Improving the characterisation of Quaternary deposits for groundwater vulnerability assessments using maps of recharge and attenuation potential

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Abstract

Assessing aquifer vulnerability is difficult for bedrock aquifers concealed by highly variable superficial deposits such as glacial till. Many current groundwater vulnerability maps, and the geological maps on which they are based, do not adequately account for regional and vertical variations in the characteristics of superficial deposits. A new methodology for characterising recharge potential and contaminant retardation potential of superficial deposits is presented here which captures primary geological and hydrogeological expert knowledge in a systematic manner. The method modifies existing superficial geology maps using Quaternary domains and their descriptions, bedrock lithology, thickness of superficial deposits and applies additional information on superficial geology and bedrock lithology. Central to the methodology is a matrix which enables local geological and hydrogeological knowledge to be incorporated in a systematic and traceable manner. The scale-independent methodology has been piloted at 1:625 000 scale to produce maps of recharge and attenuation potential for Great Britain. Preliminary verification against several indicators (HOST data, the Scottish vulnerability screening tool, and nitrate data) has been encouraging. The method is being used by the

Environment Agency as part of its vulnerability assessments for the characterization of groundwater bodies as required by the Water Framework Directive (Council of European Communities 2000).

Quaternary superficial deposits cover approximately 90% of the British landmass. Superficial deposits, of which glacial till is a major component, moderate potential recharge to underlying bedrock aquifers and are an important influence on vulnerability to pollution through their ability to attenuate pollutants. Superficial deposits also influence groundwater quality (Shand et al. 2007). Characterisation of these deposits and the processes occurring within them is critical to the assessment of groundwater vulnerability and the characterisation of groundwater bodies required by the Water Framework Directive (Council of European Communities 2000).

Groundwater vulnerability maps for England and Wales were first developed for the National Rivers Authority in the early 1990s and are still in use today, mainly as a planning tool. The maps are at 1: 100 000 scale and cover all of England and Wales (Palmer et al. 1995). 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, although on the England and Wales maps this was transposed to non, minor and major aquifer) and three soil leaching potential classes (high, medium and low). The groundwater vulnerability maps for England and Wales do not consider travel time to the water table because depth to water was not then generally available on a regional basis (Robins et al. 1994). Furthermore, they were designed for a conservative pollutant that would not degrade in the unsaturated zone (Palmer et al. 1995).

Similar maps were produced for Scotland and Northern Ireland, but have recently been replaced as part of the Water Framework Directive characterisation work. New groundwater vulnerability screening layers were produced for Scotland at an effective scale of 1: 100 000 (Ó Dochartaigh et al. 2005), and for Northern Ireland at 1:250 000 scale (Ball et al. 2005), in which the underlying bedrock aquifer class does not directly influence the 'vulnerability' rating.

In Ireland, a slightly different approach to vulnerability mapping has been adopted (Daly and Warren 1998; Misstear and Daly 2000). The topsoil was not taken into account but superficial cover (known as subsoil in Ireland) is the main feature of the maps, whereas in the original

England and Wales vulnerability maps it was generally only considered as a secondary feature. The Irish approach also considers the nature of the recharge, i.e. whether it is point or diffuse.

Superficial cover material posed a significant problem in developing the original vulnerability maps for England and Wales. Where a superficial cover occurs as a granular deposit and where it is saturated it was depicted as an intergranular aquifer. Wherever till is greater than 5 m thick, it was assumed to be of sufficiently low permeability to protect the underlying aquifer and was depicted as a stippled area denoting likely protection subject to field checking of the cover material. Glacial till may vary in composition from silty clay to sandy silt over limited horizontal and vertical distances, with corresponding variations in permeability. It may also be fractured or incised.

Improved information on the lithology, variability and thickness of superficial material is the desired next step for improved aquifer vulnerability assessments (e.g. McMillan et al. 2000; Ó Dochartaigh et al. 2005; Fitzsimons and Misstear 2006). Current geological maps of superficial deposits alone are not suitable for determining groundwater vulnerability, since superficial deposits within a particular mapped unit may vary significantly in composition, not only on a local or regional scale but also on a national scale (Anon. 2004).

This paper describes a new methodology for supporting assessment of groundwater vulnerability on a nationwide basis using improved characterisation of the superficial deposits. Figure 1 illustrates how this method seeks to improve groundwater vulnerability assessments through the incorporation of Quaternary domain conceptual models, local geological and hydrogeological knowledge, national datasets including estimates of drift thickness (part of BGS's GeoSure national dataset on natural ground instability across Great Britain) and site specific information (e.g. boreholes and site investigation reports). Amalgamation of all existing information and knowledge regarding the properties of the superficial deposits enables national maps of recharge potential and attenuation potential to be produced. In this initial phase these maps provide national coverage at 1:625 000 scale but more detailed maps i.e. 1:50 000 scale are being produced by the Environment Agency which has recently adopted the method described in this paper. Additionally, the maps should evolve to incorporate new information, allowing the vulnerability classifications to be refined and improved.

Figure 1. The available resources for improving the hydrogeological characterisation of the superficial deposits.

The influence of superficial deposits on bedrock hydrogeology

Superficial deposits influence the vulnerability of bedrock groundwater in two main ways (see Figure 2). Firstly, they affect the recharge potential (Rushton 2005): the volume of water or pollutant that can travel through the superficial deposits to the bedrock aquifer below. The relative recharge potential relates to the superficial deposits and does not reflect 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 Great Britain and their ability to accept recharge due to low storage and transmissivity can be significantly restricted). Secondly, superficial deposits have a large impact on the potential attenuation of pollutants. Superficial deposits may often reduce the vulnerability of an underlying aquifer to pollution by increasing both the travel time for pollutants to reach the water table, allowing time for degradation of some contaminants, and also retarding contaminants through sorption on clay surfaces or organic material.

Figure 2 Factors influencing recharge and attenuation in the sub-surface. The methodology described in this paper is concerned only with the processes in the superficial deposits.

Recharge

Recharge through superficial deposits is largely determined by the thickness of the deposits, lithology, vertical fracturing and the architecture of the sediments. Investigations of the characteristics of low permeability superficial deposits in North America concluded that recharge can occur through all Quaternary deposits, even where matrix permeability is very low (Keller et al. 1988; van der Kamp 2001). In Great Britain it is consistently reported that recharge occurs through glacial till (Klink et al. 1997; Foster 1998; Marks et al. 2004; Cuthbert 2005). Both Rushton (2005) and Fitzsimons and Misstear (2006) identify an important factor for recharge as the prevailing hydraulic gradient between till and underlying aquifer. Soley and Heathcote (1998) observed recharge of 36 mm a^{-1} through till on interfluves in East Anglia, decreasing to 10 mm a^{-1} in areas of thicker cover where the underlying Cretaceous Chalk bedrock aquifer is locally confined.

The role of superficial deposit thickness and permeability in controlling recharge was highlighted by Daly and Warren (1998) in the context of vulnerability mapping guidelines for Ireland and further developed by Misstear et al. (2009). As unsaturated permeability can only be measured experimentally, grain size is often used as an indicator. Primary permeability may also be enhanced by weathering and fracture development (Gerber et al. 2001).

Where fractures occur in superficial deposits, e.g. in a fractured till, gravity by-pass flow may occur and may be the dominant flow mechanism (Cuthbert 2005), although mainly restricted to the uppermost 3 m in Ireland (Misstear et al. 2008). Studies of glacial till in situ for waste disposal often indicate the importance of fracturing which can increase permeability by 1 – 3 orders of magnitude. These fractures are most common at shallow depths (<10 m) in oxidised and weathered deposits, but can also be found at greater depths (10 – 30 m) (Keller et al. 1988; Frederica 1990; van der Kamp 2001; Cuthbert 2005). Presence of fractures will, therefore, have an important bearing on recharge potential and the methodology considers this on a subjective basis.

On rare occasions, superficial deposits may increase the vulnerability of groundwater to pollution through focussed recharge draining from the periphery of the deposits and leading to the development of localised karst-like features in carbonate aquifers where runoff from superficial deposits may be acidic (MacDonald et al. 1998).

Attenuation

The processes promoting contaminant attenuation 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. The unsaturated zone, is nevertheless, of importance as it represents the most widespread line of defence against pollution of groundwater (e.g. Rodvang and Simpkins 2001). The key indicators in the unsaturated zone 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. CEC describes the process of attracting cations to a negatively charged surface – usually clay minerals (Appelo and Postma 1993). 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 (Smith and Lerner 2007). 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 contents.

Increased travel time can help the progression of attenuation processes in the Quaternary deposits and allow time for the contaminants to degrade. Therefore, vertical permeability and thickness are also factors to be considered (Foster 1998).

Quaternary domains mapping

Subdivision of the Quaternary has always been problematic. Although an approach to standardisation of mapping is currently being promoted by the BGS (Anon. 2004; McMillan 2005), to date there has not been a standard approach for Great Britain. The traditional stratigraphic subdivision of the Quaternary paid little regard to either the processes under which deposition took place or the lithologies that were deposited (see Figure 3 for 1:625 000 Quaternary map).

Figure 3 Superficial deposits of Great Britain at 1:625 000 scale (copyright BGS).

An alternative approach to classification is to define characteristic regional provinces which can be subdivided into smaller domains (Anon. 2004). The landmass may be divided into two provinces, Glaciated and Non-glaciated based on landscape evolution, geomorphology and the nature and distribution of superficial deposits. The Glaciated province includes upland and lowland Britain and the whole of Northern Ireland. In this province much of the Quaternary record has been removed or modified by subaerial erosion and successive Quaternary glaciations. In the Non-glaciated Province, which lies to the south of the southern limit of the Anglian glaciation, there remains a more complete record of the processes of weathering, erosion and deposition which were driven by climate changes throughout the Quaternary (Anon. 2004).

Within the two main Provinces, eleven domains have been differentiated (Figure 4), based partly on their geomorphology and assemblages of superficial deposits and partly on genetic linkages to the surface processes which formed them. A number of domains have been subdivided into sub-domains (40 in total) to allow for local variations which largely relate to the characteristics of the underlying bedrock, especially in southern England.

Detailed domain assessment has yet to be made for Northern Ireland but a preliminary review identified six domains, the most extensive of which is the Till dominant domain which covers 80 % of the land surface of Northern Ireland. The Till dominant domain (TD) is subdivided into two sub-domains, TD1 and TD2 on the basis of the proportion of till to rock near surface.

Figure 4 Map of the eleven main Quaternary Domains as identified by Anon. (2004). The boundaries of the sub domains are also outlined.

Methodology

Systematic use of additional information and expert knowledge has been applied to reinterpret the existing superficial deposits geological map (Figure 5). Central to the method is a data matrix. Within the matrix, the expert geological knowledge is captured and then re-interpreted by hydrogeologists in terms of recharge potential and attenuation.

Figure 5 An outline of the methodology described in this paper to develop recharge and attenuation potential maps by using expert knowledge to interpret existing superficial geology maps.

The first step is to overlay the eleven Quaternary Domains (see Figure 4) on top of the digital Superficial Deposits Geological Map (the method is scale-independent but for the purposes of a trial it was applied at 1: 625 000 scale). This allows the origin and thus possible nature of, for example, sandy till in the Scottish Highlands and clayey till mapped in East Anglia to be identified as separate entities. 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. 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 matrix describes the recharge and attenuation potential for each geological unit in each domain. This has been done by asking geological experts a series of questions for the deposits in each domain (Table 1). The matrix provides a framework for meaningful and systematic discussion between hydrogeologists and Quaternary geologists. The lithology of glacial till is governed across much of Great Britain by the nature of the bedrock. Glaciers scoured material from bedrock and in general did not move it far before depositing it to form till. In consequence, glacial tills developed on sandstones or coarse crystalline rocks tend to be sandy and permeable, while those developed on mudstones or strata such as the Coal Measures are clay rich and have low permeability. The matrix describes whether the lithology of the till within a particular domain largely reflects the bedrock lithology. If it does, the soil parent map (a simplified geological map based on bedrock lithology) was used to determine recharge potential and attenuation.

Table 1. Framework for discussion between Quaternary geological experts and hydrogeologists

Assessment of recharge potential has been made largely on the basis of the composition and grain size of the deposits, and the likelihood of encountering continuous low permeability layers. 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. The recharge potential is based on the perceived permeability of the deposits. Recharge potential assessments were made as High (H), Medium (M) or Low (L) and a rationale for the assessments provided. 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 Low but the secondary potential where the till is locally more granular may be Medium. At this stage the fracturing has not been considered – but a general likelihood of fracturing can be indicated by the thickness of the deposits (see below). 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.

Assessment of the attenuation capacity has been made by estimating the presence of clay minerals (as a surrogate for cation exchange capacity) and organic material such as peat. The soil cover is not assessed – just the likely clay and organic material within the superficial deposit.

The same primary and secondary classification is also made for attenuation potential although many primary and secondary classifications may be the same. Peat, for example, has High primary and High secondary attenuation potential. 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, but there may also be minor clay layers within that deposit. The predominant (primary) attenuation potential is low, however, where clays are present the (secondary) attenuation potential is high. It is, therefore, the interpreted understanding of the nature and variability of the superficial geological deposit which generates the assessment of recharge and attenuation potential.

Thickness can be important to recharge and attenuation potential in several ways: very thin deposits may be discontinuous, thinner deposits may be fractured throughout whereas increased travel times through a thicker deposit allow more time for degradation of contaminants. Rather than including thickness implicitly within the assessment (as part of the rating) it was left to be included explicitly as a separate layer as required. Five categories were chosen:

- 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 be fractured within the upper 10 m, therefore, where the till is less than 10 m thick there is a higher potential for bypass flow with higher recharge potential and lower attenuation potential.
- 10 - 30 m – fracture and bypass flow can occur but are less likely.
- more than 30 m thick. There is a greater chance of heterogeneity and saturated deposits, including tills, are likely to behave as aquifers in their own right unless the entire sequence is impermeable.

Central to the methodology is the assignment of glacial till lithologies derived from bedrock lithology for various Quaternary Domains. Table 2 shows the attenuation and recharge potential predicted for superficial material 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 are variable within this category. The values are amended wherever the properties of the Sedimentary Mixed bedrock are known. The 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 which reduce the 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 younger deposits in the sequence may bear little relationship to the underlying bedrock.

Table 2 Generic classification of superficial cover based on underlying bedrock lithology (L – Low, M – Medium, H – High)

The rationale for each classification is given in the matrix so that the assessment is transparent. Revisions can be made as local users add their knowledge to the matrix. The classifications and maps can mature and evolve as more data are incorporated.

GIS application of the methodology

The different geological datasets (superficial deposits, Quaternary Domains and bedrock geology) and the data matrix were integrated to create 1: 625 000 recharge and attenuation potential maps using Access™ and ArcGIS™ (version 9.1) (Figure 6). Analyses for Northern Ireland have not been presented because of the preliminary nature of the domains mapping. The shapefile of superficial deposits at 1: 625 000 scale was used as the main layer. Each polygon within this shapefile was attributed with the domain/sub domain into which it falls (Figure 4). Where the superficial polygon intersected more than one domain 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 (Table 2).

Figure 6 Process diagram of GIS application of the methodology.

Once the polygons had been created, recharge and attenuation potential were assigned to each polygon based on the classifications given in the matrix table for all the lithotypes within each domain. Modifications were made where local variations had been noted by the geologist in their assessment, e.g. to distinguish between low permeability clayey silt and clay ‘carse’ type beach deposits and more permeable raised beach deposits, both identified only as coastal deposits on the superficial deposits map. The classification for the underlying bedrock type was used (with exceptions, where known) where the lithotype was till.

The output contains nine categories for both recharge and attenuation potential which show the natural variability displayed by combining the primary and secondary classifications. The nine classes (as primary classification/secondary classification) for both recharge and attenuation potential are: HH, HM, HL, MH, MM, ML, LH, LM and LL.

Each shape file was converted into a grid or raster file of 1 km^2 grid size to provide recharge potential (Figure 7) and attenuation (Figure 8). 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). Two grids are available, one for recharge potential and the other for attenuation potential.

Figure 7 Map of recharge potential using 1:625 000 data. For high recharge potential, more water would be expected to pass through the superficial deposits. Information on the thickness of the deposits is not incorporated.

Figure 8 Map of attenuation potential using 1:625 000 scale data. For high attenuation, negligible contamination is expected through the superficial deposits. Information on drift thickness is not incorporated.

Outputs and Validation

The national 1: 625 000 scale dataset of superficial deposits was used to provide national coverage, albeit at a coarse scale, enough for proof of method. The output is at 1 km grid size. Now that the methodology has been adopted by the Environment Agency larger scale data are being used and a more meaningful output derived, however, the results so far are a guide for comparison with existing perceptions of regional recharge and vulnerability of groundwater. The current output should not, therefore, be applied to support specific environmental judgements. The map outputs have been compared with a number of other datasets including HOST data (Hydrology of Soil Types), the new groundwater vulnerability screening maps for Scotland and the results from a number of regional studies on recharge through superficial deposits. One of the best methods for testing the maps is also to compare the assessment of a particular area with the experience and knowledge of local hydrogeologists.

HOST is a dataset which is based on the 1 x 1 km National Soil Map data together with data from the Centre for Ecology & Hydrology on the behaviour of river catchments (Boorman et al. 1995). There are 29 HOST classes, which describe the dominant pathways of water movement through the soil and substrate. Standard Percentage Runoff (SPR) is given for each HOST soil class. These were used to calculate an estimate of the Standard Percentage Infiltration (SPI) for each HOST class (100% - SPR = SPI).

The calculation of SPR is based on the analysis of flood event data, i.e. collated river flow and rainfall data for storm events. SPR is the percentage of rainfall that causes a short term increase in river flow at the catchment outlet and, therefore, the SPI is not directly comparable with infiltration. Nonetheless the SPI map provides an indication of the general response of different catchments to rainfall. In general there is a broad agreement between the datasets, but areas of till which have Sedimentary Mixed bedrock parent material offer a poor match suggesting that additional local knowledge input is desirable.

Figure 9 shows the results of the statistical comparison with the HOST data for SPI. There is broad agreement i.e. areas with lower percentage SPI have a greater proportion of superficial cover assigned as low recharge potential while those with higher percentage SPI have a greater proportion of high recharge potential superficial cover.

Figure 9 Plot of recharge potential against the HOST Standard Infiltration potential.

The recharge and attenuation potential maps were also compared with the vulnerability screening maps of superficial deposits determined for Scotland (Ó Dochartaigh et al. 2005). The map of attenuation potential shows a similar pattern to the Scottish vulnerability screening map for the superficial deposits – low and medium values are prevalent over much of Scotland except where peat or other clay/organic rich materials occur. There is particularly good agreement with the lower vulnerability rating. There is also good agreement between the recharge potential map and the superficial aquifer productivity maps generated for Scotland using pumping test data, HOST data and expert knowledge (MacDonald et al. 2005).

The maps have also been examined against more detailed recharge studies reported 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). 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} (Soley and Heathcote, 1998), maybe as low as 5 mm a^{-1} (Marks et al. 2004). The recharge potential map (Figure 7) shows that the Low Medium recharge potential classification is consistent with these studies. Similarly in the Cheshire Basin, recharge to the unconfined Sherwood Sandstone aquifer has been estimated at approximately 350 mm a^{-1}, but where till cover is present, recharge to the underlying aquifer is only about 52 mm a^{-1} (Vines 1984). These variations are reflected by recharge potential classifications for the till covered areas of LM and LL and for the areas where till is absent recharge potential is classed as HM.

Initial testing of the output data layers against national nitrate concentrations in groundwater for England and Wales (Johnson 2006) shows that the GIS output reflects the expected influence of poorly permeable superficial deposits on nitrate fate and transport. However, the correlation is weak in some places largely due to insufficient local detail.

The nitrate comparison indicated that key properties of the poorly permeable superficial deposits that are required to predict nitrate concentration in groundwater are the overall coverage of the cover material (expressed as percentage cover per km^2) and its thickness, e.g. >10 m superficial cover, both of which are available as digital datasets held by BGS. The importance of these parameters varies according to the domain under consideration, e.g. depth of superficial deposits 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 superficial deposits is to be improved significantly.

Discussion

The methodology enables rapid assessment of the hydrogeological properties of superficial deposits on a national/regional scale. Use of the 1: 625 000 scale datasets provides a broad overview that is sufficient for proof of method. Now that the methodology is established it is intended that it should 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.

Inevitably there are a number of constraints imposed by the methodology. These include scale issues and use of classifications at 1: 625 000 scale which inevitably simplifies otherwise heterogeneous systems. However, the heterogeneity is captured by the primary and secondary estimates of recharge and attenuation potential, i.e. a highly variable 3D deposit is classed as HL, while homogenous deposits may be HH. In addition it has only been possible to capture some of the available three dimensional data in the matrix, for example, for the areas of thick superficial deposits in the Cheshire Basin. Application at a larger scale will enable the characterisation of the 3D data in more detail.

There are also mapping issues, for example, some areas of raised beach/estuarine deposits, particularly around the Wash, have been mapped as alluvium on the 1: 625 000 superficial geology map. For many areas moraine and till have not been subdivided and variations in the morphology and composition of these deposits have implications for permeability and attenuation potential. The matrix methodology is helpful here, since explanations can be made in the matrix by local experts so that these mapping issues can be overcome by adjusting classifications manually.

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

The coarse scale used in the trial does not allow recharge and attenuation properties to be assessed confidently at local, or even small catchment scale. However, the methodology is essentially scale independent, and can be readily adapted to apply the most commonly used geological dataset at 1: 50 000 scale, although it should be considered that the quality and precise type of mapping varies from one area to another at that scale.

The methodology represents a means of capturing existing and developing geological knowledge and extracting relevant elements to improve conceptual hydrogeological understanding. The importance of this interaction between hydrogeologists and mapping geologists who have an extensive understanding of the nature and variability of superficial deposits in a particular area cannot be over-estimated. Further development of the associated GIS and incorporation of more detailed data will allow application at local catchment/groundwater body scale. In addition, the GIS could be used as an ongoing archive of local understanding and knowledge, the layers and datasets developed complementing and enhancing existing vulnerability maps and water resource models.

Although there are a number of additional datasets available, outputs need to be evaluated before they are formally incorporated into the assessment procedure. The initial testing provides a baseline from which to judge the relative improvement in outputs due to the inclusion of any new dataset into the method. New data sets could include: soils data, land drainage data, rock head elevation, nitrate monitoring and loading data, and seasonal variability of loading.

Conclusions

Superficial deposits have been evaluated using Quaternary domain classifications to provide improved geological and hydrogeological characterisation. Geological and hydrogeological data have been integrated with expert local geological and hydrogeological knowledge using a data matrix to provide improved assessment of the impact of superficial deposits on groundwater vulnerability. New groundwater vulnerability maps of recharge potential and attenuation potential within superficial cover material over bedrock aquifers have been developed at 1:625 000 scale.

A qualitative assessment of the results compares favourably with existing recharge studies and regional hydrogeological knowledge. Favourable comparison with data from HOST provides a quantitative assessment of the method. 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 is consistently robust.

As the methodology is scale independent it is recommended that it is applied at 1: 50 000 scale subject to data licensing issues. This will enable more detailed characterisation and assessment of groundwater vulnerability at a local level. Rescaling will also provide an opportunity to add additional components to the methodology as required.

Although the method is constrained by the availability of data and local knowledge, one of its strengths is that it allows new information to be incorporated at a later date so that assessments are improved and validated. This will enable a flexible, holistic and dynamic approach to groundwater vulnerability assessments and ensure that they are based on the best available information. The methodology is currently being trialled by the Environment Agency.

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References

Anon. 2004. A guide to Quaternary mapping in the United Kingdom. British Geological Survey, Keyworth.

Appelo, C.A.J. and Postma, D. 1993. Geochemistry, groundwater and pollution. Balkema, Rotterdam.

Ball, D.F., McConvey, P. & Campbell, E. 2005. A groundwater vulnerability screening methodology for Northern Ireland. British Geological Survey Commissioned Report CR/05/103N, 41 pp.

Boorman, D.B., Hollis, J.M. & Lilly, A. 1995. Hydrology of Soil Types: a hydrologically based classification of the soils of the UK. Institute of Hydrology Report No. 126 (137 pp).

Council of European Communities. 2000 Directive establishing a framework for Community action in the field of water policy (2000/60/EC). Official Journal L327/1, 23 October 2000.

Cuthbert, M. 2005. Hydraulic processes controlling recharge through glacial drift. PhD Thesis, University of Birmingham, Birmingham, UK.

Daly, D. & Warren, W.P. 1998. Mapping groundwater vulnerability: the Irish perspective. In: N.S. Robins (Ed) Groundwater Pollution, Aquifer Recharge and Vulnerability. Geological Society Special Publications, 130, 179-190.

Fitzsimons, V.P. and Misstear, B.D.R. 2006. Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland. Hydrogeology Journal 14: 548-561

Foster, S.S.D. 1998. Groundwater recharge and pollution vulnerability of British aquifers: a critical overview. In: N.S. Robins (Ed) Groundwater Pollution, Aquifer Recharge and Vulnerability. Geological Society Special Publications, 130, 7-22.

Fredericia, J. 1990. Saturated hydraulic conductivity of clayey tills and the role of fractures. *Nordic Hydrology*, **21**: 119-132.

Gerber, R.E., Boyce, J.I. & Howard, K.W.F. 2001. Evaluation of heterogeneity and field-scale groundwater flow regime in a leaky till aquitard. Hydrogeology Journal, 9: 1, 60-78.

Johnson, D. 2006. Report on the use of GeoSure and WFD34 for the integrated assessment of nitrate project. Environment Agency Internal Technical Report

van der Kamp, G. 2001. Methods for determining the in situ hydraulic conductivity of shallow aquitards – an overview. Hydrogeology Journal, 9: 1, 5-16.

Keller, C.K., van der Kamp, G. & Cherry, J.A. 1988. Hydrogeology of two Saskatchewan tills, 1. Fractures, bulk permeability and spatial variability of downward flow. *Journal of Hydrology*, **101**: 97-121.

Klinck, B.A., Hopson, P.N., Morigi, A.N., Bloodworth, A.J., Inglethorpe, S.D.J., Entwistle, D.C. & Wealthall, G.P. 1997. *The hydrogeological classification of superficial clay: the hydrogeological characterisation of glacial Till in East Anglia*. Environment Agency. R&D Technical Report W28.

MacDonald, A.M., Brewerton, L.J. and Allen, D.J. 1998. Rapid groundwater flow and karst-type behaviour in the Chalk of southern England. In: Robins N S (ed.) Groundwater Pollution, Aquifer Recharge and Vulnerability. *Geological Society, London Special Publications*, **130**: 95-106

MacDonald, A.M., Robins, N.S., Ball, D.F. and Ó Dochartaigh, B.É. 2005. An overview of groundwater in Scotland. Scottish Journal of Geology, 41: 3-11.

Marks, R.J., Lawrence, A.R., Whitehead, E.J., Cobbing, J.E., Mansour, M.M., Darling, W.G. & Hughes, A.G. 2004. Chalk recharge beneath thick till deposits in East Anglia. British Geological Survey Internal Report IR/04/179.

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 and Hydrogeology, 33: 4, 301-323.

McMillan, A.A. 2005 A provisional Quaternary and Neogene lithostratigraphical framework for Great Britain. Netherlands Journal of Geosciences, 84-2: 87-107.

Misstear, B.D. & Daly, D. 2000. Groundwater Protection in a Celtic region: the Irish example. In: N.S. Robins and B.D.R. Misstear, (Eds) Groundwater in the Celtic Regions: Studies in Hard Rock and Quaternary Hydrogeology. Geological Society Special Publications, 182, 53-65.

Misstear, B.D.R., Brown, L. and Hunter Williams, N. 2008. Groundwater recharge to a fractured limestone aquifer overlain by glacial till in County Monaghan, Ireland. Quarterly Journal of Engineering Geology and Hydrogeology, 41**:** 465-476.

Misstear, B. D. R., Brown, L. and Daly, D. 2009. A methodology for making initial estimates of groundwater recharge from groundwater vulnerability mapping. Hydrogeology Journal, 17-2: 275-285.

Ó Dochartaigh, B.É., Ball, D.F., MacDonald, A.M., Lilly, A., Fitzsimons, V., del Rio, M. & Auton, C.A. 2005. Mapping groundwater vulnerability in Scotland: a new approach for the Water Framework Directive. Scottish Journal of Geology, 41: 1, 21-30.

Palmer, R.C., Holman, I.P., Robins, N.S. & Lewis, M.A. 1995. Guide to Groundwater Vulnerability Mapping in England and Wales. HMSO, London.

Robins, N.S., Adams, B., Foster, S.S.D. & Palmer, R.C. 1994. Groundwater vulnerability mapping: the British perspective. Hydrogéologie, 3, 35-42.

Rodvang, S.J. & Simpkins, W.W. 2001. Agricultural contaminants in Quaternary aquitards: a review of occurrence and fate in North America. Hydrogeology Journal, 9: 1, 44-59.

Shand, P., Edmunds, W.M., Lawrence, A.R., Smedley, P.L. & Burke, S. 2007. The natural (baseline) quality of groundwater in England and Wales. British Geological Survey Research Report RR/07/06.

Rushton, K.R. 2005. Estimating recharge for British aquifers. Journal of the Chartered Institution of Water and Environmental Management, 19: 2, 115-124.

Smith, J.W.N. & Lerner, D.N. 2007. A framework for rapidly assessing the pollutant retardation capacity of aquifers and sediments. Quarterly Journal of Engineering Geology & Hydrogeology, 40, 137-146.

Soley, R.W.N. & Heathcote, J.A. 1998. Recharge through the drift: a study of contrasting Chalk catchments near Redgrave Fen, UK. IN: N.S. Robins (Editor) Groundwater Pollution, Aquifer Recharge and Vulnerability. Geological Society, London, Special Publications, 130, 129-141.

Vines, K. 1984. Drift recharge. North West Water Authority. Hydrogeological Report 145.

Figure 1 The available resources for improving the hydrogeological characterisation of the superficial deposits.

Figure 2 Factors influencing recharge and attenuation in the sub-surface. The methodology described in this paper is concerned only with the processes in the superficial deposits.

Figure 3 Superficial deposits of Great Britian at 1:625 000 scale (copyright BGS).

Figure 4 Map of the eleven main Quaternary Domains as identified by QMT (2004). The boundaries of the sub domains are also outlined.

Figure 5 An outline of the methodology described in this paper to develop recharge and attenuation potential maps by using expert knowledge to interpret existing superficial geology maps.

Figure 6 Process diagram of GIS application of the methodology.

Figure 7 Map of recharge potential using 1:625 000 data. For high recharge potential, more water would be expected to pass through the superficial deposits. Information on the thickness of the deposits is not incorporated.

Figure 8 Map of attenuation potential using 1:625 000 scale data. For high attenuation, then negligible contamination is expected though the superficial deposits. Information on drift thickness is not incorporated.

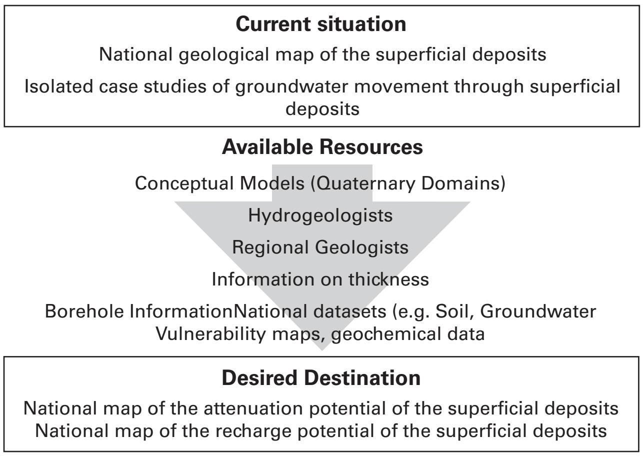
Figure 9 Plot of recharge potential against the HOST Standard Infiltration potential.

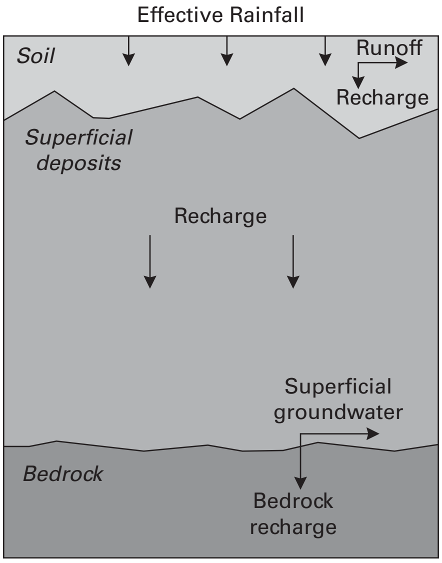
Table 1 Framework for discussion between Quaternary geological experts and hydrogeologists

Table 2 Generic bedrock classification (L – Low, M – Medium, H – High)

Matrix fields to be completed on each mapped superficial deposit within each domain type	Assessor
General Description	Geological expert
Map issues	
Sub-domains	
General Thickness	
Architecture	
Lithology	
Clay content	
Organic content	
Horizontal permeability	
Vertical permeability	Hydrogeologist
Primary adsorption potential	
Secondary adsorption potential	
Rationale for adsorption potential	
Primary recharge potential	
Secondary recharge potential	
Rationale for recharge rating	

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
Metamorphic	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


Current situation
National geological map of the superficial deposits
Isolated case studies of groundwater movement through superficial deposits
Available Resources
Conceptual Models (Quaternary Domains)
Hydrogeologists
Regional Geologists
Information on thickness
Borehole InformationNational datasets (e.g. Soil, Groundwater Vulnerability maps, geochemical data
Desired Destination
National map of the attenuation potential of the superficial deposits
National map of the recharge potential of the superficial deposits



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 presence of fractures can also increase recharge potential.

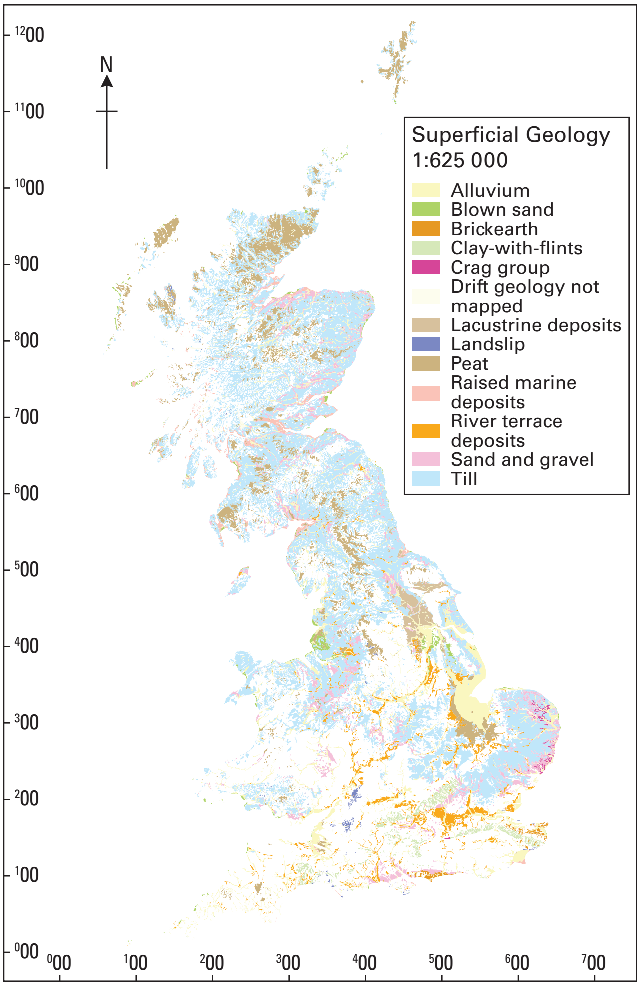
Actual bedrock recharge depends partly on the properties of the bedrock. If the bedrock has low permeability and/or low storage, and cannot physically accept all the recharge, excess recharge may flow horizontally through the superficial deposits.

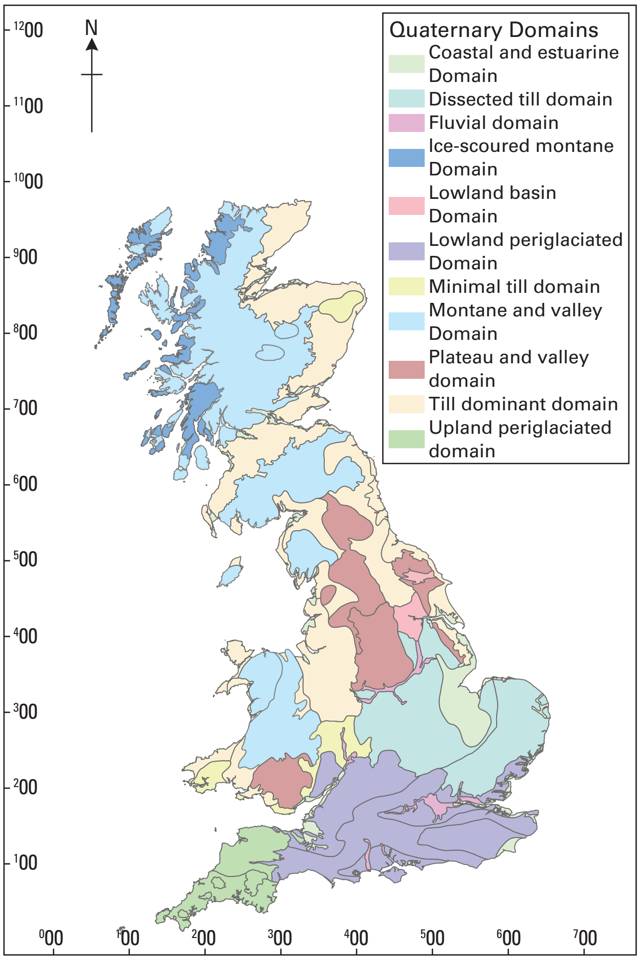
Attenuation

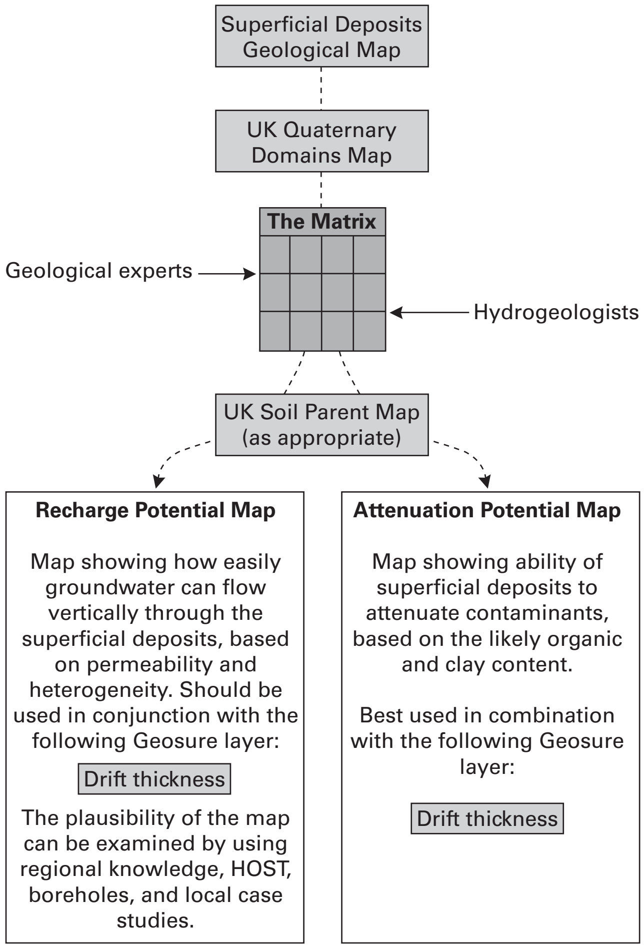
Much of the attenuation of contaminants occurs within the soil. In this biologically active zone contaminants can be subject to a range of chemical reactions, sorbed onto clays, or taken up by organic material.

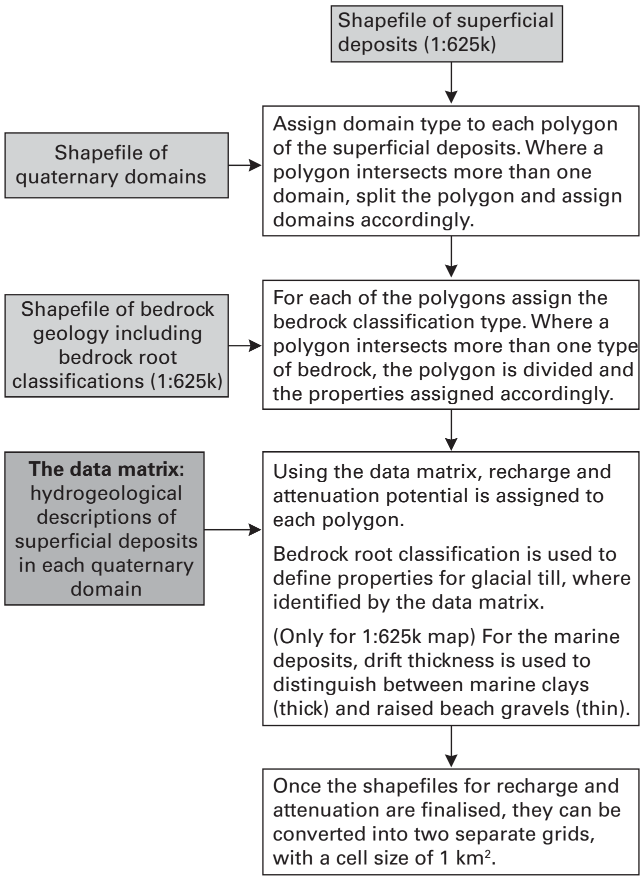
Contaminants can be attenuated in the superficial deposits, by the presence of clay or organic material. The travel time is also important as this will give more time for attenuation to occur.

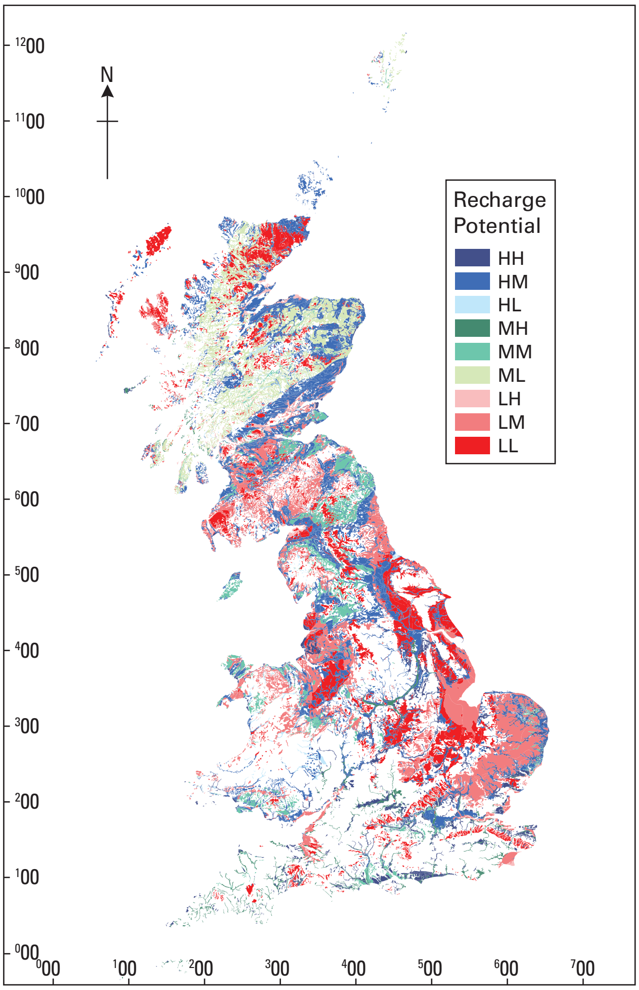
Some attenuation of contaminants can occur, but within the bedrock, dilution is generally the most significant factor.


Superficial Geology
1:625 000
Alluvium
Blown sand
Brickearth
Clay-with-flints
Crag group
Drift geology not mapped
Lacustrine deposits
Landslip
Peat
Raised marine deposits
River terrace deposits
Sand and gravel
Till
N
1200
1100
1000
900
800
700
600
500
400
300
200
100
000
000
100
200
300
400
500
600
700


Quaternary Domains
Coastal and estuarine Domain
Dissected till domain
Fluvial domain
Ice-scoured montane Domain
Lowland basin Domain
Lowland periglaciated Domain
Minimal till domain
Montane and valley Domain
Plateau and valley domain
Till dominant domain
Upland periglaciated domain
N
1200
1100
1000
900
800
700
600
500
400
300
200
100
000
100
200
300
400
500
600
700


Superficial Deposits Geological Map
UK Quaternary Domains Map
The Matrix
Geological experts
Hydrogeologists
UK Soil Parent Map (as appropriate)
Recharge Potential Map
Map showing how easily groundwater can flow vertically through the superficial deposits, based on permeability and heterogeneity. Should be used in conjunction with the following Geosure layer:
Drift thickness
The plausibility of the map can be examined by using regional knowledge, HOST, boreholes, and local case studies.
Attenuation Potential Map
Map showing ability of superficial deposits to attenuate contaminants, based on the likely organic and clay content.
Best used in combination with the following Geosure layer:
Drift thickness


Shapefile of superficial deposits (1:625k)
Shapefile of quaternary domains
Assign domain type to each polygon of the superficial deposits. Where a polygon intersects more than one domain, split the polygon and assign domains accordingly.
Shapefile of bedrock geology including bedrock root classifications (1:625k)
For each of the polygons assign the bedrock classification type. Where a polygon intersects more than one type of bedrock, the polygon is divided and the properties assigned accordingly.
The data matrix: hydrogeological descriptions of superficial deposits in each quaternary domain
Using the data matrix, recharge and attenuation potential is assigned to each polygon.
Bedrock root classification is used to define properties for glacial till, where identified by the data matrix.
(Only for 1:625k map) For the marine deposits, drift thickness is used to distinguish between marine clays (thick) and raised beach gravels (thin).
Once the shapefiles for recharge and attenuation are finalised, they can be converted into two separate grids, with a cell size of 1 km².



Recharge Potential
HH
HM
HL
MH
MM
ML
LH
LM
LL
N
1200
1100
1000
900
800
700
600
500
400
300
200
100
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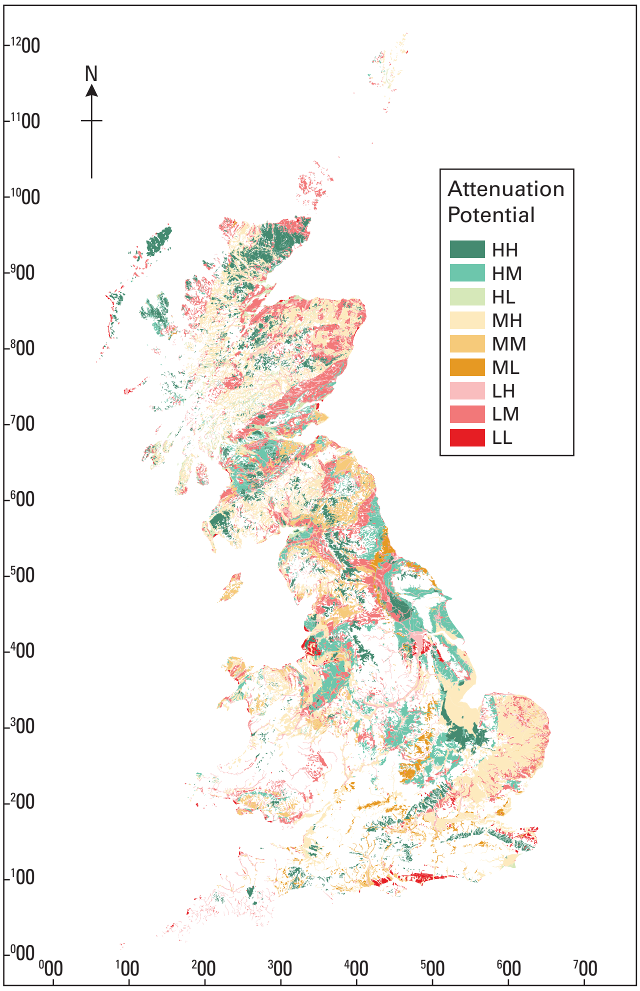
100
200
300
400
500
600
700



N
Attenuation Potential
HH
HM
HL
MH
MM
ML
LH
LM
LL
1200
1100
1000
900
800
700
600
500
400
300
200
100
000
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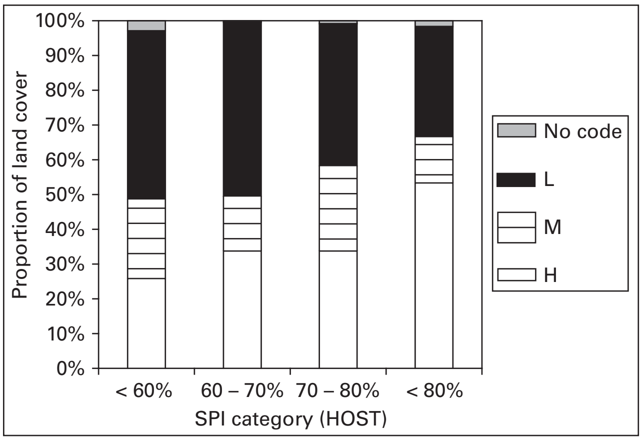
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Proportion of land cover
< 60%
60 – 70%
70 – 80%
< 80%
SPI category (HOST)
No code
L
M
H