Final Report **Project WFD 34**

An approach to hydrogeological assessment of Quaternary deposits in the UK
Part 1 Background

October 2006

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EXECUTIVE SUMMARY

WFD 34 An approach to 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 deposits are an important moderator of potential recharge to a bedrock aquifer and they form a key component of 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.

Superficial deposits may modify both storage and vertical transport of recharge. 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 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 (Part 1) presents a background to the issues and a summary of current knowledge, and includes:

- a review of approaches taken to Quaternary hydrogeological interpretation within the UK and elsewhere; and
- identification and description of the key factors for Quaternary hydrogeological assessment of water bodies as required by the Water Framework Directive.

The main components of the developed project methodology, future application and development opportunities are described in the accompanying Part 2 report.

Key findings and recommendations

The 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 produces broadly similar results to existing assessments. However, the methodology follows a rigid and defensible protocol and as such is

an attractive alternative to existing schemes. It is recommended that the methodology be used to populate a new database, derived from 1: 50 000 scale input data, in order to develop a useable vulnerability assessment to assist in the further characterization of groundwater bodies.

Key words: Quaternary, recharge potential, absorption potential, groundwater vulnerability, hydrogeological domains

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1. INTRODUCTION

Superficial deposits (of Quaternary geological age) cover approximately 90% of the UK landmass (Figure 1). Not unexpectedly, they play a significant role in hydrogeological settings across the UK. Foster et al. (1999, p 9-10) reported:

> ‘Quaternary cover plays a key role in controlling the mechanisms and rates of recharge to underlying aquifers, which are of major national importance in terms of water resources especially in the context of the requirements of the EC Water Framework Directive. Quaternary processes also determined the genesis of palaeo-recharge episodes which were responsible for the emplacement of freshwater in some deeper British aquifers. This cover also determines the vulnerability of underlying aquifers to pollution, since it offers a (highly variable) level of natural protection due to filtration, absorption and reactive capacity of the strata involved.’

Serious mapping of superficial deposits only started in recent decades, prior to which effort was concentrated on bedrock mapping, and in particular on coalfields and ore bodies. Currently, however, the focus is on the Quaternary.

The project WFD 34 *Assessment Techniques for Quaternary Deposits in the UK* aims to improve the understanding of the hydrogeological processes pertaining to recharge and attenuation of pollutants that occur in the Quaternary deposits in the UK. The work has been carried out by the British Geological Survey on behalf of SNIFFER.

Knowledge of hydrogeological processes is the key to quantifying recharge and aquifer vulnerability for further characterisation of quantitative and chemical status of designated groundwater bodies. The project develops a standard methodology for assessing these deposits and provides recommendations on data gathering and assimilation such as domains mapping. The scope of the project was constrained by the pace of implementation of the Water Framework Directive and a cost effective and achievable output is essential. The objectives were:

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

This report (Part 1) describes two components of the overall study:

- it reviews approaches taken to Quaternary hydrogeological interpretation both within the UK and elsewhere; and
- it identifies and describes the key factors for Quaternary hydrogeological assessment of water bodies as required by the Water Framework Directive.

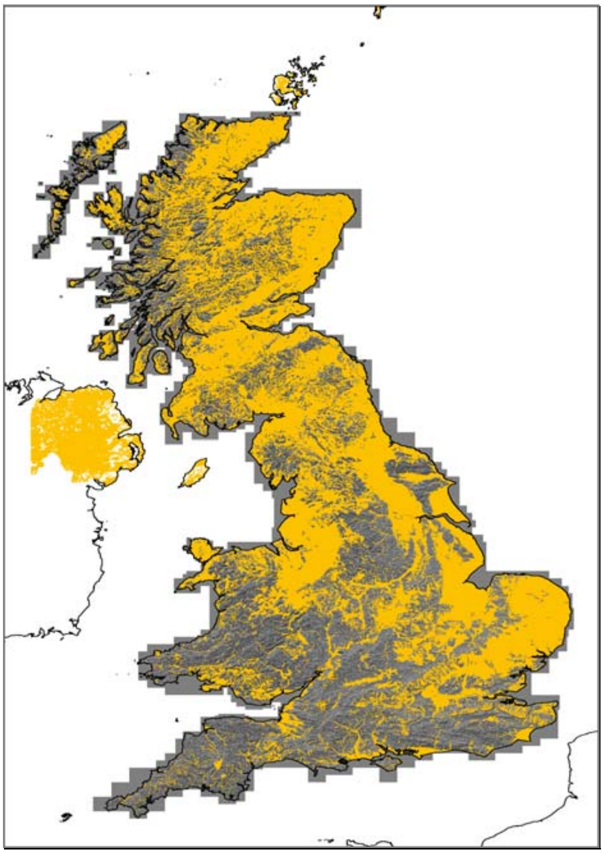
Part 2 of the study is described separately and includes:
- a review of the current status of Quaternary mapping in the UK;
- a description of the development of a methodology to assess the superficial strata in terms of recharge potential and attenuation potential;
- trialling of the methodology; and
- consideration of the methodology limitations, data scarcity, a route map for future work and data Intellectual Property Rights (IPR) issues.

1.1 Dividing up the Quaternary

Subdivision of the Quaternary has always been problematic. Mapped units have included till[1] in England and sandier morainic drift in northern Scotland, along with a variety of sand and gravel outwash deposits and lacustrine and riverine deposits. However, there is still no standard mapping technique, and available 1: 63 360 and more modern 1: 50 000 superficial maps deal with the Quaternary in a variety of different ways. An approach to standardisation of mapping is currently being promoted by the British Geological Survey (QMT, 2004).

Chronostratigraphy divides up the rock mass according to its age (Appendix I). The traditional stratigraphical subdivision of the Quaternary paid little regard to either the processes under which deposition took place or the lithologies that were deposited.

Figure 1 - Quaternary cover in the UK (note parts of Wales and South West England data are not yet available (after QMT, 2003)



Superficial cover shown in yellow. Grey shading includes areas not yet mapped: e.g. parts of Wales and South West England

1.2 Quaternary provinces and domains

An alternative approach to classification is to define characteristic regional provinces which can be sub-divided into smaller domains.

[1] The word till is used as a generic term in this report to include all sub-ice deposits including sandy tills and morainic drift. For the most part till will contain some silt and clay grade material.

1.2.1 Provinces

The landmass of the UK may be divided into two fundamentally distinct provinces on the basis of landscape evolution, geomorphology and the nature and distribution of superficial deposits (Figure 2 – note: Northern Ireland is not shown).

Lying beyond the southern limit of the Anglian glaciation, the *Non-glaciated Province* includes elements initiated in the Neogene (Appendix 1), but within this province the landscape was mostly affected by the multiple climatic changes (between periglacial, cool temperate and warm temperate) that occurred throughout the Quaternary. The processes of weathering, erosion and sedimentation have been driven by this climate change; their record and inheritance is relatively undisturbed by extrinsic perturbations and is cumulative over a relatively long period of time.

By contrast, the landscape of the *Glaciated Province* (including both Upland and Lowland Britain and all of Northern Ireland) has few elements that have survived intact from the Neogene; much of the Quaternary record has also been destroyed or fundamentally modified by subaerial erosion and successive Quaternary glaciations. The imprint of glaciation becomes greater northwards and westwards across the province, but its direct or indirect effects are encountered everywhere (Ballantyne, 2002).

1.2.2 Domains

Within the two main Provinces in Britain, eleven Domains may be differentiated (Figure 3), partly by identifying recurring patterns in geomorphology and assemblages of superficial deposits, and partly based on genetic linkages to 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, particularly in southern England.

Glaciated and periglaciated Province: Uplands
- Ice-scoured montane domain
- Montane and valley domain with seven subdomains
- Plateau and valley domain with four subdomains

Glaciated and periglaciated province: Lowlands
- Till dominant domain with seven subdomains
- Dissected till domain with two subdomains
- Minimal Till Domain with three subdomains
- Lowland Basin Domain with two subdomains

Non-glaciated, periglaciated Province
- Upland Periglaciated Domain with three subdomains
- Lowland Periglaciated Domain with five subdomains
- Alluvial, estuarine and coastal domain with seven subdomains
- Fluvial Domain

A detailed domain assessment has yet to be undertaken in Northern Ireland, but a preliminary review has recognized six Domains:

- Fluvial
- Alluvial, estuarine and coastal
- Till dominant
- Montane and valley

- Ice scoured montane
- Plateau and valley

By far the most extensive domain is the Till dominant (TD), covering around 80% of the Northern Ireland landmass. Drumlinised spreads of till characterise much of the lower ground and also blanket a significant proportion of higher ground. Variation of the degree of cover allows the Till dominant domain to be subdivided into TD1 and TD2 based on proportion of till to rock near surface. Further detail on Northern Ireland domain types can be found in Appendix II.

Figure 2 - Quaternary Provinces (after QMT, 2003)

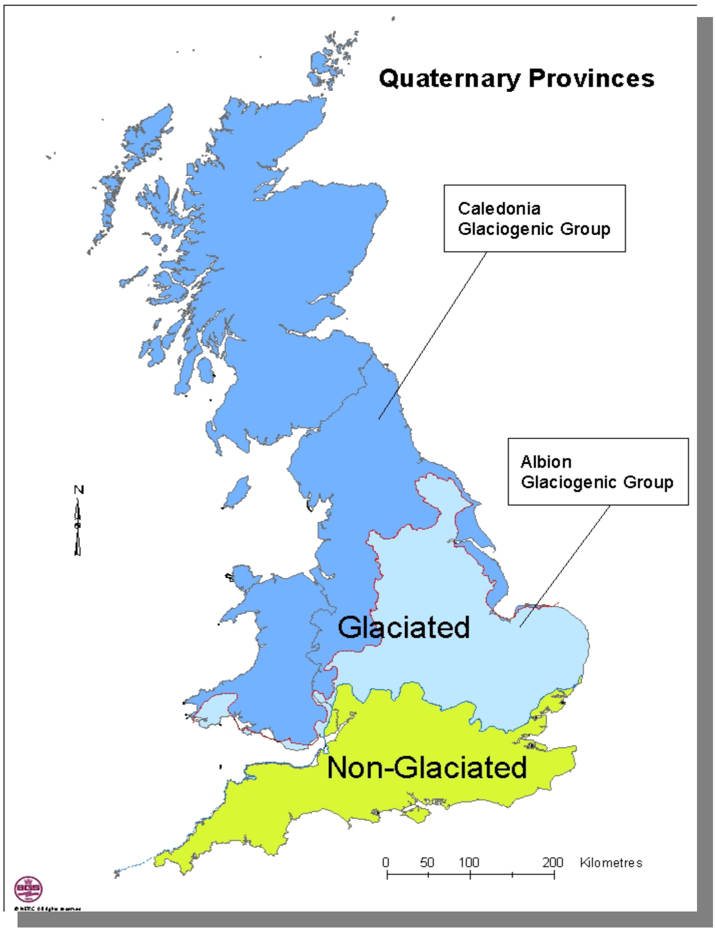
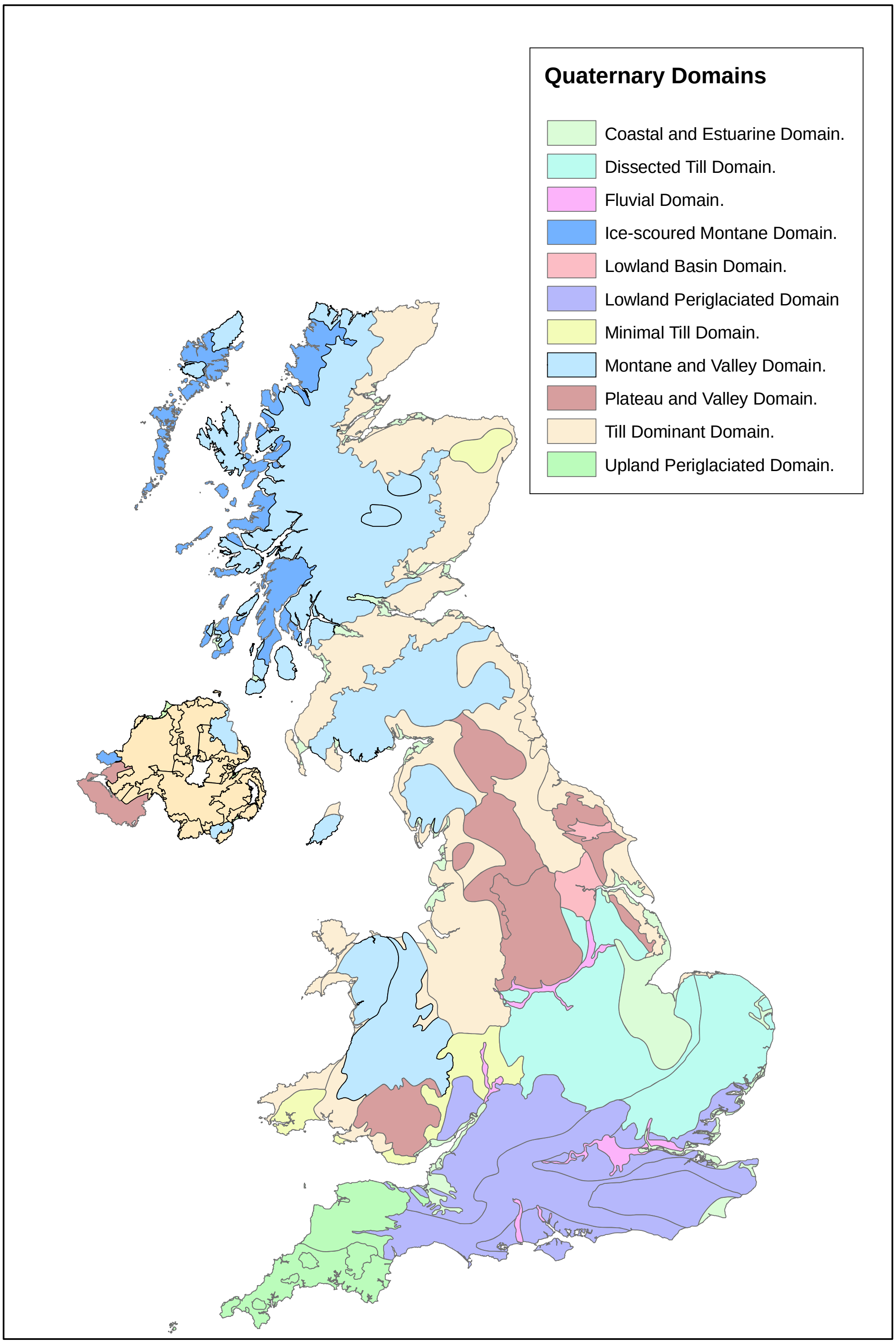


Figure 3 – Quaternary domains



1.3 Superficial deposits and hydrogeological processes

Superficial deposits can have a profound impact on the groundwater in underlying aquifers. The nature of the deposits determines the quantity and quality of natural recharge and the transport and attenuation of pollutants. The deposits may also contain perched aquifers locally and/or may form part of the saturated aquifer system as aquifers in their own right. Recharge and movement of pollutants through these deposits can, therefore, have a direct influence on wetlands and groundwater dependent ecosystems.

Superficial deposits may modify elements of both the storage and vertical transport of recharge, especially:

- 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 characteristics of the groundwater system (especially aquifer storativity);
- groundwater quality (infiltration moving downwards through these deposits to the underlying aquifer, may mobilise solutes).

1.3.1 Recharge

Factors that will control vertical transport through superficial deposits include:

- the thickness of deposits;
- their lithology and vertical permeability;
- the depth of weathering, and
- the degree of fracturing and potential for by-pass flow.

The amount of recharge and its distribution has obvious and important implications for water resources.

Superficial deposits (excluding significant highly permeable superficial aquifers) often include fine-grained and low permeability material, which tend to have low infiltration capacity. Overall, therefore, superficial deposits are likely to reduce recharge to the underlying aquifers. However, potential recharge rejected from one area because of low infiltration capacity may be rerouted to areas of more permeable deposits or where the underlying aquifer is exposed at the surface. Locally higher infiltration rates may therefore occur in permeable “windows” where recharge is more focussed. Weathering and fracturing are likely to increase the permeability of the deposits and thus their infiltration capacity.

1.3.2 Vulnerability of groundwater

Superficial deposits may, in many situations, reduce the vulnerability of the underlying aquifer to pollution by increasing both the travel time for pollutants to reach the water table, and the retardation of pollutants (because these deposits often have a large capacity for sorption, ion exchange and degradation).

Important factors influencing aquifer vulnerability include:

- the presence and thickness of any overlying superficial deposits;

- the lithology and mineralogical composition of any overlying superficial deposits (especially clay content and fraction of organic matter);
- the depth of weathering in the superficial deposits; and
- the degree of fracturing in the superficial deposits.

Fracturing in superficial deposits may increase the vulnerability of underlying aquifers to pollution by providing a pathway for rapid movement of water and pollutants to the water table. The significance of fracturing and the depth to which it may operate is poorly understood in the UK. Further discussion on this aspect can be found later within this document.

Vulnerability of groundwater to pollution may also be increased at the edge of lower permeability superficial deposits outcrops, because of focussed recharge draining from the deposits. This could lead to the development of karst-like features in carbonate aquifers where runoff from superficial deposits is acidic.

Groundwater vulnerability maps for England and Wales were developed by the National Rivers Authority in the early 1990s and are still in use today, mainly as a planning tool. The maps are at 1: 50 000 scale and cover all of England and Wales (see Palmer et al., 1995). Similar maps at 1: 50 000 scale were produced for selected areas of Scotland; additionally, there is a 1: 625 000 scale map for the whole of Scotland and a 1: 250 000 scale map for the whole of Northern Ireland. These maps classify the dominant soil strata above the saturated aquifer as the vulnerability indicator, recognising a matrix of three aquifer classes (weakly, moderately and highly permeable: on the England and Wales maps this was transposed to non, minor and major aquifer) and three soil leaching classes (high, medium and low).

More recently, as part of the Water Framework Directive characterisation work, new groundwater vulnerability screening layers have been produced for Scotland at an effective scale of 1: 100 000, and for Northern Ireland at 1:250 000 scale, in which the underlying bedrock aquifer class does not directly influence the 'vulnerability' rating.

Superficial cover material posed a significant problem in creating the original National Rivers Authority, and equivalent, vulnerability maps. Where a superficial cover occurs as a granular deposit and where it is saturated it was depicted as an intergranular aquifer. Wherever till is present and was believed to be greater than 5 m thick, it was removed from the assessment scheme and overlain on the map as a stipple. This was done to indicate that clayey cover material is likely to be present and may be adequate to protect aquifers below, provided it has not been punctured by excavations such as railway cuttings or quarries. Clearly, the integrity of till is often unknown; additionally, it can vary from silty clay to sandy silt over short lateral and vertical distances, with corresponding variations in permeability. The drawback to characterising the till as a stipple on the map is that many map readers disregard its presence.

The National Rivers Authority and equivalent maps also disregarded travel time to the water table, because depth to water was generally not known on a regional basis at that time, and because the vulnerability scheme was designed for a conservative pollutant that would not degrade during transit of the unsaturated zone.

1.3.3 Water quality

The lithology and mineralogy of superficial deposits, their thickness, and the vertical hydraulic gradient, are all important considerations when assessing the quality of recharge and its impacts on underlying groundwater quality.

For example, where the piezometric surface of an underlying aquifer lies within the superficial deposits, pumping from the aquifer may induce downward leakage through the superficial deposits to the underlying groundwater. This leakage may have a significantly different chemistry (e.g. it may be more mineralised) to the groundwater in the aquifer.

Two main datasets hold relevant information on potential recharge and groundwater quality. An extensive terrestrial sediment and stream-water sampling programme, the Geochemical Baselines Survey of the Environment (G-BASE), has been carried out in recent decades by the British Geological Survey (Johnson *et al*. 2005). The results of this programme clearly demonstrate that the mineralogical composition of most Quaternary deposits generally mirrors that of the bedrock below, because the material was generally only transported over short distances. A separate programme, the Baseline groundwater quality survey (Shand and Frengstad 2001, MacDonald and Ó Dochartaigh 2005), which is being carried out collaboratively between BGS, the EA and SEPA, indicates where, and to what degree man has changed the water chemistry and where groundwater is most vulnerable.

1.3.4 Aquifer characteristics

Superficial deposits may have an impact on the aquifer characteristics of the groundwater system. For example, relatively thick and extensive sand and gravel layers, in hydraulic continuity with the underlying bedrock aquifer, may contribute significantly to the overall storativity and transmissivity of the groundwater system. This will be especially important where the aquifer has only a limited specific yield (e.g. the Chalk aquifer), where sands and gravels increase the available groundwater stored very considerably.

In other situations, deep buried valleys may remove the more permeable upper part of the Chalk aquifer. In such circumstances, buried valleys may act as barriers to groundwater flow.

The key requirements for superficial geology mapping from the hydrogeological perspective are as follows.

- A good 3D geological model, or where this is not possible, some idea of the uncertainties based on an understanding of the processes forming the superficial deposits (e.g., how variable is lithology and thickness, and over what distances?). This indicates which geological scenarios can be safely ignored and which must be considered, and includes an understanding of the relationship of the overlying superficial deposits to the underlying aquifer.
- Identification of any significant upper weathered zone, and the presence and characteristics (spacing, orientation and aperture) of fracture systems and their likely origin (e.g., if of tectonic origin, the fractures may persist through the full thickness of the till).
- A record of shallow groundwater related "water features," including springs, sinkholes and wetlands, as well as knowledge of the groundwater level (including perched groundwater bodies) in relation to the base of the superficial deposits. An example of this is the mapping of possible karst features at the margins of the superficial deposits, in relation to the drainage pattern on the deposits.

Scale is an important issue: the detail required depends on the purpose. For a broad understanding of the impact that superficial deposits may have on water resources in a catchment, the detail required is less than that needed to understand potential pollutant movement to groundwater at a contaminated land site. However, at the site-specific scale, contaminated land problems benefit from a knowledge of the variability and uncertainty that is likely to be found at a larger scale across the superficial deposits. This knowledge indicates how detailed a site investigation may need to be.

1.3.5 Superficial aquifers

The role of Quaternary deposits as aquifers in their own right is illustrated using Scotland as an example. Table 1 gives a summary of the productivity of superficial deposits aquifers in Scotland. All superficial deposits are assumed to have primarily intergranular groundwater flow (although fracture flow may be important in some tills), and they are divided into high, medium and low productivity, or as non-aquifers (MacDonald et al. 2005). The classifications were made using BGS geological and hydrogeological data and the Hydrology of Soil Types (HOST) classifications of the Macaulay Institute (Boorman *et al.* 1995; Lilly *et al.* 1998). The productivity is only potential, because many of the deposits may be too thin to actually contain useable quantities of groundwater. Ó Dochartaigh *et al.* (2005) explain the methodology used to determine areas of partially saturated or dry superficial deposits.

Table 1 – Quaternary aquifer productivity in Scotland (after MacDonald *et al*. 2005)

Productivity rating and approximate yield	**Superficial deposits**
High > 10 l s^{-1}	Glaciofluvial sand and gravel & mixed deposits Alluvium River terrace sand & gravel
Moderate 1 to 10 l s^{-1}	Raised marine deltaic deposits *(mixed)* Raised beach and marine deposits Blown sand
Low 0.1 to 1 l s^{-1}	Sandy and gravelly glacial till Hummocky moraine Mixed lacustrine deposits Landslip

High productivity superficial aquifers comprise deposits that have significant sand and gravel content, such as alluvium and glaciofluvial sand and gravel. All mapped alluvium and glaciofluvial deposits are included in this category – there are insufficient data to account for variations in permeability and thickness within alluvium and glaciofluvial deposits. Alluvial deposits within valley floodplains, although possibly less than 10 m in thickness, can have the capacity to support very large abstraction rates wherever there is good hydraulic contact with adjacent watercourses. Some of the highest yielding boreholes in Scotland are from high productivity alluvial aquifers, including several large public water supply abstractions.

Moderate productivity superficial aquifers comprise mainly raised marine deposits. Typically, these contain a high proportion of silt and clay, and therefore have lower permeability than the coarser, well-sorted, high productivity deposits. They are also generally thin, which further reduces their potential for yielding large volumes of groundwater. Blown sand is also included in this category since, despite its high permeability, it is rarely more than a few metres thick and is generally distant from large rivers. Small public water supply abstractions have been located within moderate permeability aquifers in parts of rural Scotland. However, geophysical techniques are often required to help find the best locations for boreholes.

Low productivity aquifers comprise sandy and gravelly tills, moraines, mixed lacustrine deposits and landslip material. Much of Scotland is covered by till, but only high permeability till and moraine – dominated by sandy and gravelly material – are considered as aquifers. Although variations in till lithology are recognised by geologists across Scotland, there is little relevant information on till lithological variation in the currently available maps. However, till can be subdivided according to permeability using the Hydrology of Soil Types (HOST) dataset of soil hydraulic properties developed jointly by the Soil Survey and Land Research Centre, the Macaulay Institute and the Centre for Ecology and Hydrology (Boorman et al. 1995; Lilly et al. 1998). The methodology for subdividing the tills is described in detail in Ball *et al.* (2003). In general the more permeable tills are found across much of the Highlands, Aberdeenshire and southern Scotland, reflecting the crystalline and granular nature of bedrock, whereas the softer strata of the Carboniferous sedimentary rocks produces more clayey, less permeable tills.

Superficial deposits determined as having no useful aquifer potential (non aquifers) in Scotland include the moderate and low permeability tills of Strathmore and central Scotland, and estuarine, marine or lacustrine clays. However, given natural geological variability even these deposits may be capable of supporting small yields in isolated areas.

2. QUATERNARY HYDROGEOLOGICAL INTERPRETATION

2.1 Hydrogeological characteristics and recharge

The focus of this project is the assessment of recharge potential to and vulnerability of aquifers which are situated beneath weakly permeable Quaternary strata. A range of techniques has been developed in recent years to assist classification of Quaternary deposits to facilitate investigation of the hydrogeological properties of the strata.

Whilst the more permeable Quaternary deposits have been studied generally with respect to their potential for resource exploitation, much less work has been carried out regarding less permeable superficial deposits. Generic investigation of the characteristics of weakly permeable superficial deposits has largely been undertaken in North America. A key conclusion is that recharge can occur through all Quaternary deposits, regardless of permeability (van der Kamp, 2001): for example, at velocities of more than 1 m a^{-1} in heterogeneous sandy, silty till with a hydraulic conductivity of only 10^{-9} m s^{-1} (Gerber *et al*, 2001).

Generic studies of the hydraulic behaviour of till in the UK include Foster (1998); the debate on how the presence, thickness and nature of superficial deposits affect groundwater vulnerability is covered in Palmer *et al*. (1995). Authors are consistent in reporting that recharge to bedrock aquifers does occur through till. For example, Soley and Heathcote (1998) reported a recharge rate of 36 mm a^{-1} through boulder clay-covered interfluves in East Anglia, decreasing to 10 mm a^{-1} in areas of thicker cover where the bedrock aquifer was locally confined. Identifying the processes by which transport in such deposits takes place is not easy, but considering their potential role and significance is essential to determining the recharge component of the water balance for a given catchment. Extrapolation of data may not be easy as recharge processes and recharge quantities are likely to be more site specific than generic. The ameliorating potential of thick till to pollutants such as nitrate and some pesticides passing through the strata has been described by Rodvang and Simpkins (2001).

The complexity of Quaternary lithologies, coupled with the wide variety of depositional environments, means that a large number of recharge scenarios are possible. These need to be identified from the outset and their influence on recharge assessed. Where superficial deposits overlie aquifers, they can have a significant influence on the recharge to the aquifer, particularly where they are dominated by low permeability lithologies, such as clays (Table 2). The thickness of the deposits is also critical. For example, a tried and tested 'rule of thumb' is that where a clayey till is less than 3 m thick, it is likely to be sufficiently weathered as to increase its permeability significantly. Where clayey till is between 3 and 8 m thick, by-pass flow mechanisms may dominate vertical flow paths (but see below), whereas where it is greater than 8 m thick, it may form an effective protective cover material, depending on the sand content (Table 2). Where the superficial deposits are of limited lateral extent their influence may be of less significance. One important and as yet unresolved issue is the degree of importance of fissure-related by-pass flow in lower permeability, clay-rich deposits, but comparison of Quaternary and soil maps will at least reveal where tills are self-draining and where they are not (Table 2). Additionally, features such as gravel eskers deposited by sub-glacial streams, buried valleys now filled with superficial material, and other small scale glacial features may locally affect recharge and attenuation processes within the superficial cover.

Table 2 – Generic features common to till deposits

Feature	Hydrogeological consequence
< 3 m clayey till	Likely to be weathered such that it becomes permeable
3 to 8 m clayey till	Fracture paths through the till may allow by-pass flow to predominate over inter-granular percolation
> 8 m clayey till	Effective cover to deeper aquifers
Clayey till on interfluves	Till under tension and may split to create vertical fractures
Clayey till in valleys	Till likely to be compacted and weakly permeable
Free draining soils over clayey till	Indicate vertical transfer of water through till likely
Surface ponding in depressions over till	Will promote recharge locally

2.2 Hydrogeological domains

Domains approaches to classifying superficial deposits aquifers and non-aquifers help to evaluate areas of vulnerability and recharge potential. All superficial deposits allow rainfall recharge to take place to some extent, depending on their permeability, and all offer some degree of storage (Lerner *et al.* 1990). The typical range of hydraulic properties for the generalised lithologies found in superficial deposits is shown in Table 3. However, it is uncommon to find just one lithology in any given Quaternary sequence, and sequences of interbedded sands and gravels or sands silts and clays are more typical for most fluvial and glacial deposits. These sequences can be assembled into geological domains to aid the interpretation of 2D mapping information combined with borehole log data (McMillan *et al.* 2000). An early example of Quaternary domains mapping work was carried out in the Glasgow area (Browne & McMillan 1989), and concentrated solely on classifying the superficial sequences into recognisable and defensible domains. Later work focussed on applying such classifications to practical problems, including groundwater-related issues. Hydrogeological domains mapping was pioneered in the west Cumbrian coastal belt, where deposits from a number of glacial stadials are present. Quaternary geological domains were defined by distinctive landform-sediment associations and structural characteristics. The geological domains were then interpreted as hydrogeological domains using hydraulic properties data available from borehole drilling and testing. The hydrogeological domains were assigned a potential rainfall-recharge index, which could be quantified by detailed digital time variant groundwater flow model of the area. In west Cumbria, depending on the domain type, between 35% and 100% of the long term effective rainfall (rainfall minus evapotranspiration and runoff) recharges to the superficial deposits or the bedrock below.

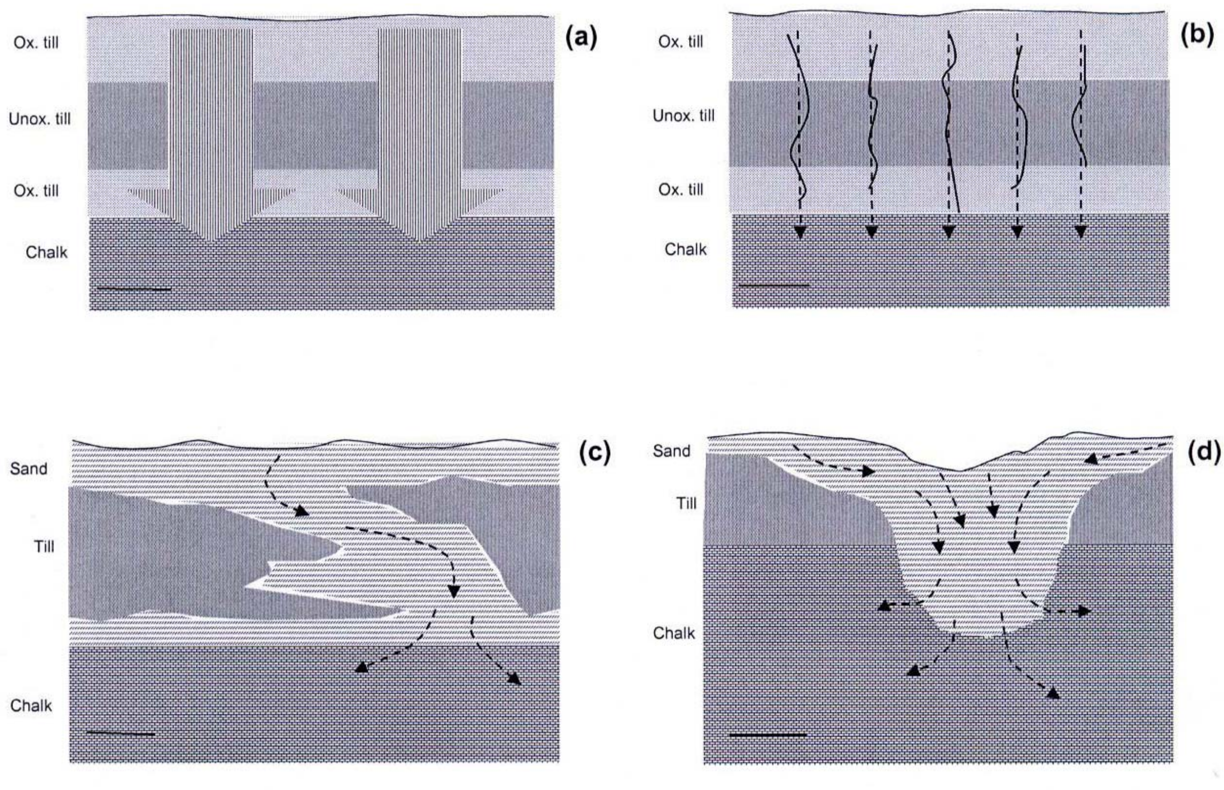
Table 3 - Generalised hydraulic properties for superficial deposits (after Smart and Herbertson 1992)

Lithology	**Hydraulic conductivity (ms^{-1})**	**Porosity (%)**	**Storativity**	**Comments**
Gravel	10^{-2} to 10^{-1}	0.20 to 0.30	0.10 to 0.25	May be in hydraulic contact with surface waters
Sand	10^{-4} to 10^{-3}	0.25 to 0.40	0.10 to 0.25	
Silt	$< 10^{-5}$	0.35 to 0.45	0.05 to 0.10	Fracture flow possible
Clay	$< 10^{-7}$	0.10 to 0.20	< 0.10	Fracture flow possible
Peat	$< 10^{-3}$ to $<10^{-6}$	0.20 to 0.40	0.30	Permeability depends on peat type, moisture content and overburden

2.3 Recharge routes

The route taken by recharge in areas covered by superficial deposits can vary significantly. The predominant route may be more or less direct, either via intergranular movement (Scenario (a), Figure 4) or fracture flow (Scenario (b), Figure 4) (Klinck et al., 1996). It may also be indirect, via permeable lenses (Scenario (c), Figure 4), or via past or present topographic features such as valleys (Scenario (d), Figure 4). There is also the possibility of no significant recharge at all (Scenario (e)). One way of differentiating between the scenarios is to determine the age of water in the various units involved, using isotopes or other environmental tracers as appropriate. For example, in Scenario (a), modern water (generally recharged during the last decade) would be expected to be present in both the oxidised and unoxidised tills, demonstrating relatively rapid recharge through the till matrix, although the unoxidised till layer remains isolated from oxygen in the atmosphere or in the Chalk below. In Scenario (b), old water (recharged more than 10 years ago) would be expected within the pores in the till, contrasting with modern water in the fractures in the till and/or in the underlying Chalk, indicating that intergranular flow is slow and that rapid fissure flow is an important recharge route to the Chalk. Scenarios (c) and (d) also relate to high permeability routes for recharge within the till, but are difficult to resolve from each other, although geological or geophysical evidence (to identify the presence of the more permeable features) may enable a distinction to be made. If the water is old in both environments, little, if any, recharge is likely to be occurring.

Figure 4 – Drift sequence scenarios (after Klinck *et al*. 1996)



Ox. till – oxidised till; Unox.till – unoxidised till

2.4 Estimating recharge

There is a distinction between actual recharge, which reaches a bedrock aquifer, and potential recharge, some of which may go to another destination – e.g., as shallow flow through superficial deposits to discharge to surface water.

Estimates of potential recharge are complicated by processes such as:

- by-pass flow through sub-vertical fractures in otherwise weakly permeable strata;
- water distributed into fractures via relatively permeable soil and weathered zones;
- concentration of saturated zones beneath topographic lows and wet areas of ground;
- rapid recharge into gravel horizons followed by seepage into less permeable adjacent or underlying strata; and
- bank side storage (into and out of) rivers and streams adjacent to the superficial deposits.

2.4.1 Penman soil moisture deficit approach

One of the most common techniques for recharge estimation is the Penman (1948, 1963) soil moisture deficit approach. However, the range of possible hydrogeological controls and processes, as described above, means that this approach is unlikely to be useful when dealing with complicated superficial sequences. Much of the data required for the Penman approach is too generalised to be applicable to highly heterogeneous Quaternary sequence: for example, best estimates of evapotranspiration (from MORECS) are available as averaged data for 40 x 40 km squares, and soil moisture deficit calculations (from MOSES) are available on a 5 km grid (both from the Meteorological Office). The Penman approach has, however, been usefully applied in distributed recharge models where more detailed local hydrogeological information is available (e.g. Jackson *et al.* 2005).

2.4.2 Instrumented catchments

An alternative approach to recharge estimation is to develop a series of instrumented catchments, each containing representative Quaternary and bedrock typologies. Estimates of recharge to and through these typologies can be input to models of other areas to assist in developing catchment water budgets and vulnerability risk estimates. However, there are a number of drawbacks in the associated recharge calculations, particularly in areas of high relief and in coastal areas. Orographic rainfall and steep topography mean that areal variation in rainfall may be difficult to determine within a single catchment. The diversity of superficial deposit typologies within a given catchment may complicate the estimate of recharge beyond the tolerance of the water budget.

2.4.3 Aquifer typology

Of the various techniques that have been promoted to classify aquifer types in superficial strata, that of aquifer typology was a precursor to the aquifer domains concept (Foster et al. 1999).
Aquifer typology is a system which looks at both superficial and bedrock aquifers together and can be used to characterise shallow geological sequences according to their basic hydraulic properties (Table 4). It provides a framework for the evaluation of hydrogeological types, with regard to their resource potential, their groundwater quality status and their vulnerability to pollution; i.e., the role of superficial deposits in reducing or redistributing recharge. As such, aquifer typology could provide a valuable foundation towards satisfying some of the more significant groundwater data requirements of the EU Water Framework Directive. It is a technique particularly suited to glacial cover over bedrock aquifers, where the geology is diverse and groundwater flow complex and difficult to evaluate.

The aquifer types are ranked in terms of likely resource potential, likely water quality, vulnerability to pollution, flow mechanisms (granular/fissure) and size and shape of groundwater source capture zones. The aquifer classification can be designed as a matrix containing the basic aquifer characteristics, and the typology classes can be described in terms of a range of different fields, such as resource potential, water quality, or vulnerability. The fields may also include trends: for example, whether groundwater is likely to be of good status by 2009. The typology classification can be as large or as small as the user demands, and may include grouped types each containing sub-groups of related type.

The typology classification combines bedrock and superficial deposits, and could also incorporate parameters such as soil type, groundwater resource potential or groundwater quality, with a weighting if appropriate. It takes account of the type and role of superficial cover: for example, whether in an upland or lowland area, a recharge or discharge zone, or with gaining or losing rivers. This broad classification is a desk level assessment using available data and an understanding of the generic hydraulics of the rock types and the risk posed by local activities, and provides a basis for more detailed investigations. Once the typology classification framework is established, there is a process of investigating groundwater conditions according to each typology, assuming common processes within each.

Table 4 – Examples of superficial/bedrock types

	Parameters		**Overall rating**	
Superficial and bedrock domains	**Resource potential**	**Natural Water quality**	**Overall recharge potential**	**Overall aquifer rating**
Till/sandstone	High	High	Low/moderate	Moderate
Till/sandstone	Low	Low	Low	Low
Raised beach/ sandstone	High	High	High	High

2.5 Quaternary hydrogeology domains case studies

2.5.1 Sellafield

The first hydrogeological domains study was that carried out at Sellafield in order to understand the relationship between shallow groundwater in the superficial deposits and the deeper regional groundwater flow system in bedrock (McMillan *et al.* 2000). The study was driven by the need to assess the performance of a proposed deep laboratory to investigate disposal of selected radioactive waste types (Chaplow 1996).

McMillan et al. (2000) assigned the complex superficial sequence of the Sellafield area of the west Cumbrian coast into generalised packages of sediment with common depositional and deformational histories (see also Section 2.2). Using these as a basis, six basic superficial deposits domains were identified, with a seventh domain representing bedrock with little or no superficial cover (Table 5). The characterisation assumed near surface water tables and identified part of only one domain as likely to include perched water. This typology approach could, therefore, be applied as a basic hazard map to indicate a potential for problems due to shallow groundwater occurrence and a particular warning of perching in one sub-domain.

The critical aspect of this study was that a far larger volume of data was available than is normally the case even for site-specific studies, let alone for regional or national assessments. The available data included trial pit and borehole data and point source permeability based on sieve analysis. This study was therefore unique in that there were sufficient resources both to collect primary data and to thoroughly analyse the resultant hypotheses. It is this validation process that is normally lacking in hydrogeological domains studies, most of which remain subjective.

Table 5 - Hydrogeological superficial domains in the Sellafield area (after McMillan *et al.* 2000)

Hydrogeological domain	Lithological characteristics	Groundwater characteristics
Bedrock at or near surface	Up to 1 m of till.	Recharge acceptance is controlled solely by bedrock characteristics.
Thin till <5 m) and other deposits	The till is characterised by vertical fractures 20 mm wide on a 300 mm spacing	Recharge and interflow are largely controlled by bedrock characteristics. Fractures in till allow ingress of water from the ground surface. Trial pits indicate discrete sub-horizontal flow along discontinuities away from the fissures.
Alluvial deposits	Generally coarse grained sequences, including alluvial floodplain and estuarine deposits	A minor aquifer recharged from surface water and direct rainfall. It provides direct hydraulic connection with otherwise isolated parts of the Quaternary sequence.
Till-sand-till	Thin discontinuous upper till, locally fissured; sands faulted and disturbed.	The upper till allows ingress of water to the sands, which may be locally confined. The lower till acts as a barrier to further downward flow.
Till and clay	A till and clay sequence with variable amounts of silt and very fine sand and with a network of sub-vertical fissures.	It forms a weekly permeable cover through which limited recharge to bedrock could take place.
Lacustrine	A thick coarsening upwards sequence with occasional interbedded tills.	With one interbedded till: generally a thick aquiclude. With two interbedded tills: sequence capped by sands and gravels, blown sand, raised beach gravels and peat.
Buried channel	A discontinuous lodgement till overlain by granular deposits.	The sand and gravel forms a hydraulic continuum with the bedrock aquifer below.

2.5.2 East Shropshire

A recent study in East Shropshire by Bridge *et al.* (2002) uses the same concepts as the Sellafield study, identifying Quaternary domains according to their depositional history. Unlike the Sellafield study, which developed a 3D domain model from a 2D map, this project concentrated on creating 2D vertical sections through the superficial sequence to identify appropriate Quaternary domains. The resultant domains (Table 6) lend themselves well to hydrogeological interpretation, and given some knowledge of the hydraulic characteristics of the key lithologies it is a simple step to convert this into a hydrogeological domains map (see also Bridge *et al.* 2001). However, although such a map has been created it is recognised that it cannot be validated until relevant hydrogeological data become available, and that it remains subjective. Bridge *et al.* (2002) concluded that the resulting domains map adds a third dimension to the conventional superficial deposits map and distinguishes zones within the Quaternary where differing hydrogeological behaviours can be expected.

Table 6 - Hydrogeological superficial domains in East Shropshire (after Bridge *et al.* 2002)

Hydrogeological domain	Lithological characteristics
1	Bedrock at surface
2	100% clay from ground surface to rockhead
3	100% sand and gravel from ground surface to rockhead
4	> 50% sand and gravel from ground surface to rockhead
5	> 50% clay from ground surface to rockhead, divided between sand and gravel at the surface and clay at the surface
6	Undifferentiated fluviatile deposits, divided between those resting on bedrock and those overlying other superficial deposits
7	Peat, divided between that resting on bedrock and that overlying other superficial deposits

2.5.3 Manchester

Another major Quaternary hydrogeological domains exercise has been carried out across a 30 km^2 area in central Manchester, including Trafford Park (Lelliot *et al., 2006*). For this work, data from 3000 site investigation boreholes were available, which were invaluable in creating the geological framework for the Quaternary deposits. The superficial deposits geology was analysed by creating numerous cross sections through the sequence and thence by assigning a series of generalised, lithologically-based domains. The final step was the interpretation of these in terms of hydrogeological domains. This is easy to do at the generic and subjective level, but considerably harder so at a more quantitative level. Although the geological control on the domains, based on borehole data, is good, the hydrogeological control is poor, and the hydrogeology of the area is complicated by the presence of considerable zones of perched groundwater. Most of the available hydrogeological data refer to the first water strike observed by drillers: analysis showed that this correlates best with elevation, and offers little insight into the location of the water table, perched or otherwise. There are few useable measurements of the permeability of the deposits, and permeability interpretations had to be made largely using generic data. The hydrogeology is further complicated by the presence a large cone of depression around a brewery borehole that effectively dewaters part of the Quaternary deposits, and by the connectivity between surface water in rivers and groundwater in the underlying bedrock aquifer. At best, the hydrogeological domains mapping indicates where rainfall recharge is likely and where it is not. To enable the hydrogeological domains to be validated, measurement of piezometry in the bedrock aquifer is needed, coupled with mathematical simulation of groundwater transport.

The hydrogeological domains were largely defined by lithology, which is the major control on groundwater occurrence: for example, a till-dominated terrain is likely to be relatively impermeable (unless the till is excessively fractured), while a glaciofluvial sand and gravel is relatively permeable. Approximately 400 water strike values were correlated along cross sections with the superficial deposit geology in order to identify the geological units in which groundwater is located. Several assumptions were made:

- any adjacent permeable deposits are in hydraulic continuity (e.g. alluvium, sandstone);

- till or clay deposits that are less than 5 m thick do not prevent groundwater recharge;
- till or clay deposits that are greater than 5 m thick are assumed to restrict recharge to underlying deposits, and may cause overlying perched groundwater;
- made ground is permeable and in continuity with underlying strata.

Seven hydrogeological domains were classified in the project area, representing groundwater-bearing strata and identifying where there is hydraulic connectivity between the superficial deposits and the underlying Permo-Triassic sandstone aquifer (Figures 5 and 6, Table 7). There is a certain amount of uncertainty regarding the location of the domains boundaries, because of the coarse and often poor distribution of data. The domains give a broad indication of the location and distribution of groundwater in the project area, allowing preliminary assessments of groundwater vulnerability and recharge to the Permo-Triassic sandstone aquifer.

The role of cross sections based on hydrogeological superficial domains should not be understated. This method has been used in a number of studies, for example, to identify low hydraulic gradients in the Crag aquifer in East Anglia. The usefulness of the method will continue to develop, but it must be coupled with adequate supporting hydrogeological data, both in terms of formation hydraulic conductivity and piezometric levels, before it can usefully be used to support regional groundwater flow simulations.

The use of hydrogeological domains depends heavily on scaling-up from site-specific data, and on validation. It may create as many problems as it is intended to solve, but it is nevertheless a useful tool with which to provide a rapid assessment of Quaternary geology and its hydrogeological characteristics. Given adequate hydrogeological control, as in the Sellafield case, a validated domains system can be created that can support a regional hydrogeological flow model.

Table 7 – Hydrogeological domains for Manchester (after Lelliot *et al., 2006*)

Group	Domain		Lithologies/geo-morphological units
Major aquifer	1	At outcrop	Permo-Triassic sandstone.
	2	Permeable superficial deposit on a major aquifer	Single or multiple layers of: river channel, river terrace, outwash sheet, basal gravel, and glaciolacustrine sand and silt deposits.
Minor aquifer	3	At outcrop	Coal Measures sandstones.
	4	Permeable superficial deposit on a minor aquifer	Single or multiple layers of: river terrace, outwash sheet, basal gravel, and glaciolacustrine sand and silt deposits.
Potential perched aquifer	5	Perched superficial deposit	River channel, river terrace, outwash sheet, glaciolacustrine sand and silt deposits overlying > 5m till, glaciolacustrine clay, river overbank deposits or Manchester Marls (non-aquifer).
Aquitard	6	Weakly permeable superficial deposit	> 5 m till, glaciolacustrine clay, or river overbank deposits.
Non-aquifer	7	Non-aquifer bedrock	Manchester Marls Formation.

Figure 5 - Schematic hydrogeological domains for Manchester (after Lelliot et al., 2006)

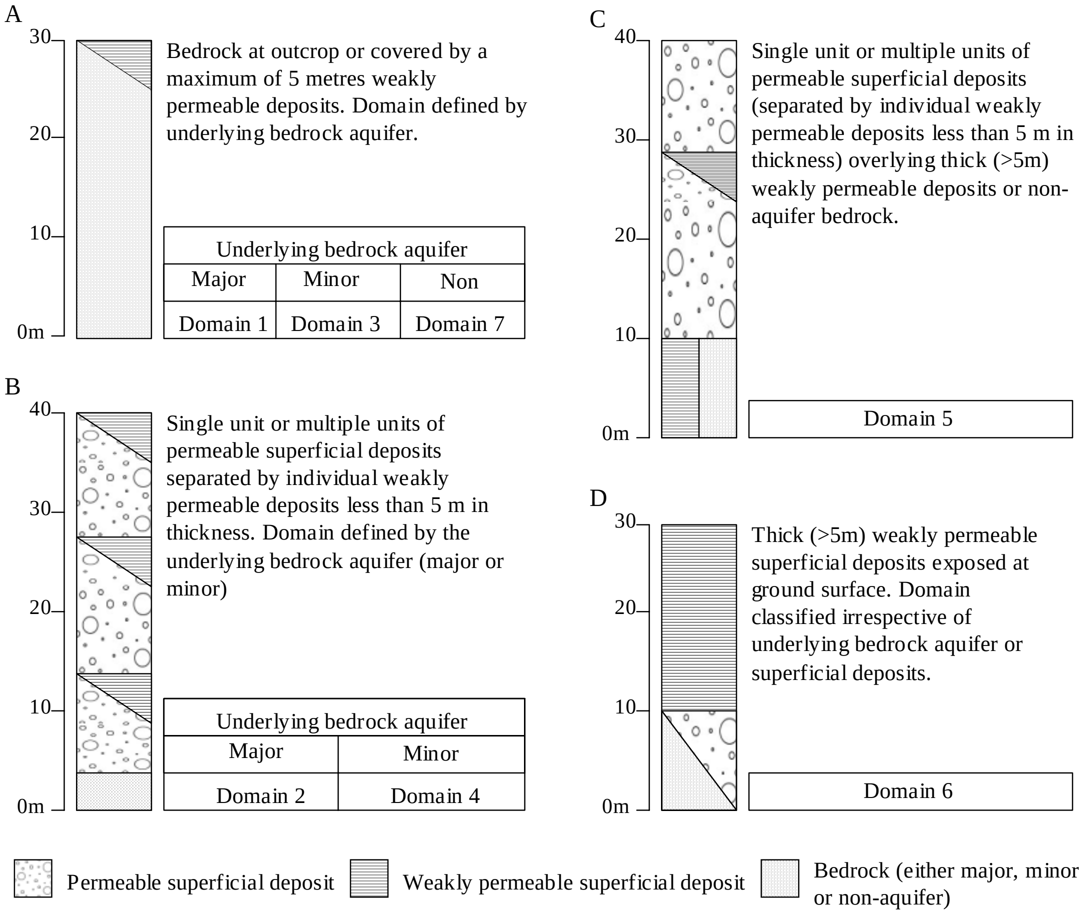
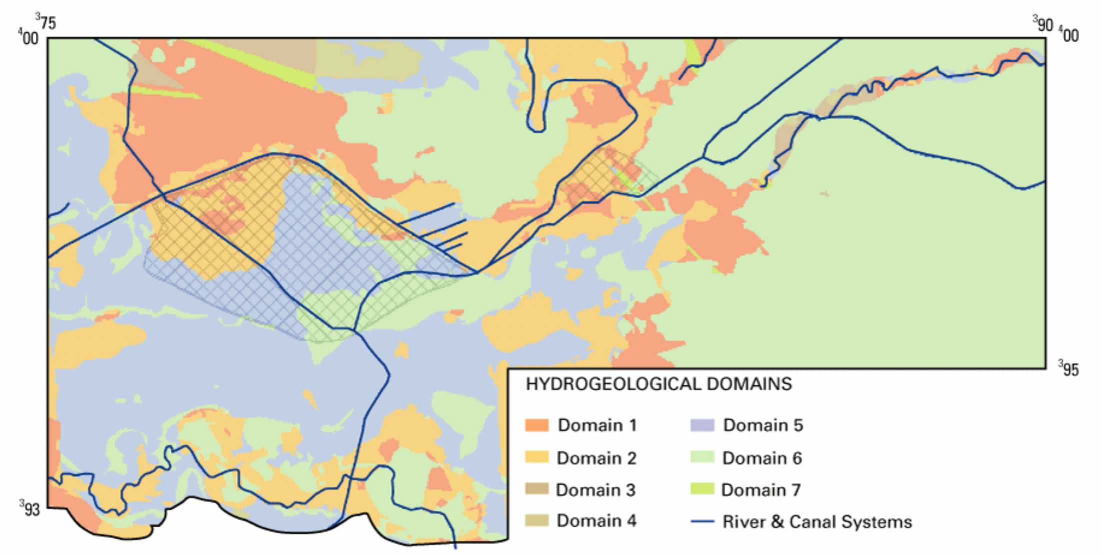


Figure 6 - Hydrogeological domains derived for Manchester (after Lelliot *et al., 2006*)



Domain descriptions are given in Table 7.

2.6 Recharge through low permeability cover

The role of superficial deposits thickness and permeability in controlling recharge was highlighted by Daly and Warren (1998) in the context of vulnerability mapping guidelines for Ireland, and is summarised in Table 8.

Table 8 - Irish vulnerability mapping guidelines (Daly and Warren, 1998)

Vulnerability rating	**Hydrogeological requirements**				
	Sub-soil (superficial deposits) permeability, type, and thickness			**Unsaturated zone**	**Recharge type**
	High permeability (sand and gravel)	Moderate permeability (sandy till)	Low permeability (clayey till, clay, peat)	(sand and gravel aquifers only)	
Extreme	0 – 3m	0 – 3 m	0 – 3 m	0 – 3 m	Point (< 30 m radius)
High	> 3 m	3 – 10 m	3 – 5 m	> 3 m	Diffuse
Moderate	n/a	> 10 m	5 – 10 m	n/a	Diffuse
Low	n/a	n/a	>10 m	n/a	Diffuse

In particular, till thickness is an important control on recharge rates, but one that should be considered relative to the depth of both weathering and intensive fracturing. Thin tills, where the zone of weathering (and more intensive fracturing) may account for much of the till layer, are likely to permit higher infiltration rates than considerable thicknesses of unoxidised and unweathered till (Table 9). Other controlling factors on recharge, some of which have been discussed previously in this report, are:

- till clay content and clay mineralogy
- land use, soil type and topography
- prevailing rainfall events
- soil moisture deficit
- peripheral recharge

Table 9 - Estimated recharge rates in East Anglia through till deposits (after Marks *et al.* 2004)

Till thickness (m)	**Recharge rate (mm/a)**	**Description**
Absent	High At potential rate	Commonly permeable superficials overly the bedrock aquifer allowing high infiltration rates.
<5 m	Moderate – high Could be up to potential rate	Till likely to be largely weathered throughout; pathways for high infiltration rates are provided by root openings and fractures.
5 – 10 m	Moderate 20 – 40 mm/a	Till will include several metres of weathered till; some fractures may extend to 10 m but fracturing probably less intense than at shallower depths.
>10 m	Low <20 mm/a (and maybe as low as 5 mm/a)	Considerable thickness of unweathered till; fractures may provide pathways for some recharge, but rates are low.

Rushton (2005) summarises these factors into three broad scenarios for recharge through till:

1. When the superficial deposits are partially saturated and have low hydraulic conductivity (less than 1×10^{-4} m d^{-1}), a small constant volume of drainage will occur from their base to any underlying bedrock aquifer. This may vary from 0.05 mm d^{-1} for till over the Lincolnshire Limestone or 0.1 mm d^{-1} for clay-with-flints over the Chalk in Kent.

2. If the effective vertical hydraulic conductivity of the till is greater than 5×10^{-4} m d^{-1}, and the till is largely saturated, leakage through it can be calculated using Darcy's Law (i.e., permeability divided by thickness times the groundwater head difference across the till). The effective hydraulic conductivity derives from the overall permeability of the till, including such features as by-pass fractures and silt or sand partings.

3. If the superficial deposits comprise a complex suit of lithologies and have variable thickness, but the amount of runoff is known, recharge can be estimated by multiplying potential recharge by a recharge factor. In the Lower Mersey area, where thick till overlies sandstone, a factor of 0.02 was used, based on regional groundwater modelling.

A further scenario is focussed or induced runoff recharge, which may occur if runoff from a clay-covered area passes off the clay onto an area of bedrock aquifer outcrop.

Consideration of the influence or otherwise of by-pass mechanisms in Irish hydrogeological settings has been undertaken by Daly (2002). This review concluded that such mechanisms may be highly significant where soils and superficial deposits are thin (less than 2m), although it recognised that little direct information is available and further research is needed.

2.7 Groundwater vulnerability through low permeability cover

A new groundwater screening methodology for assessing groundwater vulnerability and the risk of groundwater contamination was developed for use in Scotland to address the needs of the Water Framework Directive, with allowance made for its adaptation for use in Northern Ireland, England and Wales (Ball *et al.* 2003). Groundwater vulnerability was defined as a component of the pathway element in the context of the hazard-pathway-receptor model commonly used for risk assessment work, where the hazard, pathway and receptor are defined as follows:

- Hazard: land use activities, including waste disposal, urban development, farming, and mining that pose a threat to groundwater.
- Pathway: all material between the hazard and the receptor is part of the pathway. It occurs from the point of release of contaminants to the uppermost 'main' water table. The properties of the pathway determine the vulnerability rating.
- Receptor: In the case of groundwater vulnerability mapping for the Water Framework Directive, the receptor is the principal water table within an aquifer vertically below the hazard. Once contamination has reached this initial target, subsequent receptors could include abstraction boreholes and surface water ecosystems that are fed by groundwater.

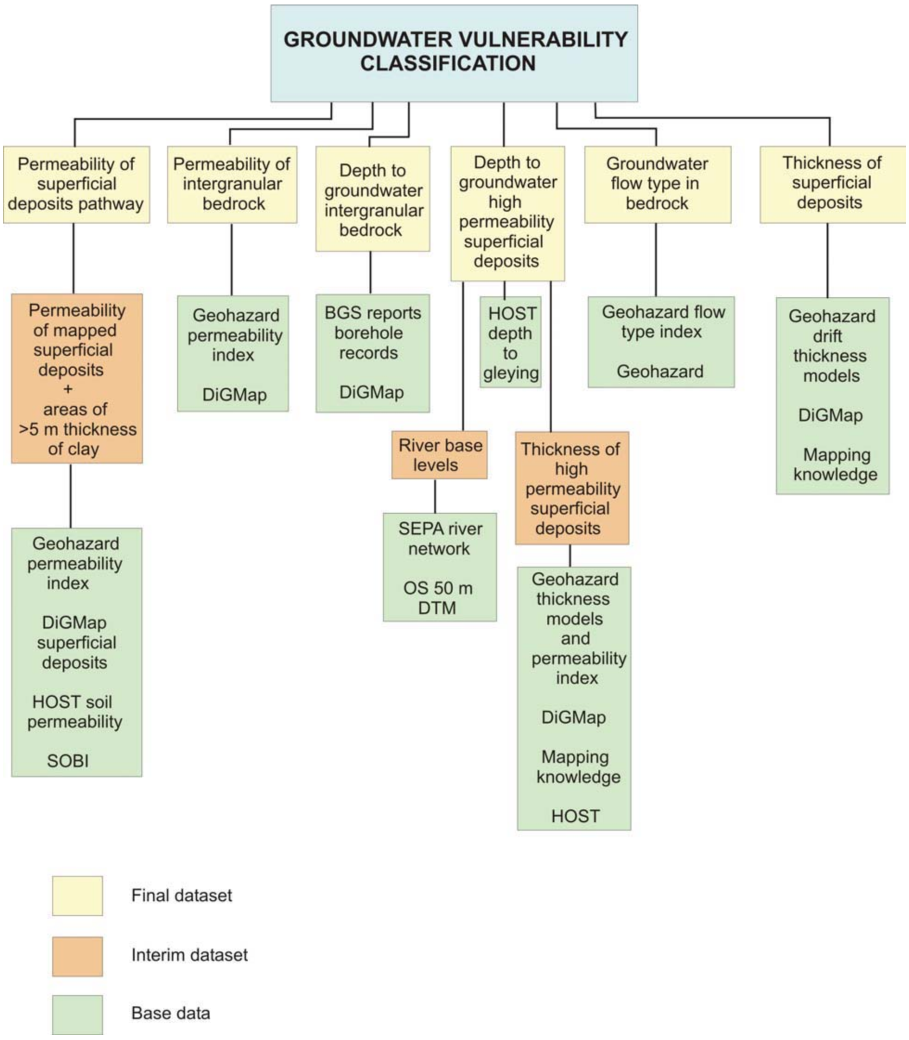
Two main attributes of the pathway materials were assumed to influence groundwater vulnerability: travel time and attenuation capacity (Table 10). Five key datasets were identified that control these attributes, and are therefore fundamental to the vulnerability assessment (Figure 7):

1. Permeability of the superficial deposits, including soil.
2. Permeability of intergranular and intergranular-dominant bedrock aquifers.

3. Groundwater flow type in bedrock (intergranular or fracture flow).
4. Thickness of superficial deposits.
5. The depth to the water table (in superficial and intergranular bedrock aquifers only).

A sixth key dataset, the location of point recharge features such as karstic swallow holes, was also recognised as valuable but was not incorporated because of a lack of relevant data for Scotland.

Figure 7 - Data sources for the Scottish groundwater vulnerability classification methodology (after Ball *et al.* 2003)



Superficial deposits were classed as having high, moderate or low permeability. If high permeability deposits contain a water table they were classed as aquifers in their own right.
Where the superficial cover is classed as a pathway rather than an aquifer in its own right, the nature and thickness of the deposit are crucial to the vulnerability rating of the bedrock aquifer below. If the dominant flow type in the bedrock aquifer is fracture flow, there will be no effective attenuation of contaminants in the bedrock.

In the absence of adequate groundwater level information for most areas of Scotland (in common with the rest of the UK), a map of the estimated depth to water in superficial deposits was produced, based on the concept that the water table is shallower beneath valley floors or near the coast than beneath relatively high ground. It was assumed that rivers or sea level equate to the water table surface in the aquifer immediately adjacent. In unconfined intergranular aquifers, the elevation difference between the surface water feature and ground surface with increasing lateral distance was interpreted as an equivalent increase in the depth to the water table.

Table 10 –Attenuation mechanisms and contaminants (after Morris *et al.* 2003)

CONTAMINANT	ATTENUATION MECHANISM				MOBILITY	PERSISTENCE
	Biochemical Degradation	Sorption	Filtration	Precipitation		
Nitrogen	•	•[a]	x	x	Very High	Very High
Chloride	x	x	x	x	Very High	Very High
Faecal Pathogens	•••	••	•••	x	Low - Moderate	Generally Low
Dissolved Organic Carbon	•••	•••	•	x	Low - Moderate	Low - Moderate
Sulphate	•	•	x	•	High	High
Heavy metals	x	•••	•[b]	••	Generally low (unless pH low)	High
Halogenated solvents (DNAPLS)	•	•	x	x	High	High
Fuels, lubricants, oils, other hydrocarbons (LNAPLS)	•••	••	x	x	Moderate	Low
Other synthetic organic	Variable	Variable	x	x	Variable	Variable

••• highly attenuated •• significant attenuation • some attenuation x no attenuation

[a] ammonia is sorbed

[b] where they occur as organic complexes

The resultant map categorises areas of fractured rock with a generally thin, permeable cover of superficial deposits as highly vulnerable to pollution – including the majority of the Highlands and Borders areas. Areas where there are thick, often weakly or moderately permeable, superficial deposits, including areas where clays are at least 5 m thick, are classed as having moderate or low vulnerability – including much of central Scotland.

This methodology recognises the importance of the hydrogeological characteristics of the pathway between the hazard at or near surface and the receptor, which in this case is the uppermost main water table. It does not distinguish between highly productive aquifers (receptors) with high recharge acceptance potential and large volumes of groundwater storage, and low productivity aquifers with low recharge acceptance potential and only small volumes of groundwater.

A similar methodology could be applied to England and Wales, as the digital datasets used in Scotland are available across Britain. Ireland has adopted a similar approach to vulnerability to that in the UK, but there are a number of significant differences (Swartz *et al.* 2003). It is assumed that till deposits derive from local bedrock, and the broadest classification of superficial deposits reflects this, such that Carboniferous shales and mudstones produce clay tills; limestones produce moderate permeability tills; and granites produce sandy, more permeable tills. Grain size analysis (according to British Standard BS 5930) allows further classification of most till deposits. Surrogate information such as vegetation type and drainage density are also used to support permeability mapping of the tills. Soil type is also a useful indicator, with differentiation between free draining soils and gley soils supporting areas where infiltration is and is not taking place.

3. THE QUATERNARY AND THE WATER FRAMEWORK DIRECTIVE

The European Union introduced the Water Framework Directive (2000/60/EC) as a single piece of framework legislation in December 2000. The Water Framework Directive expands the scope of water protection to all waters, surface waters and groundwater with the aim of achieving ‘good status’ by December 2015. In doing so it also contributes to the provision of supply of water through the quantities and qualities needed for sustainable development.

At the heart of the Directive is the requirement to produce a strategic management plan for each river basin, setting out how the objectives are to be achieved. The plan requires a detailed analysis of the pressures on the water bodies within the river basin, and an assessment of their impact to allow a comprehensive programme of measures to be drawn up. These should target improvements and monitoring effort on those water bodies most at risk of failing to meet their environmental objectives.

The aim is to take a holistic approach to water management, updating current EC water legislation by:

- introducing a statutory system of river basin analysis and planning;
- the use of ecological and chemical standards and objectives;
- the integration of groundwater and surface water quality and quantity; and
- the phased repeal of some European Directives.

Article 5 of the Water Framework Directive requires that Member States undertake an analysis of the characteristics of each River Basin District and review the impact of human activity on the status of groundwaters, in accordance with the technical specifications set out in Annex II of the Directive. A major element of groundwater characterisation is the mapping and description of ‘groundwater bodies’. Characterisation is sub-divided into two stages – initial characterisation and further characterisation, where further characterisation is required for groundwater bodies deemed to be ‘at risk’. This characterisation phase had to be completed and reported upon by the end of 2004. At risk groundwater bodies are subjected to monitoring and trend analysis so that unacceptable anthropogenic trends in groundwater quality are detected and management measures introduced to reverse these trends.

The role of superficial cover to these requirements impinges both on quality and quantity aspects of the Water Framework Directive. Weakly permeable superficial material tends to reduce the potential from recharge to bedrock aquifers below thus protecting them from anthropogenic pollution, but reducing their groundwater throughput. Permeable drift cover, conversely, may enhance recharge to a bedrock aquifer and make the underlying aquifers more vulnerable to polluting activities at surface. In addition permeable drift deposits themselves play an important part in catchment water balance, offering shallow storage often in hydraulic contact with both surface waters and deeper groundwaters and can themselves form groundwater bodies.

Characterisation of bedrock groundwater bodies (a distinct volume of groundwater within an aquifer or aquifers) depends not only on bedrock conditions but also on the superficial cover. Each area has its own properties with regard to resource potential, hydraulic interaction with surface waters, vulnerability to pollution, and inherent chemical properties. The superficial material, however, is a controlling factor in the quality and quantity of groundwater within the sandstone aquifer at any given place. From a management point of view the sandstone basin is an obvious candidate to be designated a single groundwater body. From a hydrogeological processes point of view and from the stance of understanding the catchment hydraulics and processes required by the Water Framework Directive, it is a complex of sub-units each with its own discrete hydraulic properties.

3.1 The key issues and controlling factors

In order to achieve the objectives and to manage surface and groundwater in an integrated way, the Water Framework Directive introduces River Basin Districts (RBD) and requires that a River Basin Management Plan (RBMP) be produced for each District. The initial phase of the River Basin Management Plan is the delineation of bodies of water within the River Basin Districts and their characterisation to assess their uses and the degree to which they are at risk of failing to meet the environmental objectives set for them. For groundwater bodies the Article 4 environmental objectives include the need to achieve good status. This has two components, quantitative and chemical status. The achievement of good chemical status involves meeting several criteria, including meeting quality standards and avoiding damage to receptors, of which associated surface waters and terrestrial ecosystems are specifically mentioned. Thus the key elements are recharge (quantity) and vulnerability (quality) of water newly arriving at the water table of an aquifer.

The risk assessment component of groundwater body characterisation therefore involves both an assessment of the nature and magnitude of pollution pressures and the likelihood that the pressure at the surface will adversely affect the underlying groundwater body to the extent that its chemical status in 2015 will be poor.

The status and integrity of the superficial cover is critical to these assessments, both physically in terms of volumes of recharge and chemically in terms of attenuation and absorption available within the cover material. Diverted infiltration to field drains, perched water to springs and soil interflow all act to divert recharging water, and conversely by-pass mechanisms, surface ponding and loosing streams act to accentuate it. The relevant processes are identified here in order that data requirements can later be identified to assess the role of the Quaternary to satisfy the demands of the Water Framework Directive.

The key intrinsic factors are:

- infiltration to runoff ratio – broadly the same as surface water Base Flow Index.;
- infiltration velocity – dependent on vertical hydraulic conductivity of discrete lithologies and soils. Requires measurement of hydraulic conductivity and grain size;
- soil moisture content – dependent on soil structure, porosity and storativity, coupled with land use, slope and aspect;
- surface and groundwater relationship – depending on losing streams and ponding in small depressions;
- time to arrive at water table – depending partly on depth to water table, and affects breakdown of transient phases before they reach the aquifer;
- by pass systems – depending on availability of sub-horizontal fractures or interconnected sand and gravel horizons in low permeability tills and silts. These features also provide a direct route for pollutants to access the water table;
- shallow diversion of infiltration back to surface - to field drains, soil interflow or shallow systems such as scree;
- dispersion – mixing of groundwater and polluted water due to different lengths of flow lines travelled through pore centres and pore edges, by short routes and longer routes;
- adsorption – dependent on clay content and type; and
- biological soil activity – depends on availability of carbon in the soil.

The likely available data sources to address at these factors, and the importance of each, are given in Table 11. In addition, the British Geological Survey produces datasets showing the potential location of geological hazards, GeoSure, which provide information about factors such as soluble rocks, shrink swell, landslides, compressible ground, running sand and collapsible rocks. The principal data sets are soil type and its characteristics, derived from HOST, and the physical properties of the superficial sequence, derived from available 1: 50 000 scale Quaternary geology maps.

The key to identifying a uniform methodology for assessing the superficial strata for the Water Framework Directive, based on the data listed in Table 11, is to adopt a generalised approach on a large scale and then to refine the focus in selected areas of interest at a smaller scale, as data allow.

Table 11 – Availability of data

Data type	**Importance**	**Availability**
Superficial deposits geology maps	Critical	Digital at 1: 50 000; partial coverage at 1: 10 000
Soil maps (ands soil grain size analyses)	Critical	Largely available at 1: 50 000 but not digital
2D bedrock geology	Critical	Digital at 1: 50 000
3D superficial deposits lithology	Critical	Unlikely to be available
Borehole records	Critical	Over 200 000 sites, coverage variable
HOST	Critical	Available under licence
Depth to water table	Essential	Partially available
Depth to rock head	Essential	Partially available
Recharge estimates	Essential	SNIFFER project WDF 12
Air photography	Useful	Stereo pairs at 1: 10 000
Base Flow Indices	Useful	Available for larger catchments
Slope	Useful	Digital as DTM
Drift hydraulics	Useful	Unlikely to be available
Groundwater vulnerability and resource maps	Useful	1: 625 000 coverage, selected areas at 1: 100 000 (SNIFFER Project WFD 28)
Nitrate risk areas	Useful	e.g. MLURI work for Scotland
Pollution potential (risk) map	Useful	Information is available for some areas
Topography	Useful	NEXTMAP

3.2 Quaternary typology

When considering the role of the Quaternary, particularly with regard to further characterization of groundwater bodies, it is useful to provide a typology to illustrate the key processes occurring in the more common environmental settings.

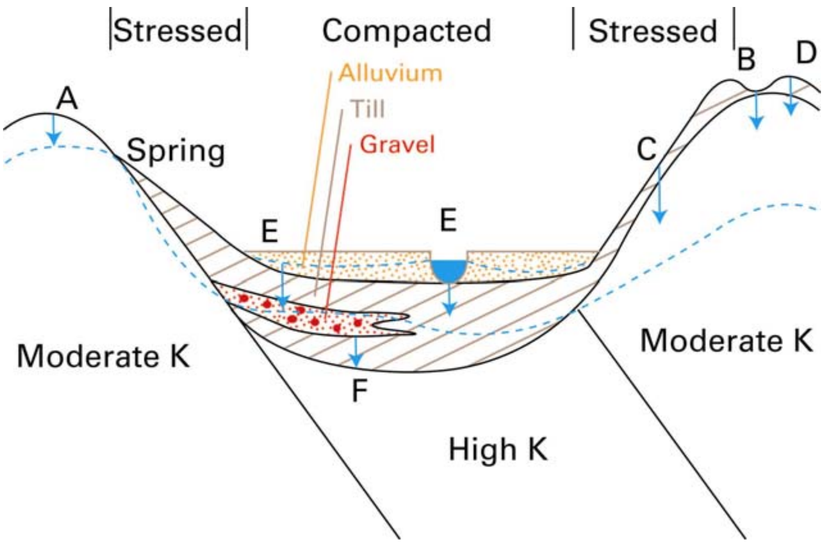
A range of possible settings and the dominant processes within them are illustrated in Figure 8. These can be further developed with a series of schematic cross sections, each based on a real situation, which demonstrate the processes and flow paths likely to occur in a range of hydrogeological settings. It is visualized that about 15 or 20 such sections would be needed to cover the likely range of settings in order to describe a single Quaternary hydrogeological domain type.

Examples of hydrogeological settings are:

- thick, very low permeability clay-rich till, with little if any groundwater transport;

- clay-rich till with by-pass flow facilitated either via fractures or interconnected lenses of moderate permeability which allow some groundwater transport;
- moderate permeability alluvium, providing bank side storage to surface waters, with sand and gravel at the ground surface promoting infiltration, but with limited storage. May be in hydraulic continuity with bedrock or perched on till;
- topographical hollows with low permeability Quaternary deposits, in which standing surface water promotes saturation and infiltration despite the low permeability;
- thin and weathered or absent Quaternary cover.

Figure 8 – Typical settings and the associated infiltration processes related to till (k – permeability)



A. No cover
B. Ponding in till hollow
C. Stress cracked till on hill sides
D. Highly stressed and deeply cracked till on hill top
E. Possible connection between perched groundwater and river water to gravel lenses
F. Possible connection through sandy lenses to bedrock

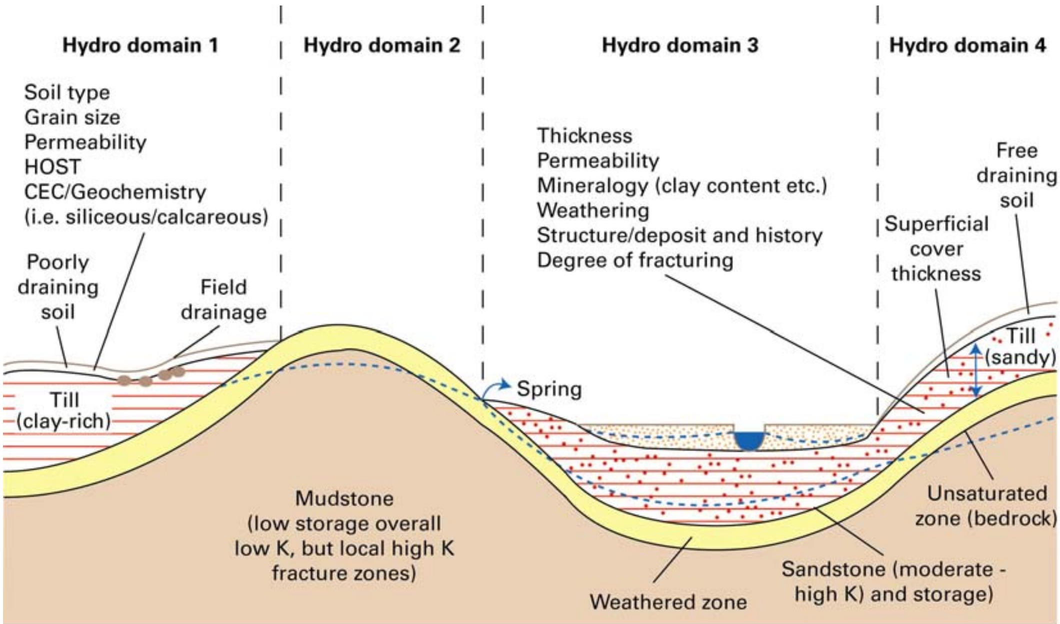
3.3 Possible ways forward

This review document highlights the available techniques which could be adopted to assess Quaternary deposits across the UK, and their influence on recharge and vulnerability. A possible way forward is described below.

- The development of regional Quaternary geological domains classifications using an initial generalised approach, with refinement towards catchment scale as data allow, making best guesses where data are not yet available.
- The further interpretation of these Quaternary domains as Quaternary hydrogeological domains (Figure 9). This could utilise available data from a variety of sources.
- The description of each hydrogeological domain with a schematic cross-section to illustrate the principal recharge mechanisms and hydrogeological processes characteristic of each domain. It is likely that there would be up to eleven such domains to cover the UK.

- The development of conceptual flow models for the principal hydrogeological domains, using real examples if possible.
- The classification of the Quaternary hydrogeological domains according to recharge potential, based on the perceived permeability of the whole Quaternary sequence, and absorption potential, based on clay mineral and organic content (as a surrogate for cation exchange capacity).
- Within each domain type, the role of field drains, prevailing effective rainfall and rejected recharge should be highlighted.
- Validating the output of the conceptual flow models against existing recharge and vulnerability data.
- A review of the uncertainties in hydrogeological domain classification at catchment scale, and the identification of a programme of work to reduce these uncertainties.
- The production of a map (or series of maps) in GIS format, using a 1 km grid resolution.

Figure 9 – Examples of hydrogeological domains



K – permeability

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GLOSSARY

Bedrock: The currently accepted term for consolidated rocks of pre-Quaternary age. Bedrock may crop out at the ground surface or be overlain by superficial deposits.

Drift: The traditional term used to describe natural sediments deposited by ice. This definition soon evolved to include all superficial deposits of Quaternary age, but has now largely been replaced by the term superficial deposits.

Engineering rockhead: in general terms this applies to the surface of the deposit that has the engineering properties of a "rock" (for example with a strength > 1.25 MPa). Engineering rockhead may be very complex particularly in heterogeneous and fractured rock successions or in bedrock that weathers in a non-uniform manner with weaker material below stronger material.

Geological rockhead: This is normally taken at the base of Quaternary deposits, and is usually unrelated to a weathering profile. However, local difficulties are experienced with the placement of the geological rockhead boundary, where there are similarities between the weathered bedrock and overlying Quaternary deposits, such as sands above completely weathered sandstone.

Quaternary deposits: Sediments laid down during the Quaternary era (the last c.2.5 Ma or 1.81 Ma depending on which base-Quaternary time reference is used).

Soil (engineering): an aggregate of mineral grains that can be separated by such gentle means as agitation in water. Most superficial deposits with the exception being certain types of landslide deposits are classed as engineering soils. Apart from the basal part of the Crag Group, all of these deposits would be considered as 'soils' under this engineering definition. The mass properties of 'engineering soil' are largely influenced by its material characteristics (e.g. mineralogy, grain size/shape, plasticity, density). They can invariably be excavated by hand or by mechanical excavator and can be investigated and sampled by light cable percussion/mechanical auger boring techniques.

Soil (pedological/geological): rock or superficial deposits that have been affected by the processes of physical reorganisation and/or chemical change dependent on their continued proximity to the atmosphere and biosphere.

Solid: The traditional term for consolidated rocks of pre-Quaternary age, now largely replaced by the term bedrock.

Superficial deposits: The currently preferred term, encompassing all deposits of Quaternary age, including artificial materials and the products of in-situ weathering.

APPENDIX I QUATERNARY STRATIGRAPHIC FRAMEWORK

The Quaternary is the second period of the Cenozoic era, following the Neogene, and consists of two epochs – the Pleistocene and Holocene. It is a period marked by a progressive increase in global ice volume and the cyclical glaciation of high and mid-latitude regions. The Quaternary period is widely considered to have begun at c.2.5Ma, coincident with the first evidence of ice-rafting within the North Atlantic, the appearance of aeolian loess within the Chinese stratigraphic record, and the first appearance of the early hominid *Homo habilis* in Africa.

The Pleistocene, the earliest Quaternary epoch, spans the time from the onset of the Quaternary (c.2.5Ma) to the beginning of the Holocene (c.11.5ka). The Pleistocene is sub-divided into Early, Middle and Late Pleistocene. The Early-Middle Pleistocene boundary occurs at the Bruhnes-Matuyama palaeomagnetic reversal (c.0.78Ma) during MIS 19, whilst the Middle-Late Pleistocene boundary is situated at the beginning of the Ipswichian / Eemian (c.0.125Ma) at MIS 5e. The Holocene, the second Epoch of the Quaternary, extends from c.11.5ka years ago until the present day.

The current stratigraphic framework for the Quaternary is based on the geological and geomorphological processes that have acted on the British mainland and adjacent seas over the last c. 3 million years - an event/process-driven stratigraphy. There have been six distinct driving episodes to the development of the Quaternary strata in the UK:

1. *Soils and shallow-marine systems.* This is the earliest episode of the Quaternary, during which low-energy terrestrial processes and moderate-energy, shallow-marine processes dominated, and rates of landform change were small. Deposits from this episode are largely confined to residual soils, locally derived marine sediments, and occasionally locally derived river deposits. Examples of marine sediments are the shelly, shallow marine Red and Norwich Crags of East Anglia; the St Erth marine deposits in west Cornwall (Mitchell et al., 1973); and the rare patches of coastal deposits elsewhere in Britain. Examples of river sediments are the Nettlebed river deposits in the Thames (Turner 1983); and the Brassington river muds, silts, sands and gravels in the south Pennines. There are also residual deposits such as the Clay with Flints of the Chalk and Tertiary bedrocks; the cherty clayey gravels of the Cretaceous Greensand bedrock; and occasional patches of deeply weathered parent material elsewhere in upland England, Wales and Scotland.

2. *Major river systems*. This is also relatively early in the Quaternary, before the main glacial/interglacial cycles, during which moderate-energy river and shallow-marine processes dominated. The dominant geological process at this time was river activity in large, well-defined catchments, and the most powerful forces were periglacial climate processes with local-scale, upland glaciation. This period is also represented by fluvial and marine sediments with far-travelled lithologies. Shallow-marine processes were effective, operating under predominantly high sea-level conditions. Deposits include the shelly sands, gravels and muds of the Wroxham Crag, (Rose *et al.* 2002); the fluvial sands, gravels and silts of the River Thames and former Rivers Bytham and Ancaster (Rose *et al.* 1999); and the freshwater sands, gravels and organic sands and muds of the fluviatile Cromer Forest-bed (West 1980).

3. *Glacial/ interglacial cycles.* This episode is defined by major changes in the energy levels of both onshore and offshore geological processes, caused by extreme climate variations associated with glacial/interglacial cycles. A wide range of processes operating together, at different energy levels and at different rates, to produce highly complex lithofacies with complex lithological signatures. Deposits are highly variable, fragmented and of limited extent. Glacial deposits are the most characteristic products of the geological systems operating at this time and are extensive throughout the Midlands of, and eastern and northern, England, Wales, Scotland and Ireland (Bowen *et al.* 1986, Rose 1989).

4. *Last Glacial/Interglacial Transition.* This was characterised by a wide range of processes which operated with varying effects for a short period of time, on a landscape not in equilibrium with its surroundings. The result was a pattern of discontinuous and unstable landforms and materials. Typical deposits dating from this episode are glacial deposits, including tills, meltwater sands and gravels and glacial lake (glaciolacustrine) silts and clays. The surface expression of these deposits is highly variable, including lineated relief (drumlins), moraine ridges, subdued hillocks and enclosed depressions (kames and kettle holes), sinuous ridges (eskers), low gradient plateaus and plains (outwash sandar) and shorelines, and basin flats (glacial lake flats). Deposits are limited to northern and western Britain. Also associated with this episode are erosional landforms such as the glacial troughs of the Scottish, northern English and Welsh mountains.

5. *Last Glacial Maximum.* The products of the processes operating during the Last Glacial Maximum can be identified by morphostratigraphy in a way that is not possible for systems operating earlier in the glacial/interglacial cycles. As with the earlier glacial episodes, glacial sediments and landforms are the most visible products. These include tills, sands and gravels, and lake clays forming, respectively, moraine ridges, hummocky moraine, kames and kettle holes, lineated surfaces (drumlins and flutes), eskers and outwash plains represent the effects of ice sheet, ice cap, valley and corrie glaciation in Scotland, and valley and corrie glaciation in northern England (Lake District, Cheviot, northern Pennines) and Wales (Snowdonia, Rhynogs, Brecon Beacons) (Sissons 1968). Outwash from these deposits forms distinctive sandur plains and terraces along adjacent valleys and lowlands, sometimes modified by kettle holes in their ice proximal region. Close to, and within the limits of this glaciation, lake silts and clays and lake shorelines represent the formation of ice-dammed lakes.

The glaciated terrain can be subdivided at the southernmost Devensian glacial limit in order to distinguish those areas that have been glaciated during the last, c. 100 000 year glacial-interglacial (Devensian-Holocene) cycle, from those lying south of the Devensian limit with deposits and landforms that relate to earlier Quaternary glaciations.

6. *Holocene climate and human activity*. The most recent episode is determined by a combination of the effects of relatively low-energy natural processes, and human activity, which comprises high-energy materials and forms. In a period of time when human activity contributed indirectly and directly to the way that natural geological processes acted on the landscape, it is often very difficult to clearly identify the evidence in terms of either 'natural' or 'influenced by human activity'. Indeed there is now good evidence that even the climate that is forcing the geological processes has been influenced by human activity, and that human-induced greenhouse warming has been influential over the last c. 6 ka.

Each of these six episodes has provided a characteristic suite of lithologies. Maps based on the Quaternary episodes, therefore, provide the user with a targeted sequence of lithologies representative of each episode.

APPENDIX II NORTHERN IRELAND DOMAINS

A preliminary assessment has identified six Domains for Northern Ireland:

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

The Fluvial Domain is ubiquitously spread across all six counties. Notable examples of which include the Foyle system of counties Londonderry, Tyrone and Antrim, and the Bann system of County Antrim.

Low ground adjacent to Lough Foyle in County Londonderry and inland as far a Strabane in County Tyrone, fall within the Alluvial, estuarine and coastal Domain with thick sequences of alluvial, lacustrine and estuarine (locally known as sleech), beach and aeolian deposits that commenced formation in the Holocene and continue to accumulate today.

By far the most extensive domain is the Till Dominant (TD) covering between * and *% of the Northern Ireland landmass. The sub-division of this domain into TD1 and TD2 is based on the proportion of till to rock near surface. TD1 areas are predominately till covered while TD2 areas can contain (on average) greater than 50% of rock near or at surface.

Montane and Valley are restricted to relatively small areas across Northern Ireland. The Mountains of Mourne in County Down and the uplands and glens of east County Antrim are two such areas, the latter being a deeply dissected upland plateau.

The ice scoured montane domain appears limited to west County Tyrone. In the Drumquin and Killeter area, there is much rock at or near surface, and when combine with ice-flow indicators and the location of deposition in Donegal Bay, the domain classification is strong.

In County Fermanagh, the area southwest of Lower and Upper Lough Erne of the Carboniferous basin, display many of the Plateau and valley Domain characteristics. These include scarp and dip-slope features resulting from the differential erosion of limestones, sandstones and shales.