much of the arable land on the till sheet has had field drains installed and these contribute to the bulk of the runoff; as a consequence nitrate concentrations in the runoff are high
- The Chalk-till groundwater system and the spatial distribution of recharge to the Chalk aquifer determine the shape and dimensions of the catchment areas of abstraction boreholes. This in turn controls the proportion of modern water pumped by abstraction boreholes, which has implications for the concentration of nitrate in pumped water. One consequence of the redistribution of recharge by the till is that boreholes close to the edge of the till sheet are likely to

pump a greater proportion of modern recharge than previously believed and these are likely to produce water with higher nitrate concentrations.

- The Chalk groundwaters at the edge of the till sheet are vulnerable to pollution because of the potentially high recharge rates (due to runoff recharge) and the relatively shallow depth to the water table. As a consequence, travel times through the unsaturated zone may be short.

The slow component of recharge beneath the interfluves can be estimated by considering the depth of penetration of modern water in the porewaters of the till. The slow recharge component is defined as infiltration that undergoes diffusional exchange with porewater in the till. The porewater profiles obtained by Marks et al (2005) show that tritium has penetrated to 8 m but not yet to 12 m. Other porewater data (chloride, nitrate) suggest that modern water (post-1960s) has not penetrated beyond 8 m depth. The moisture content of the till was determined as about 0.2 which suggests that rates of infiltration could be as high as 30 mm/a. However, it may be more realistic to consider that recharge from the ground surface would rapidly reach the base of the weathered till (at 5.3 m) suggesting that the infiltration rate in the shallow weathered zone of the till may be closer to 20 mm/a. Data from another site show that modern (post-1960) water has not penetrated beyond 5 m depth and probably has not reached 3 m, which suggests an infiltration rate for the slow component of recharge of <25 mm/a, and probably <15 mm/a for the upper weathered zone only.

A permeability of 1×10^{-10} m/s for the till matrix was determined in the laboratory using borehole cores. Based on this value and assuming a maximum unit vertical hydraulic gradient, an infiltration rate through the matrix, of 3 mm/a at most was estimated. If the slow component of recharge for the upper weathered zone is as much as 15 to 20 mm/a as estimated from the porewater profiles then it suggests that water movement is mostly through fractures. Diffusion between the water in the fractures and the porewater causes the 'front' of modern water to advance more rapidly through the matrix than would occur by advective flow alone. Thus three recharge mechanisms through the till are proposed: (i) matrix flow which probably contributes <3 mm/a and would take more than 1000 years to migrate through a 20 m thick till layer, (ii) flow through fractures with diffusion exchange between porewaters and water in fractures (this recharge mechanism constitutes approximately 15 to 20 mm/a within the upper weathered zone of the till), and (iii) rapid flow through fractures with minimal diffusion exchange with the matrix. The latter recharge mechanism contributes the small component of modern water (as indicated by CFC results) observed in the Chalk aquifer beneath thick till. Modelling of groundwater levels suggests that recharge to the Chalk aquifer beneath the interfluves is likely to be <20 mm/a and could be as low as 5 mm/a.

This lateral flow above and within the till sheet may recharge the Chalk aquifer either where it discharges directly onto the exposed Chalk in the valley floor or where it crosses the lower thin till zone within the valley side (where the till and basal sands are <10 m thick and where unweathered till is either absent or thin).

Given that the interfluves and upper slopes of the valley sides comprise about 75% of the catchment areas in East Anglia, and that most of the effective rainfall of 155 mm/a (of which only 5 mm/a infiltrates the till) will runoff from these areas to the valley side, then the water available for infiltration may approach 600 mm/a in the latter recharge areas. However, not all of this available water will necessarily recharge the Chalk aquifer and some of this water may flow directly into rivers.

The conceptual model for the dissected till domain is presented in Figure B. It shows two distinct flow systems, one beneath the interfluves characterised by slow water movement, older groundwaters and limited recharge and discharge, the other beneath the valley floor and valley sides, with relatively rapid groundwater flow. Recharge to the valley groundwater system is considerable and occurs both as direct rainfall recharge on exposed Chalk outcrop and via lateral flow from adjacent till-covered areas. Estimated recharge rates of about 5 mm/a for the Chalk aquifer beneath the interfluve are less than had previously been assumed.

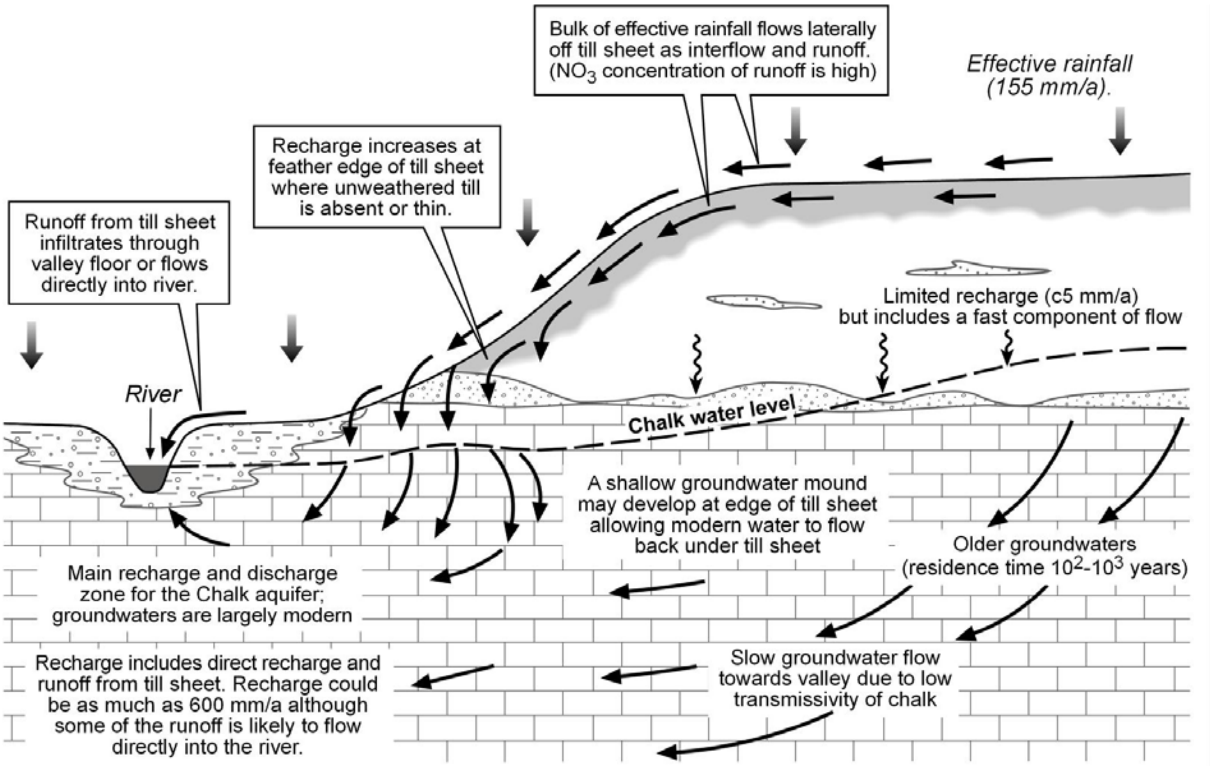


Figure B Conceptual model

The conceptual model indicates that the till has a major impact on recharge. The till restricts recharge to the Chalk aquifer beneath the interfluves (probably reducing this to <10 mm/a and possibly as low as 5 mm/a) but increases recharge at the edge of the till sheet as a result of runoff from the till cover. The Chalk groundwaters beneath the interfluve are largely of older water (probably 10^2 to 10^3 years old) and are of low nitrate concentration. The groundwaters beneath the interfluves have a small modern component; CFC results in these groundwaters suggest that this could be as much as 15%, suggesting minor input from by pass flow through fractures.

Equivalent data from experimentation for the Permo-Triassic aquifer beneath dissected till are not available. However, evidence from resource modelling work and other investigations indicate that the till cover works in broadly the same manner over the sandstone aquifer. As the overall permeability of the more sandy tills of the East Midlands may be higher than the Chalk tills of East Anglia, it is likely that diffuse ingress of rainwater will occur at a correspondingly greater rate.

The till comprises largely rock flour but will also contain some clay minerals derived from mineral weathering processes. Attenuation of pollutants in the till will take place because of the prolonged retention period of percolating water, but the reactivity of the till matrix is otherwise not likely to be significant.

Infilled buried/tunnel valleys can have a major effect on the hydrogeology of the underlying deposits. Where infilled with predominantly fine-grained low permeability material, they act as barriers to flow. In the few cases where they are filled with predominantly coarse-grained permeable material they can act as major flow conduits. The effects of buried channels on the hydrogeology of the underlying aquifers are unclear. Often high yields have been found associated with buried channels and in the Great Ouse catchment, above average transmissivities occur in the Chalk in the vicinity of buried channels where they crossed higher ground.

Buried channels are likely to be poor sites for groundwater development, as the zone of enhanced permeability has been eroded. Hydraulic connection between the buried channel deposits and the Chalk may often be prevented by the presence of a layer of putty chalk. No significant movement of the piezometric surface in the permeable silts, sands and gravels of the very deep Stour buried valley, were observed due to abstraction from the underlying Chalk.

Summary

% cover	65
Lithologies	Till and alluvium
Recharge potential	Poor except in valley alluvium
Attenuation potential	Moderate where till is present
Protection of underlying bedrock	Generally good

References

Klinck B A, Barker J A, Noy D J & Wealthall G P 1996. Mechanisms and rates of recharge through glacial till: Experimental and modelling studies from a Norfolk site. Technical Report British Geological Survey WE/96/1.

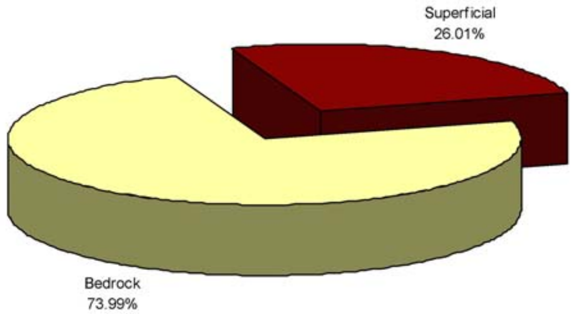
Marks R J, Lawrence AR, Whitehead E J, Cobbing J E, Mansour MM, Darling W G & Hughes A G 2005. Chalk recharge beneath thick till deposits in East Anglia. Technical Report British Geological Survey IR/04/179.

PROVINCE: GLACIATED AND PERIGLACIATED, LOWLANDS

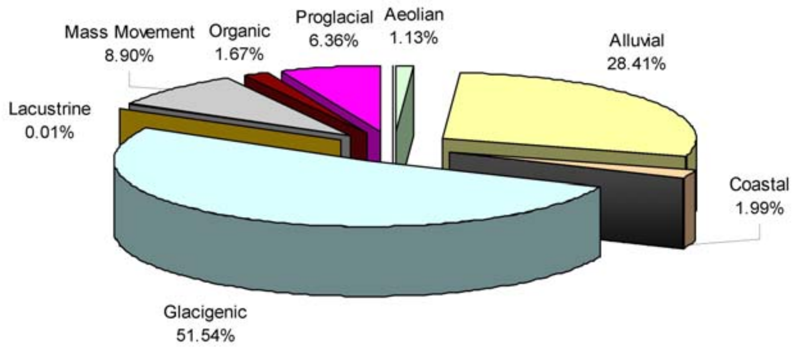
DOMAIN: MINIMAL TILL – NORTH EAST SCOTLAND, SOUTHERN WELSH BORDERLAND AND SEVERN VALLEY

Domain: MT Minimal Till

Bedrock/Superficial ratios



Superficial component ratios



Landforms, deposits and processes
This domain includes two discrete areas:

1. Within the limits of the Devensian glaciation - north-east Scotland in which little till or glaciofluvial material was laid down. However, many older maps of the area show till as being widespread; in reality, it is commonly less than 1m thick. In this region, there are occurrences of deep (<30 m) chemically weathered bedrock, mostly of granular type, but locally complete decomposition to kaolinitic sandy clay. Associated with these regoliths are remnant deposits of Neogene flint and quartzite gravel. The predominant processes that have shaped this landscape are prolonged subaerial denudation during the Palaeogene and Neogene, and severe periglacial processes during the Pleistocene.

2. Beyond the limits - Southern Welsh borderland and Vale of the Severn where there are no glaciogenic landforms and glacigenic cover is generally patchy, consisting of some weathered glacial deposits on valley sides and glaciofluvial deposits in the valley bottoms. Glacigenic deposits comprise glaciofluvial gravels, tills and glaciolacustrine silts, and are confined to 'buried' valleys, as in the Mathon Valley. Periglacial slope deposits are extensively distributed over valley sides. Fluvial deposits include possible pre-Anglian sands and gravels and post-Anglian glaciofluvial outwash terraces, river terraces and alluvium.

Hydrogeological Processes
The north-eastern Scotland sub-domain is characterised by partial cover of thin weathered and granular till covering about a third of the area, with subordinate alluvial deposits (Figure A). Along with head deposits and proglacial gravels, none of the superficial material inhibits potential recharge in any significant way. However, clay minerals are abundant in the deeply weathered bedrock and attenuation of infiltrating pollutants is likely to be moderate, inhibited only by the thinness of the superficial deposits.

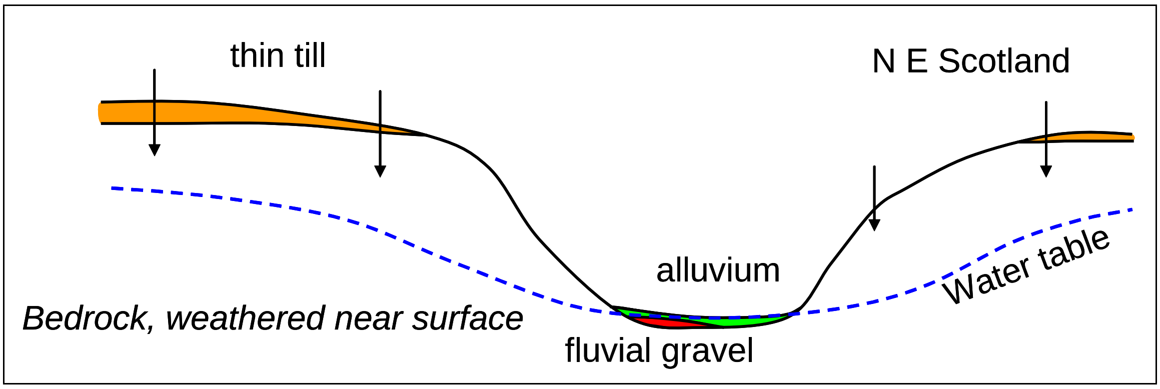


Figure A Schematic cross section showing potential recharge zones in the Minimal Till Domain

The same is broadly the case for the southern Welsh and vale of Severn area where partial cover of largely granular material covers about one quarter of the land surface area. The main difference is that clay minerals are not common and attenuation of pollutants is likely to be weak, especially compared with the system in north-east Scotland.

Summary

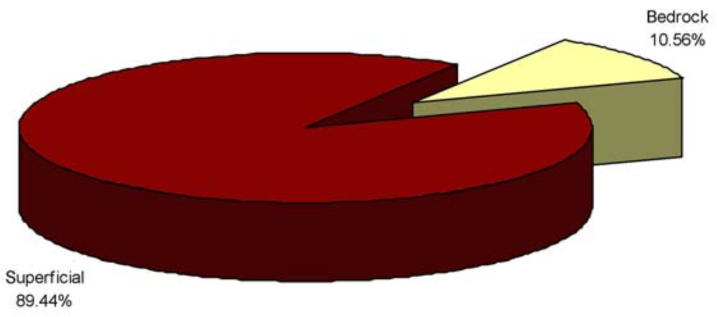
% cover	26
Lithologies	Till, head and fluvial gravels
Recharge potential	Moderate
Attenuation potential	Moderate
Protection of underlying bedrock	Moderate

PROVINCE: GLACIATED AND PERIGLACIATED, LOWLANDS

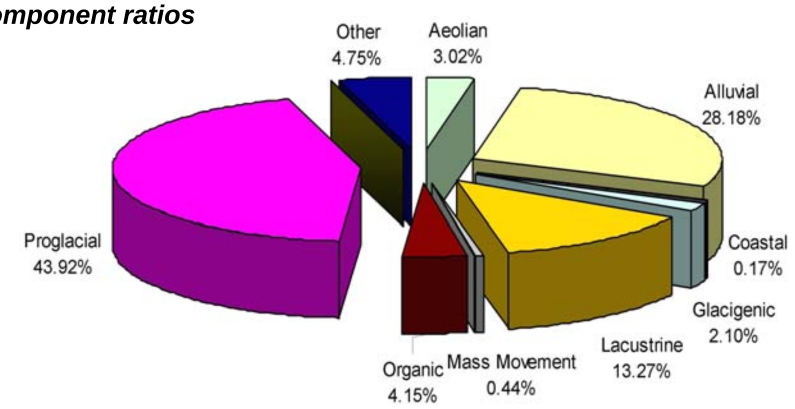
DOMAIN: MINIMAL TILL – VALES OF YORK AND PICKERING

Domain: LB Lowland Basin

Bedrock/Superficial ratios



Superficial component ratios



Landforms, deposits and processes

This domain includes several areas of low to very low relief ground underlain by thick, stratified sequences of Devensian to Holocene age, dominated by glaciofluvial sand and gravel and glaciolacustrine silt and clay.

Around the margins of parts of the domain there are relict areas of till that may be Pre-Devensian. The deposits have yet to be formally defined on lithostratigraphical grounds, although they could equate with either the Lowestoft or Sheringham Cliffs formations of the East Anglia

Hydrogeological Processes

The small domain is characterised by a thick sequence of lacustrine silts and clays and alluvial sands and gravels. The clay sequence is sufficiently thick (10s of metres) and continuous as to effectively prevent vertical ingress of percolating water to bedrock. However, perched horizons of saturated sands and gravels provide transport and storage of groundwater within the overall superficial sequence.

In the Vale of York (Figure A) the superficial deposits are variable in both thickness and lithology, and there is potential for upwelling of deeper groundwater through the superficial deposits. Around Doncaster the deposits contain a high proportion of sand, but recharge is still limited. North of the River Don, little recharge occurs through the thick low permeability glacial lacustrine deposits that confine groundwater in the underlying Sherwood Sandstone. North of River Aire in the Selby area drift is thin or absent. Sandy drift frequently found on higher ground, with clayey drift in river flood plains.

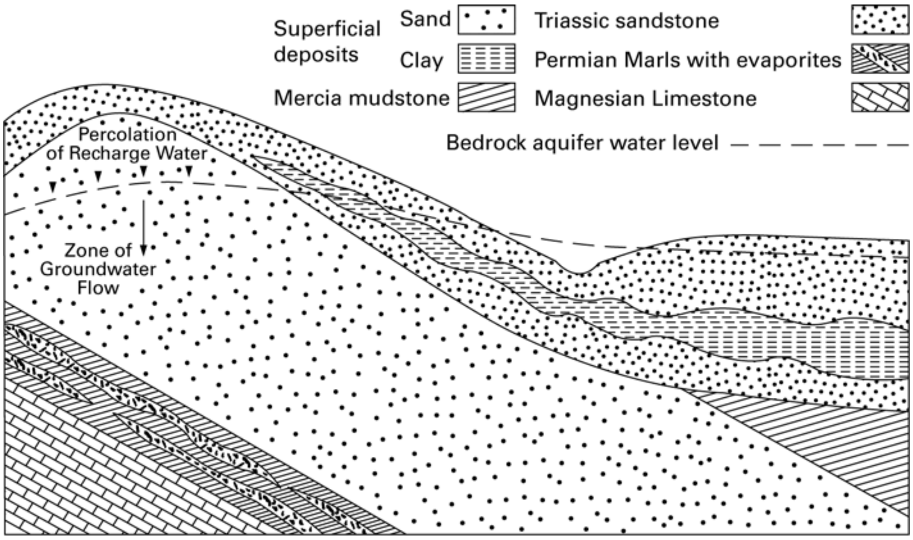


FIGURE A Vale of York – showing potential for upward flow beneath the superficial deposits

In the Vale of Pickering, the underlying bedrock geology is Kimmeridge Clay.

Attenuation of pollutants is aided by the presence of clay minerals within the clay and silt layers.

Summary

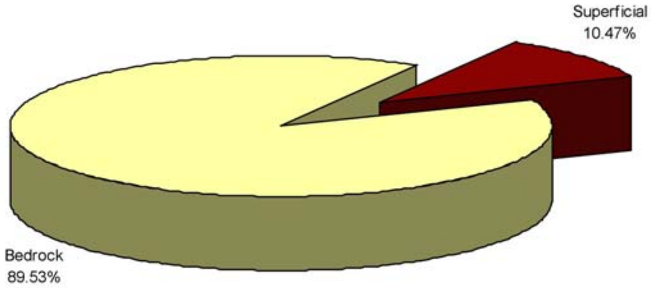
% cover	89
Lithologies	Thick sequence of clay and gravels
Recharge potential	Poor
Attenuation potential	Moderate
Protection of underlying bedrock	Generally well protected

PROVINCE: NON-GLACIATED, PERIGLACIATED

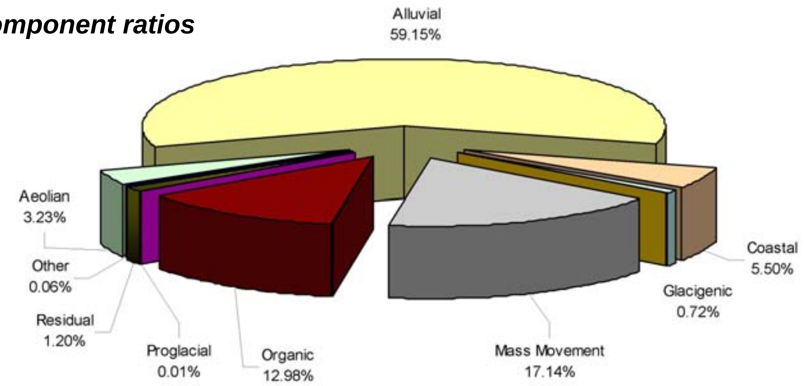
DOMAIN: UPLAND PERIGLACIATED – DEVON AND CORNWALL

Domain: UP Upland Periglaciated

Bedrock/Superficial ratios



Superficial component ratios



Landforms, deposits and processes
This Domain lies entirely in south-western England. The landscape is a product of numerous geomorphic cycles, acting over a long period of time (since the Neogene) during which the climate has fluctuated from warm temperate to Arctic 'tundra'. Recent research suggests that perhaps very localised ice caps with associated valley glaciers developed in this area during the Middle and Late Quaternary; however, others consider the evidence to be ambiguous. The residual deposits overlying this relict landscape resulted from multi-phase reworking associated with periglacial processes such as solifluction and frost shattering; they include deeply-weathered regolith, landslip, solifluction drapes (Head) and hillwash (Colluvium).

The sub-domains partly reflect regional changes in bedrock and also significant landform differences.

Hydrogeological Processes
This domain is characterised by weathered bedrock with only 10% of the land area covered in superficial material of which the majority is alluvial in origin or comprises head (Figure A). Thick granular head deposits occur along some valleys and tend to be in hydraulic continuity with streams. River terrace deposits are generally limited in extent, but where present possess sufficient vertical permeability to allow direct rainfall recharge to bedrock. The head deposits are generally in hydraulic continuity with the underlying deeply weathered granite with water levels normally within 10 m of the ground surface.

Clay minerals are common in the area, deriving as a weathering product (Kaolinite) from the granites. Where present they form an ideal medium to promote attenuation of pollutants, but their limited areal extent does not amount to any significant protection of bedrock below.

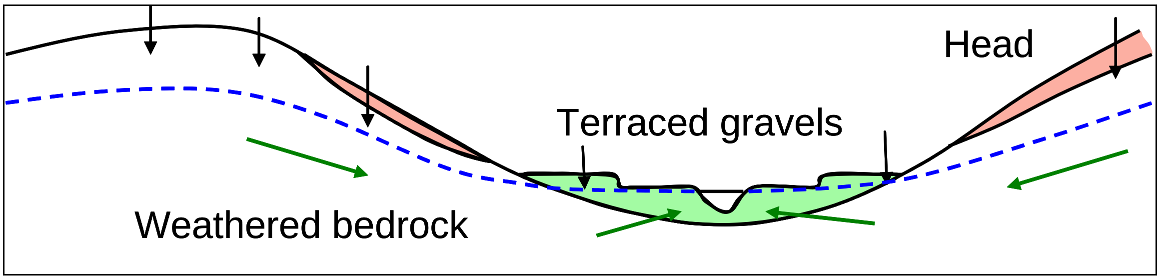


Figure A Schematic cross section showing features typical of the Upland-Periglaciated Domain

Summary

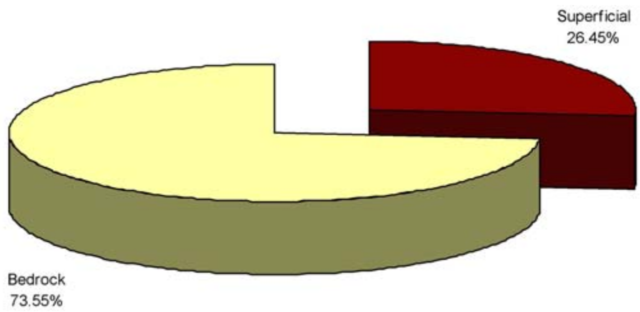
% cover	10
Lithologies	Head and terrace gravels
Recharge potential	Good
Attenuation potential	Poor to moderate
Protection of underlying bedrock	Poor to locally moderate

PROVINCE: NON-GLACIATED, PERIGLACIATED

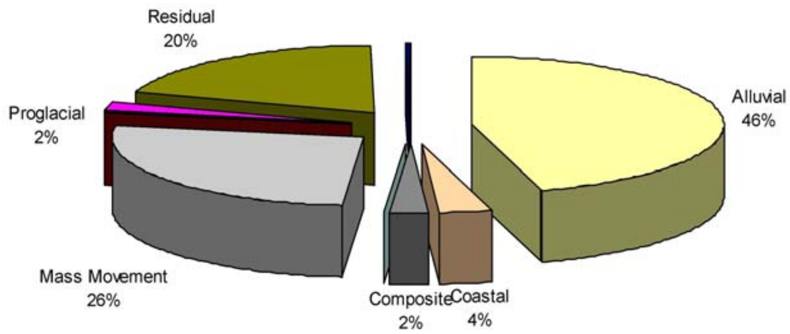
DOMAIN: LOWLAND PERIGLACIATED – SOUTHERN AND SOUTHEASTERN ENGLAND

Domain: LP Lowland Periglaciated

Bedrock/Superficial ratios



Superficial component ratios



<u>Landforms, deposits and processes</u>
This Domain lies in southern and parts of southeast England, beyond the known southernmost limits of both the Anglian and Devensian ice sheets. The landscape is a product of numerous geomorphic cycles, acting over a long period of time (since the Neogene) during which the climate has fluctuated from warm temperate to Arctic 'tundra'. The residual and mass movement deposits overlying this relict landscape include deeply-weathered regolith, landslip, solifluction drapes (Head) and hillwash (Colluvium). Relict structures (ice/sand wedges) failures (cambering) are locally common. Early mapping either failed to recognise these deposits and structures or failed to understand their significance; certainly their widespread extent was omitted from published maps. These omissions critically impact on geoenhanced products based on early mapping particularly if compilers unaware of these issues undertake the geoenhancement. The Domain includes terrace deposits of former river systems e.g. Kesgrave Formation in Essex.

As variations in the Bedrock geology have to some extent controlled the geomorphic processes, any sub-Domain divisions would be largely based on underlying rock-type.

<u>Hydrogeological Processes</u>
Direct recharge to the Chalk is limited beneath overlying low permeability Clay-with-flints and Palaeogene deposits (Figure A). However, around their margins infiltration of acidic water has led to an above average density of solution features, creating rapid recharge and potentially rapid pathways for pollutants into a major aquifer. However, wherever Neogene sands directly overlie Chalk they are generally unsaturated as recharge drain freely through them.

Sands and gravels from the overlying Palaeogene deposits may be washed down through solution features in the Chalk to clog the fracture network. At Warningcamp (TQ 058 067), running sand entered borehole from fractures as deep as 70 m below ground surface.

In valleys the rivers and Chalk aquifer are generally in hydraulic continuity and any fluvial or other valley bottom deposits are unlikely to inhibit recharge to any extent.

The presence of clay minerals in the Clay-with-flints (a weathering product of the Chalk) provides it with the ability to attenuate any pollution ingress. However, the limited areal distribution of the Clay-with-flints and other superficial deposits in this domain restrict any real potential for attenuation.

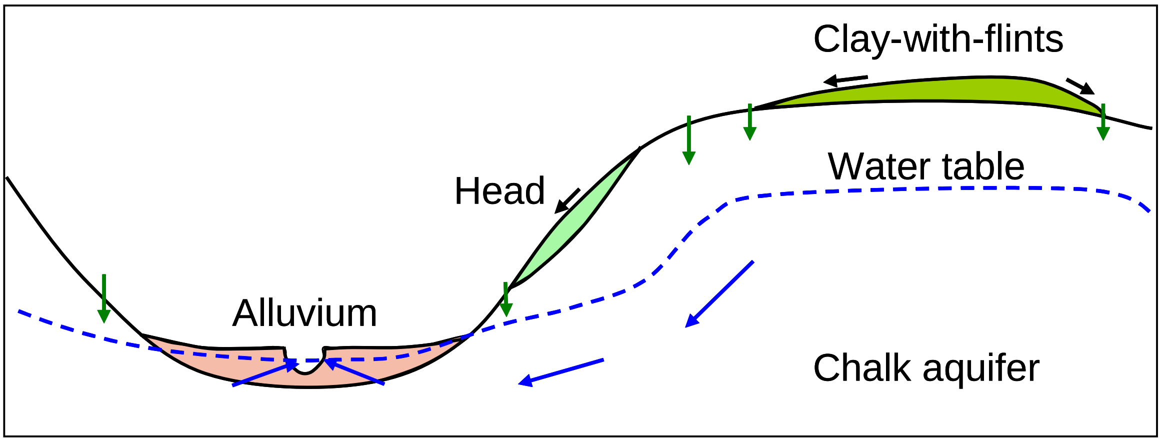


Figure A Schematic cross section showing recharge zones with typical Chalk cover

Summary

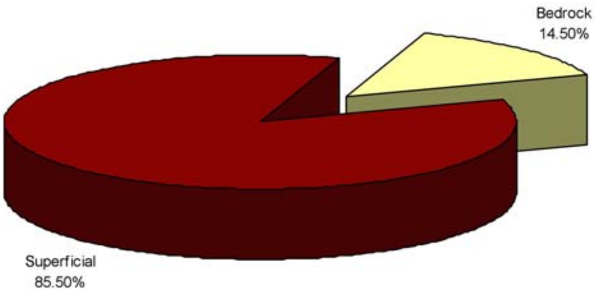
% cover	26
Lithologies	Clay-with-flints and head
Recharge potential	Poor, good around periphery of deposit
Attenuation potential	Locally good but poor overall
Protection of underlying bedrock	generally poor to locally moderate

PROVINCE: NON-GLACIATED, PERIGLACIATED

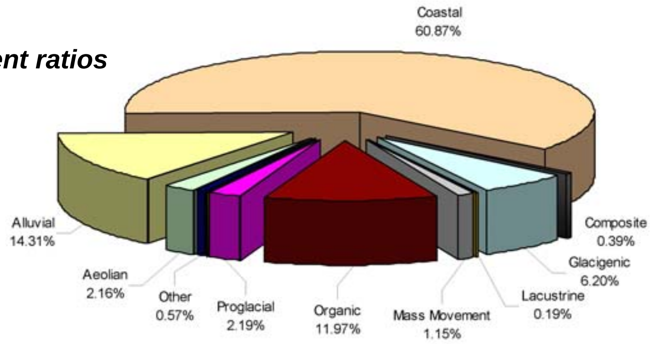
DOMAIN: ALLUVIAL, ESTUARINE AND COASTAL – THE FENS AND SOME LOW LYING COASTAL AREAS

Domain: CE Alluvial, estuarine and coastal

Bedrock/Superficial ratios



Superficial component ratios



Landforms, deposits and processes
This domain includes the larger expanses of Holocene sediments and landforms throughout Britain, with the exception of blanket peat on the hills. It mainly includes areas of very low relief and low-lying coastal tracts underlain by thick sequences of alluvial, lacustrine, estuarine, beach, aeolian and marine deposits, locally concealed by, and extensively interbedded with, peat.

The Holocene sedimentation across Britain has been influenced strongly by changes in sea level during the last c. 14,500 years. Large areas of raised beach and estuarine alluvium occur only to the north of a hinge line crossing northern England from about Barrow-in-Furness to Newcastle. South of this line sea level has generally risen continuously up to the present day. Generally, rising sea levels have caused 'ponding back' and increased sedimentation in the lower reaches of river valleys whereas falling sea levels have brought about periods of floodplain incision. Estuaries and coastal inlets have experienced continuous changes leading to complicated interdigitation of deposits. Thus flood risk, compressible 'soils' and ground contamination are important issues in these areas especially where they coincide with developed areas such as the Thames Gateway.

Hydrogeological Processes
Areas within this domain include Dungeness, the Thames marshes, the Fens and the Lincolnshire coast, the Forth Tay and Clyde valleys, northern Fylde, the Southport area and the Severn. Deposits range from course granular and permeable cobble beds of Dungeness to the silty estuarine material of the Forth, Tay and the Thames. Groundwater within storm gravel beach deposits such as Dungeness is often saline. However, yields can be substantial, e.g up to 25 l/s at Denge Beach (TR 068 201). Raised beach deposits such as those around Irvine on the Lower Clyde estuary are permeable but contain fossil peat and clay horizons which inhibit vertical transport. Other apparently granular deposits also contain fine grained and silty horizons which inhibit vertical transport.

Widespread peat deposits in the Fens provide a poorly transmissive medium with high attenuation potential except where the peat has been drained.

Clay minerals are scarce in these deposits and attenuation of pollutants is generally poor.

Summary

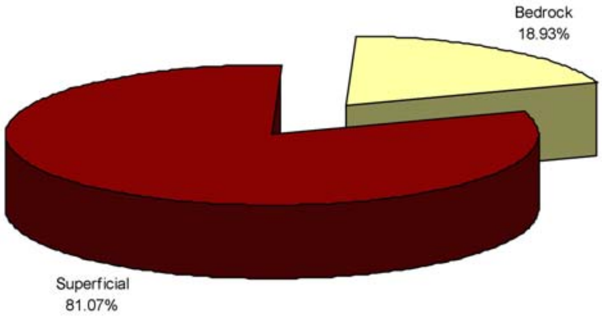
% cover	85
Lithologies	Coarse to fine granular deposits and peat
Recharge potential	Good except in peat areas
Attenuation potential	Poor, high in peat areas
Protection of underlying bedrock	Generally poor

PROVINCE: NON-GLACIATED, PERIGLACIATED

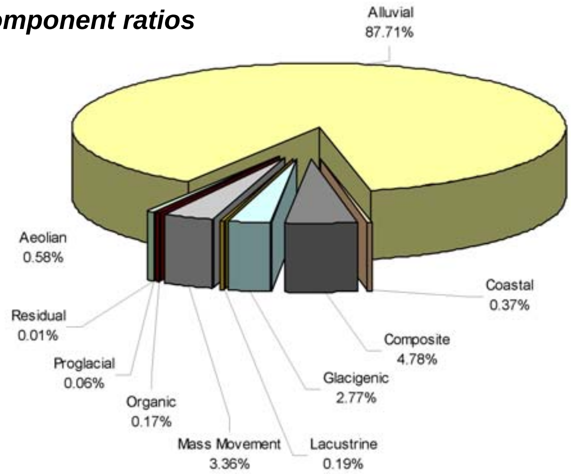
DOMAIN: FLUVIAL – PRINCIPALLY THAMES, TRENT AND WESSEX RIVERS

Domain: FP Fluvial

Bedrock/Superficial ratios



Superficial component ratios



<u>*Landforms, deposits and processes*</u>
This domain encompasses all the alluvial tracts that characterise the drainage systems of Britain; it therefore 'cuts across' most domains and sub-domains. It is an important domain economically, because low-lying ground of this type has been the favoured location for siting major communications routes, industries and settlements.

The landform is essentially the floodplain and associated river terraces. These are distinguished geomorphologically and lithologically. The typical floodplain consists of the alluvium of the active channel. This tract is bordered by a (generally) subtle concave slope break that marks the edge of the alluvium against the more steeply sloping ground of the valley side. Alluvial tracts are seldom completely 'flat' and in most cases the presence of fluvial features such as gravel bars, levees, abandoned channels etc, imparts a topographic 'roughness', in which a vertical height range of up to 2 m is commonly encountered. River terraces can be considered in two ways: the features formed by the terrace surface and edges, which are generally the most significant landforms for mapping purposes, and the aggradational terrace deposits, which underlie terrace surfaces and define the outcrops of terrace units on geological maps. In the larger and wider, lowland floodplains alluvial deposits commonly comprise a silt of clay/silt upper layer a few metres thick, underlain by sand and gravel of similar or greater thickness, some of which may represent the incised parts of earlier river terrace deposits. Both lithological associations can include lenses of lacustrine clay and peat-rich organic deposits; peat may also form significant surficial thicknesses in abandoned channel situations.

Hydrogeological processes

For the most part the fluvial deposits are permeable sufficient to allow rainfall recharge access to bedrock. However, finer grained material may be present which reduces the vertical permeability and encourages lateral flow to rivers and springs.

Along major valleys the river terrace deposits are generally in hydraulic continuity with the rivers, and sand and gravels may be present beneath the alluvium in the river valleys. Workings in these deposits tend to flood and along the major rivers (Thames, Severn and Trent) the deposits form major aquifers, which due to their high permeability are very vulnerable to pollution. However, the higher terraces may be hydraulically isolated from the rivers, leading to the development of spring lines round their margins and the possibility of the deposits becoming unsaturated in extended periods of dry weather.

Floodplain silts and clays overlying coarser-grained material may confine water in these sands and gravels, causing water to rise above the level at which first struck.

Clay minerals are only present in the fluvial deposits where parent material also contains clay minerals either as primary minerals or as weathering products. The attenuation role of these strata is, therefore, generally limited, the more so given the limited areal extent of the deposits.

Summary

% cover	81
Lithologies	Generally coarse grained granular
Recharge potential	Generally good
Attenuation potential	Poor
Protection of underlying bedrock	Poor