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A classification scheme for pollutant attenuation potential at the groundwater – surface water interface

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Steve Killeen

Head of Science

Executive summary

This report describes a classification scheme for the pollutant attenuation capacity of the sediments at the groundwater–surface water interface, or hyporheic zone (HZ). The interface between aquifers and rivers is a critical transitional zone that can attenuate the migration of certain pollutants as they move across it. Understanding processes that occur at this interface is important for environment managers who need to manage groundwater and surface water environments in a holistic manner, as required by the Water Framework Directive (WFD).

The first objective of the project described in this report was to develop a classification (or typology) of the hyporheic zones found within WFD-defined surface water bodies (SWBs) within England and Wales. The classification scheme was specifically designed to help the Environment Agency achieve two key goals:

- To identify examples of the different types of hyporheic zone, in order to aid design of future research projects that will investigate the processes occurring within different types of hyporheic zone.
- To give information on the nature of hyporheic zones across England and Wales, in order to provide data useful for the 'further characterisation' of water bodies (under the WFD). In particular, to help understand the likely relative significance of water exchange and pollutant attenuation processes occurring at the groundwater–surface water interface in different water bodies.

For this part of the project, the definition of the hyporheic zone is taken as 'the water-saturated transitional zone between surface water and groundwater' (after Smith 2005), in which there is exchange of water between river and the subsurface. The hyporheic zone classification is based on a number of properties or 'axes': sediment thickness, sediment permeability, subsurface permeability and geochemistry). An additional two axes are used in the derivation of these four (stream power and sediment supply). The geochemistry axis is itself composed of three separate attenuation criteria that describe the cation exchange capacity, organic carbon content and acid buffering capacity of sediments.

The hyporheic zone classification for each SWB consists of a collection of classes (low, medium or high) for each of the above axes. Each axis class ascribed to each SWB was based on information derived from available national datasets held by the Environment Agency or the Centre for Ecology and Hydrology (CEH). A summary of the method used is given within Appendix E. While the resulting classification is represented by a single class on each of the defined axes, the underlying data used to define these classes has been retained so that the data may be used in future if further analysis or reclassification (in the light of new data) is required.

The second part of the project turned the classification into a compendium of the hyporheic zone classes for all SWBs in England and Wales. The resulting compendium represents a first approximation of the likely nature of the hyporheic zone within any of the defined SWBs, based on available data. While two axes (sediment supply and stream power) were used only for determination of other axes, and thus are not explicitly represented within the final classification scheme, the total number of possible axis class permutations was still large. For example, there were potentially 81 different types of hyporheic zone (4 axes of 3 classes), though in practice not all of these groupings will be populated.

Validation work using field data collected within the River Severn catchment showed a good correlation with the nature of the hyporheic zone predicted by the classification. However, it is suggested that further field testing is needed to validate the compendium

over a wider range of river types. It is envisaged that such work may take place simultaneously with sub-SWB-scale investigations to assess the variability of habitat, geomorphology and additionally the nature of the hyporheic zone within a SWB. Such investigation may incorporate the use of locally or regionally available data (as opposed to national) to explain the reasons for any such variability.

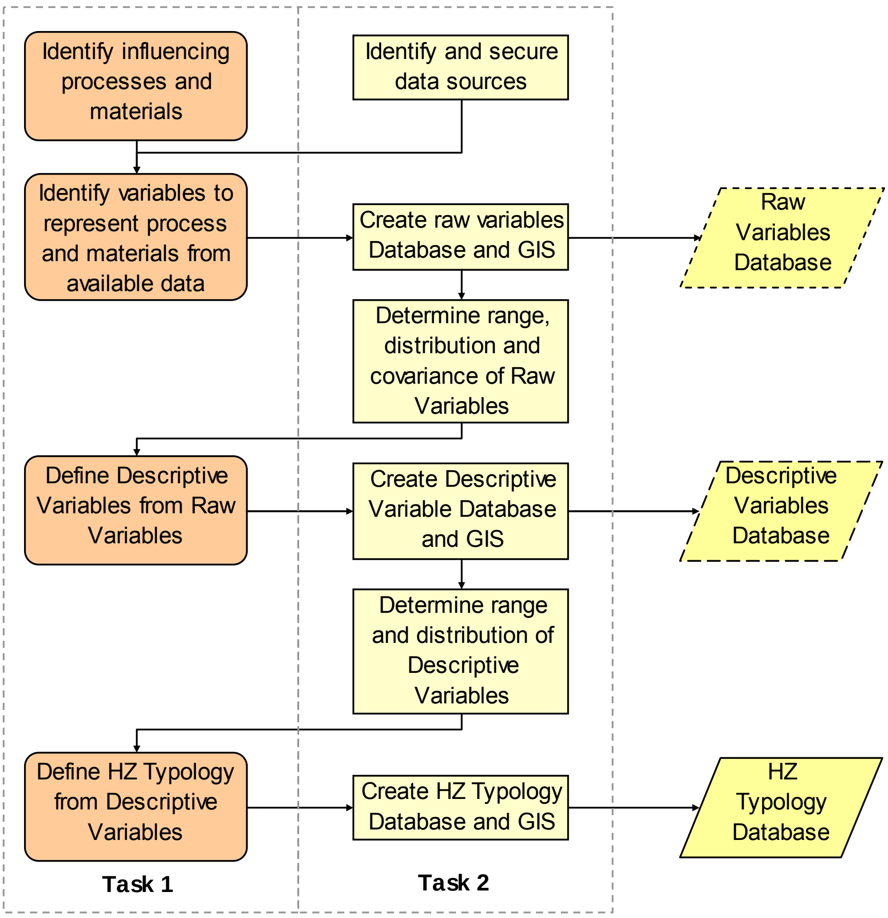
Contents

1 Introduction

The objective of this project was to develop a classification scheme (or typology) of the pollutant attenuation capacity of river-bed sediments and hyporheic zones (HZ) found in rivers within England and Wales. The typology aims to distinguish between different HZ types (based on the pollutant attenuation capacity for selected pollutants). Subsequently, the classification scheme was used to prepare a compendium of HZ types for the whole of England and Wales (based on Water Framework Directive [WFD] surface water body scale). The compendium consists of GIS files, which describe the nature and spatial distribution of HZ classes across England and Wales.

The development of a classification scheme of the pollutant attenuation capacity of HZs for WFD-defined water bodies in England and Wales is based on an initial identification of processes and materials that may influence the nature of the HZ found within any water body. Since no national dataset exists that describes the HZ in the UK, it is necessary to infer the properties of water body HZs from available data, through the identification of the magnitude and nature of influencing processes and materials respectively. Figure 1.1 illustrates the stages followed in the development of the classification scheme and its implementation in a compendium of HZs across England and Wales. The first step was to identify the processes and materials that are most likely to affect the nature of the HZ. For this, a comprehensive literature review was performed (see Section 2). Simultaneously, potential data sources for deriving HZ properties were interrogated, and information relating to database format, scale and compatibility were determined (Table 1, Appendix A).

Figure 1.1 Schematic diagram of the decision-making (Task 1) and data manipulation (Task 2) processes. Also shown are intermediate (raw and descriptive) variable, and final typology databases



It can be seen that the development of the HZ typology is an iterative process between theoretical development and data interrogation (as opposed to the originally envisaged method of predefining a typology and then fitting over the available data). This approach is designed to create typology classes that give a better representation and definition to the more frequently occurring HZ types (e.g. lowland, permeable-bed water bodies).

The method employed within the project has evolved from the original tender document. Instead of first defining the typologies within respect to environmental variables and then implementing within a database using available datasets, the available data was first investigated in order to determine the distribution and variability of such parameters across England and Wales. This approach was used in order to prevent the creation of redundant HZ types that have none or very few members within the UK water bodies. The environmental variables used to define each HZ type (as described in Appendix A represent processes identified as having an influence on the nature and extent of the HZ at any location (through reference to related literature and expert knowledge).

A tiered approach to the use of data in the creation of the classification has been adopted. In the first instance, each HZ type is defined by information derived from national datasets (Tier 1). The typology is then tested against additional local-scale data (e.g. River Habitat Survey data), in order to place confidence levels on the description and accuracy of the defined HZ type. This and other local-scale data can be further used to create a second, locally scaled typology, if required in the future (Tier 2).

Of the 7816 Environment Agency-defined surface water body (SWB) polygons (Figure 1.2), 6280 have associated WFD river typologies, the remaining 1536 being defined as coastal SWBs. It was the task of this project to define the nature of the HZs within the 6280 water bodies for which river typologies have already been assigned.

A large amount of information for the identified WFD SWBs was derived from the Flood Estimation Handbook (FEH) and Low Flows 2000 (LF2000) datasets. In order to retrieve adequate spatial coverage from these datasets, accurate X and Y co-ordinates of catchment outlet points were required. Some additional work was required within this project to ensure accurate estimates of these co-ordinates (see Appendix C).

1.1 Definition of hyporheic zone classification axes

In order to assign an HZ class to any WFD-defined SWB within England and Wales, each HZ class is described by a number of properties or 'classification axes'. The initial classification as defined by the Environment Agency included just three axes: sediment supply, stream power and geochemistry. To allow greater definition within each HZ class, however, the *sediment* axis will include likely thickness of sediments, and their geochemical and physical (hydrological) properties. In a similar manner, the *geology* axis is represented by permeability and geochemistry of underlying bedrock. The *power* axis is now used to describe the average stream power regime of the SWB. The resulting HZ typology is thus composed of the following axes:

- Sediment supply
- Stream power
- Sediment thickness
- Sediment permeability
- Subsurface permeability
- Sediment geochemistry.

Figure 1.2 The 7816 Environment Agency SWB polygons, of which 6280 have been assigned WFD river typologies

In order to define class boundaries within each axis (initially described as high, moderate and low) the distribution of variables describing each of the axes (e.g. sediment erosion and transport), or a specific dataset (e.g. geology data), was determined for all SWB catchments (total of 6280). From these variables a set of procedures (or rules) were then developed to define each axis range and class.

Figure 1.3 illustrates the conceptual model of the HZ used within creation of the compendium. The figure represents the three main layers that are represented by the above axes; however, it is possible that within some SWBs only two or even one of these layers will be present. The top layer (transported fine sediments) represents clay, silt and sand particles that have been transported from catchment or channel surfaces into the river channel by erosive processes. The thickness and permeability of this layer will depend on both the amount of sediment transported to the river channel and the average power of the SWB. The second layer (coarse sediments/drift) represents a layer of predominantly coarser sediments (gravel, pebbles, cobbles etc.), that are derived from largely *in situ* sediments sourced from pre-existing drift deposits within the channel network or from the longer term erosion of the bedrock geology. Again, the permeability of this layer will be related to the range and size of sediments found within these deposits. For this reason the amount of smaller sediments within this layer will also be considered. The third layer represents underlying bedrock geology. In particular, the geochemical properties of this layer are used to define the geochemical properties of the above two layers if they are present. The permeability of this underlying layer will also be represented.

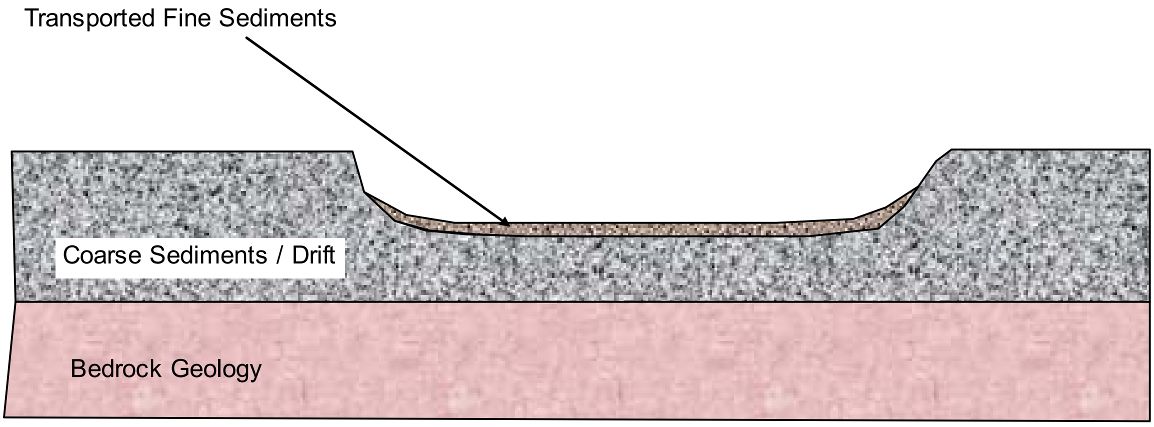


Figure 1.3 Simple conceptual model used during the creation of the HZ classification scheme

2 Controlling factors on the hyporheic zone

Identification of processes and materials that influence the structure, permeability, chemistry and extent of the HZ was initially made with respect to the categories of geology, sediment supply and stream power (following an initial proposal by the Environment Agency for a simple three-axis classification scheme).

Geological influences include both bedrock and superficial geology distributions. In addition to the WFD-related typologies of calcareous, siliceous and organic rocks, properties of cation exchange capacity (CEC), fraction of organic carbon (f_{OC}) and carbonate content are described for each geological substrate.

Stream power and sediment supply influences on the HZ have been addressed as 'in-channel' and 'out-of-channel' influences. 'In-channel' influences refer to the channel structure, dimensions and processes that control whether the water body is an erosive, transporting or depositing system, and the size and nature of the sediments that are likely to occur there. 'Out-of-channel' influences refer to the nature, quantity and type of upstream sediment sources, and process that will affect transfer of sediments into the water body network.

The following sections describe the processes and properties (of sediment, catchments and their rivers) that were considered significant in controlling the properties of sediments at the groundwater–surface water interface.

2.1 Sediment geochemistry

Few conceptual models exist that relate geology and mineral type to derived fluvial sediments and their hydraulic and geochemical properties. A general model of HZ physical and chemical properties with respect to a range of different geologies and morphological environments is therefore extremely useful. For this purpose, the geochemical composition of sediments found within the HZ needed to be a reflection of underlying and upstream geologies, the existence of drift, and other contributing sediment sources. The generic geology types defined by the WFD typologies of calcareous, siliceous and organic provided a useful starting point to a geology-based classification system.

2.1.1 Sediment physical characteristics and permeability

Lithological structure affects the porosity of derived sediments, which in turn affects ecological diversity (Creuzé des Châtelliers *et al.* 1994; Gayraud and Philippe 2003; Olsen and Townsend 2003). Weathering produces a combination of rock fragments, mineral grains and residual material. New materials may then be produced as mobile products transfer into and out of the weathering zone. Denitrification and biodegradation rates may be indirectly affected by grain size distributions (Albrechtsen *et al.* 1997), highly permeable sediment with lower clay contents not favouring denitrification. Grain size controls on denitrification are related to restricted import of oxygen from the surface, and to increased residence time within the lower permeability sediments that permit a greater consumption of oxygen and nitrate by degradation of organic matter present. British Geological Survey (BGS) 1:625,000 bedrock and drift geology maps can be used in combination with BGS descriptions of UK aquifers and WFD groundwater typology data in order to broadly define underlying strata permeability.

2.2 Sediment supply

A number of fluvial geomorphology studies have investigated the relationship between form, process and sediment transfer. However, few of these studies have provided universal understanding of the relationship between form and process. This is because the process by which a river exerts power to erode sediment is affected by complex feedbacks between form and process that allow the river to adjust over time. River channel and floodplain forms are affected by processes that occur over a wide range of spatial and temporal scales. This implies an ability to absorb change and assume an equilibrium form (Knighton 1984). Thus, present channel form may be the product of past as well as present processes. Rivers affected during and immediately after the last glaciation may have retained features from that time (Wharton 1995a, 1995b). These features may include large quantities of gravel in the current-day channel or floodplain. For this reason the sediment supply axis of the HZ compendium has been designed to include historical (i.e. glacial and post-glacial) influences. However, in their present state fluvial fine sediment transport systems in the UK are generally supply limited (Walling and Webb 1987; Newson and Sear 1997). Therefore, it is the conditions that make excessive fine sediment available for transport that are considered of major importance.

2.2.1 In-channel influences on sediment supply

Glacial outwash legacy (in-channel) and glacial legacy (out-of-channel)

The location of present-day river channels and floodplains in relation to glacial activity and post-glacial events is an important factor in the present distribution and condition of the HZ. This is because floodplain models are only valid for defined channel and vegetation conditions and must be specified/determined from palaeoenvironmental conditions (Brown 1997). Large quantities of gravel sediments were made available for fluvial transportation across the UK as a result of glacial outwash events following periods of glaciation. It has been estimated that during the deglacial phase of a glacial cycle rates of sediment yield may increase by approximately ten times that of the geological norm, and then rapidly subside (Church and Ryder 1972). Outwash plains and spreads of gravel along valley floors provide large quantities of material to be worked by fluvial processes (Maizels 1983). In many river valleys large quantities of sediment made available through glaciation have been reworked during the Holocene. For example, Passmore and Macklin (2000) showed that, for a reach of the River South Tyne, few parts of the post-glacial valley floor have escaped channel reworking or floodplain sedimentation over the past 3000 years. This has created a floodplain associated with a coarse-grained migratory bed and bar assemblages associated with episodic braiding and bank erosion. At this site fine-grained sediment units deposited by overbank flows were less prevalent. Another example of a detailed investigation showing how climatic changes during and following the close of the Late glacial Interstadial (11.3–11 ka BP) caused a period of increase erosion followed by aggradation is given for the Gipping Valley in south-east England (Rose *et al*. 1980).

Bed material and bank material (in-channel)

Groundwater–surface water interactions will be affected by the composition of material on the river bed (Dole-Olivier 1998; Gayraud and Philippe 2003). This is one of the factors that we are trying to assess for WFD water bodies. Observations of bed sediment material can be used to determine the nature of the HZ. It should be noted that non-intrusive observations of bed material (i.e. looking at it) may be influenced by the time at which the observations were taken. For example, observation of fine sediments will be more likely during periods of low flow. As a result, observations of bank material may be a more reliable indication of the sediments contained within the HZ.

Bank vegetation

Coverage of bank vegetation can have a significant affect on supply of fine and gravel sediments to the channel (Millar and Quick 1993). For example, bank erosion was measured at 91 stream banks located in 15 Danish rural first and second order streams by Laubel *et al*. (2003). They found that bank erosion rate over a 2-year period was significantly related to a number of site-specific characteristics, including bank angle, bank vegetation cover, and estimated stream power.

River restoration

There have been many attempts to rehabilitate rivers that have been substantially modified in order to aid land drainage, protect urban centres from flooding and support the intensification of agriculture. River rehabilitation strategies often involve the addition of gravel. Gravel may be added to restore channel bed morphological features (e.g. to create artificial riffles, Harrison *et al*. 2004) or to protect against erosion (Brookes 2005). The addition of gravel will have local affects on the porosity of the river bed, and on bedform-generated stream–subsurface exchange.

Channel bank stability

Channel banks can be a very important source of fine sediment. They can supply more than 50% of a catchment's sediment output (e.g. Grimshaw and Lewin 1980; Duysings 1986, 1987). However, they may be of minor importance in chalk streams where high magnitude flow events rarely occur and channel cross-sections are typically wide and shallow (Walling *et al.* 2006). Some report a downstream increase (Hooke 1980; Hasegawa 1989). Others report a middle reach maximum (Lewin 1987; Prestegaard 1988).

Position in long profile

The storage of fine sediments on channel beds has been observed to increase in a downstream direction in many river systems (e.g. Walling *et al*. 1996, 2006; Gomez *et al*. 2001). In upland source areas river channels are likely to be controlled by either coarse glacial deposits or bedrock (Newson and Leeks 1987). Coarse sediment deposition often occurs in piedmont channels as in a downstream direction discharge usually tends to increase at a slower rate than slope decreases (Newson 1981; Newson and Leeks 1987). In downstream environments fine sediments are likely to be abundant because of additional local sources and their preferential transport from more distal upstream weathering/erosion sources. Furthermore, the channel is likely to be reworking alluvial floodplain deposits (unconsolidated bed).

Reservoirs

Reservoirs and lakes are known to trap both fine and coarse sediment (Meade and Parker 1985; Vörösmarty *et al*. 2003). For example, Gilvear (2004) showed how impoundment of the River Spey, Scotland, caused significant spatial and temporal patterns of adjustment in terms of river morphology; see further comments on the affects of dams on power to erode in Section 2.2.4 below.

Dredging, bank protection and other engineered structures

Gravel and fines sediment may be removed from a river channel to increase its capacity to convey flood waters and to permit river navigation. Dredging will reduce the thickness of the HZ, while the act of dredging may release fine sediments. Bank protection is used to reduce river-bank erosion. Bank protection can reduce inputs of fine sediments by reducing bank erosion. Engineering structures such as weirs and sluices can have the affect of trapping fine sediment (Bond 2004).

Tributary inputs

Tributary inputs are sources of fine sediment, especially where an unregulated tributary flows into a regulated river. The regulated river, with a damped flow regime, may be unable to transport the inputted fine sediment and this will result in it being deposited locally (e.g. Petts 1988).

Gravel cleaning

Hyporheic water quality can have an effect on developing salmonids between spawning and hatching (Malcolm *et al*. 2003a; Soulsby et al. 2005). In particular, mortality rates have shown a clear negative relationship with mean dissolved oxygen (DO) concentrations for experiments conducted on a low-lying degraded agricultural catchment compared with those from a near-pristine upland spawning stream (Malcolm *et al*. 2003b). Gravels may be cleaned in an attempt to respond to the affect of siltation causing an increasing hindrance to salmonids' spawning success (Shackle *et al*. 1999). However, this cleaning may be targeted locally in order to improve spawning for salmonids. The overall process of gravel cleaning may release fine sediments that are transported and redeposited downstream.

2.2.2 Out-of-channel influences on sediment supply

Valley side slope

All processes that deliver sediment to river channels or floodplains are driven by gravity. The steepness of valley side slopes can affect the supply of sediment to the river channel (Trimble 1995). Valleys with steep, high sides have greater potential energy with which to transport sediment to the river channel. Therefore, valley side slope and the average slope in the catchment as a whole are important factors in determining the resulting character of the HZ. Sediment delivery can occur through a range of processes including formation of alluvial fans from small tributaries

However, valley side slope should be considered in the context of catchment size and hydrological regime. Strahler (1950) argued that high sediment yield from steep valley side slopes demands a steep channel gradient for continuity of transport, resulting in a direct relationship between regional average side slopes and channel gradients. Newson and Leeks (1987) state how, beyond the uplands, rivers become typically 'misfit' with a small river in a wide valley. In these circumstances sediments from valley slopes are not directly supplied to the river unless meanders impinge on valley side slopes.

Land use

Erosion rates are known to be sensitive to land use. Walling (1999) describes how land use impacts on fluvial sediment yield are less clear owing to the buffering capacities of catchments. Disturbance of natural vegetation may be expected to enhance erosion rates. Agricultural practices are the most common disturbances to affect soil erosion. Field-based measurements of soil redistribution on catchment slopes have shown erosion to be greater on cultivated than on pasture land (Walling *et al*. 2006). Cultivated land may be particularly susceptible to erosion where autumn-sown crops are grown. The use of heavy machinery during cultivation results in tracks that concentrate runoff and enhance sediment delivery. Poaching by livestock enhances erosion from pasture land.

The natural rate of erosion in British uplands is extremely low. However, it may be increased (up to 100-fold) when the land is disturbed, typically for forestry (Newson and Leeks 1987; Soutar 1989; Leeks 1992). When disturbed, these soils are extremely susceptible to erosion due to their low cohesivity and the steep catchment slopes on which they are found. Although upland forestry operations mostly enhance the yields of coarse sediment, fines are also affected (Newson 1980).

Vegetated buffer zones

Vegetated buffer zones are narrow strips of land that run parallel to river channels. These buffer zones are used to trap fine sediments and pollutants before they enter the river system (Mander *et al*. 2005). However, there is a lack of evidence to support the success or failure of these buffer zones, and the extent to which buffers can restore riparian and stream function and species composition is not well understood (Parkyn *et al*. 2003).

Sediment delivery ratios have been estimated for several catchments. For instance the sediment delivery ratios estimated for the Pang and Lambourn catchments in Berkshire (approximately 1%) indicate that approximately 99% of the sediment mobilised within the catchment is subsequently deposited on catchments slopes and within the upstream river channel (Walling *et al*. 2006). This exemplifies the potential importance of buffering within the catchment.

Urban extent (including point discharges) and developments

Urban surfaces are likely to contribute sediment to river systems (see Ellis 1979). Concentrations in urban surface runoff may be higher than in raw sewage. These sediments may enter the river via point discharges (surface water drains). It is not clear whether the quantities will be greater or smaller than under natural conditions. Carter *et al*. (2003) state that road dust and particulates from sewage treatment works may contribute between 14 and 18% of the suspended sediment load in the lower Aire/Calder river system in Yorkshire. This sediment contribution is likely to be of greater importance in terms of its quality than quantity. Fine sediments may also be contributed to urban rivers by combined sewer overflows (Ellis 1979; Crabtree 1989; Ashley *et al*. 1992). Construction works have also been shown to greatly enhance the transport and deposition of fine sediment in river systems (e.g. Guy 1967; Wolman and Schick 1967; Walling and Gregory 1970).

Mass movements

Mass movements, such as landslides, may contribute large quantities of sediment to the river. This is likely to be a local phenomenon, however, which is difficult to predict.

2.2.3 River power regime

The power available to transport sediment in a river channel will affect the bed sediment found in that channel and therefore the nature of the HZ. Essentially the ability to transport sediment depends on the relationship between shear stress, sediment entrainment thresholds and sediment supply. Shear stress is a function of velocity and flow resistance. Resistance relates to the type of bed sediment. Velocity depends on the relationship between flow regime and channel structure, channel gradient and form roughness.

Stream power (P) can be defined as:

$$P = w.d.v.s_b$$

where w is stream width, d is mean stream depth, v is mean stream velocity and s_b is channel slope (Richards 1982). There are a range of river and catchment characteristics that can influence any of these terms.

2.2.4 In-channel influences on stream power regime

Channel structure

Channel structure is defined as the cross-sectional size and shape of the river channel. The shape of a channel will affect the capacity of that channel to convey water downstream and therefore the velocity in the channel during competent events. This is because channel conveyance is dependent upon cross-sectional area (Shiono *et al*. 1999).

Hydraulic geometry is a concept that is used to relate mean depth, mean velocity and channel width with discharge (Leopold and Maddock 1953). This concept attempts to describe the affects of channel structure on mean hydraulic conditions using empirical power functions of discharge (Wharton 1995b). This method has shown potential for improving analyses of fluvial processes and physical habitat across catchments (Stewardson 2005). Channel width is also an important influence on the HZ because it can be used to assess plan-form river-bed area.

Channel gradient

Channel gradient is the controlling factor on how potential energy is transferred into kinetic energy. Assessment of downstream rates of change in channel gradient and specific stream power across four river systems were carried out by Reinfelds et al. (2004) using analysis of a digital elevation model. They suggested that some of the river reaches most susceptible to high magnitude floods occur in zones where these variables rapidly decrease downstream. Therefore, at-site gradient, as well as changes in gradient along the river long profile, are influences on both the power to erode and the relationship between power to erode and sediment supply.

Flood alleviation, widening or confinement

Hydraulic engineers have long recognised that cross-sections of artificial channels must be designed to transmit their sediment load given a specified water discharge regime and an imposed valley gradient (Richards 1982). Where a channel has been widened, or deepened, to increase flood capacity, there may be an excess of sediment supply over power to erode and therefore deposition. Alternatively, where a channel has been confined to protect urban areas or limit bank erosion, there may be an excess of power to erode over sediment supply and therefore overall erosion (e.g. Brookes 2005).

Roughness – form resistance

Roughness represents the forces that act as resistance to flow and can be related to velocity (Wiberg and Smith 1991) as in Manning's equation (Richards 1982). Form resistance, which includes grain protrusion, pebble clusters, dunes, bars (Hey 1988), pool–riffle sequences and meander bends, has been shown to be significant, in comparison with grain resistance, at bankfull flow (Millar 1999). In-channel vegetation can also be seen as a component of form resistance (Green 2005a).

Sinuosity

Feedbacks exist between meandering, sediment dynamics and channel hydraulics. Highly sinuous channels can be created in large rivers with low gradient conditions and can be an indication of more stable sedimentary dynamics (Richards 1982). For example, Sweet *et al*. (2003) demonstrated how sediment dynamics were linked to channel sinuosity on the River Culm in Devon. Sinuosity is also one component of form resistance.

Reservoirs

Reservoir dams influence the downstream hydrological and hydraulic regimes, potentially changing the sediment regime and channel structure. Assani and Petit (2004) give an example of how a dam has dramatically affected the channel structure of the Warche River in Belgium. In this case the dam significantly reduced the number of discharges that are higher than bankfull. The impacts of hydrological modifications on the bed morphology included a doubling of the width of the channel in 45 years, a reduction in the number of riffles and pools, an increase in the number of gravel bars and islets, and an increase in bedrock outcrops in the channel. Moreover, the finest bed particles are mobilised by the almost daily releases, inducing a significant increase in bed-material size sorting. The reduction of sinuosity and the disappearance of bed differentiation and riffle/pool sequences in this river produced a diminution of bed roughness and an increase of the competence of the river. (See also the comments on affects of dams on sediment supply in Section 2.2.1 above.)

Vegetation

In-channel vegetation causes local obstructions to flow and therefore influence patterns of velocity (Nezu and Onitsuka 2001). However, these influences can be complex and are affected by the type and density of the vegetation as well as discharge and channel structure. Green (2005b) measured velocity and turbulence patterns in and around a common macrophyte species. He found that there was a sharp velocity gradient at the plant boundary, with velocities dropping to a constantly low value after no more than 5 cm into the plant, thus forcing most of the flow over and around the macrophyte. In-channel vegetation can therefore create areas of faster velocity as well as dead-zones immediately downstream.

Roughness – skin roughness

Skin friction, or grain roughness, controls resistance to flow in the near-bed zone. It therefore has a direct affect on shear stress and sediment entrainment. Semi-logarithmic friction equations can be used to estimate mean velocity using a friction factor obtained from depth and grain size information (Richards 1982). Although such equations have a semi-theoretical basis, in natural gravel-bed channels, an empirical constant (6.8 or 3.5) has to be introduced to scale up the characteristic grain size (D50 or D84) to represent the effective roughness length. The multiplier of characteristic grain size is attributable to the effect of small-scale form resistance, reflecting the occurrence of microtopographic bedforms in gravel-bedded environments.

Floodplain connectivity

Rivers that are connected to their floodplains have great potential for exchange of sediment between channel and floodplain (Walling *et al*. 1996). In contrast, those that are not connected to their floodplain may be indicative of channels whose sediment transport capacities have either been increased because of channel confinement or decreased due to enlargement of channel dimensions.

Engineered structures

Engineered structures such as weirs and bridges have localised affects on patterns of scour and deposition (Johnson 1995), which will depend on the design of the structure and its location. Locks may control the flow regime of navigable rivers.

Abstractions and discharges

Abstractions from rivers may potentially decrease stream power, although this increase is likely to be insignificant at high flows. Discharges into rivers may potentially increase stream power, although this increase is unlikely to be significant at high flows.

2.2.5 Out-of-channel influences on stream power regime

Flow regime

Catchments with greater, and more flashy, discharges are likely to have greater power to erode. The shape of a catchment's flow duration curve can be used to indicate its characteristic response to rainfall history and catchment size. There is likely to be a significant difference in the power of a river to erode in a permeable as opposed to an impermeable catchment. As stated above, hydraulic geometry is one concept that can be used to estimate mean depth, mean velocity and channel width from discharge (Leopold and Maddock 1953).

Valley slope

As gravity is the driving force behind transporting water through a catchment, valley slope plays a controlling role affecting the quantity of timing of water reaching the river channel. Catchments with steeper valley side slopes will have quicker runoff and therefore faster response times and more flashy flows.

Catchment size

In general in the UK, larger catchments have a greater total runoff. However, continuity of sediment transfer within the drainage basin is rare (Richards 1982). This is particularly the case where a floodplain exists. Larger catchments therefore have more potential areas to store sediments and have lower sediment delivery ratios (Roehl 1962).

Altitude and rainfall

Higher catchments have more precipitation and therefore more runoff. In temperate oceanic regions such as the UK, catchments with more precipitation generally have more runoff (Shaw 1988; Bower *et al*. 2004).

Stream order

Stream order (Horton 1945) is an indication of channel size, although the catchment configuration and drainage density (Gardiner 1995) can also influence how stream order is interpreted. Stream order has been used as a proxy indicator of river scale in studies of sediment geochemical anomalies (Carranza 2004), fish (Fayram *et al*. 2005), invertebrates (Schmera and Eros 2004) and sediment (Meybeck 2001).

Urban extent

During urbanisation, runoff volumes increase and response times shorten, generating larger flood volumes and higher peak discharges (Hall 1984; Startin and Landsdown 1994; Niemczynowicz 1999). Runoff volumes are high because urban development results in large areas of the catchment surface becoming impermeable. Thus, infiltration and surface storage is reduced. Response times are short in heavily urbanised catchments because runoff reaches high velocities over relatively smooth impermeable surfaces, before entering artificial drainage systems, which effectively increase drainage density and the rate of conveyance (Hollis 1975; Ellis 1979; Packman 1979).

Floodplain connectivity

The degree to which a river is connected to its floodplain could be used as an indication of its power to erode. See Flood alleviation, widening or confinement in Section 2.2.4 above.

3 Available datasets

After consideration of factors that influence the composition and structure of HZs, available national datasets were interrogated to identify representative variables for each factor A short description of each dataset is given below and summarised in Appendix A .

3.1 Bedrock and drift geology datasets

'Bedrock geology', formerly known as 'solid geology' by the BGS, is the term used to describe the main mass of rocks, whether exposed at the surface in outcrops or concealed beneath superficial deposits or water. Firstly, 1:625,000 scale BGS bedrock and drift geology maps were considered for use within the project. However, these maps have a number of spatial inconsistencies that make them incompatible with national coverage digital terrain models and river data. The 1:250,000 scale bedrock geology maps were also found to exhibit similar inconsistencies at the national scale. For this reason, the 1:50,000 scale bedrock and drift geology maps have been used. However, data processing times associated with the use of these maps are greater due to the increase in the number of rock classes with scale (see Table 3.1) and the resolution at which features are mapped.

Table 3.1 Number of class members in differently scaled bedrock and drift geology maps

		1:625,000	1:250,000	1:50,000
Bedrock geology	Rock type	134	87	354
	Lexicon	-	734	2259
	Lex_Rock	-	1102	3757
Drift geology	Rock type	9	-	46
	Lexicon	16	-	400
	Lex_Rock	-	-	594

The more detailed lexicon classes will be used to infer geochemistry. Suggested ranges and geochemical characteristics are shown in Table 3.2.

Table 3.2 Suggested ranges for geochemical properties for association with bedrock and drift geology classes

	High	**Moderate**	**Low**
Carbonate (as TIC)	>2%	0.2–1%	<0.2%
CEC (meq/100g)	>20	5–20	<5
FOC	>0.02%	0.002–0.02%	<0.002%

3.2 Water Framework Directive typologies

3.2.1 Rivers

UK-defined SWBs are based on river confluences. Each catchment, or polygon, represents a stretch between river confluences obtained from an area accumulation grid at the 1:50,000 scale. This grid shows the location of physical changes in the river network that correspond to the EU WFD System A typology parameters for mean catchment altitude, size and dominant geology. The variables in the river typology of most use to this project include:

Altitude (m): Highland (>800); Intermediate (200 to 800) and Lowland (<200).

<u>Size (km^2)</u>: Very small (<10); Small (10–100); Medium (>100–1000); Large (>1000–10000); Very large (>10000).

<u>Geology</u>: Calcareous, Siliceous, Organic, Salt.

The typology allows for a theoretical 48 river types, but in reality only 21 can be identified within England and Wales. The dominant river type (38%) was found to be small (10–100 km^2), low altitude (<200 m), calcareous rivers. Construction of river typology maps used 1:250,000 geology maps (bedrock and drift), and an Environment Agency devised method of determining the dominant geology type (validated by BGS). The typology does not deal with artificial linear watercourses, such as canals.

3.2.2 Lakes

Lake typology for the UK follows the System B approach of the WFD, based on divisions of altitude, latitude, depth, geology and size. Catchment geology is used as the base control of lentic water body typology. Three geology types (siliceous, calcareous and organic) are subdivided to create a total of six lake types with respect to alkalinity (base status), conductivity and colour (see Table 3.3). A measure in the confidence of defined geological types is also made.

Table 3.3 Lake typology geological classes and associated properties of alkalinity and conductivity

Geology	Abbrev.	Catchment	Alkalinity		Conductivity
			Ueq/l	MgCaCO$_3$/l	uS/cm
Organic	P	>75% peat			
Siliceous	LA	>90% siliceous solid geology	<200	<10	<70
	MA	>50% siliceous solid geology	200–1000	10–50	71–250
Calcareous	HA	>50% calcareous geology	>1000	>50	251–1000
	Marl	>65% limestone			
Brackish	B				>1000

3.2.3 Groundwater

Within the groundwater typology, aquifer bodies are defined as being productive, unproductive, or occurring within drift deposits. Unproductive aquifers are classed as those that could not supply an average 10 m^3/d (or supply water for 50 persons over the whole body), and would not detrimentally affect dependent SWB or terrestrial ecosystems. Productive aquifers are divided into primary and secondary classes. The drift classification occurs only in four locations in England and Wales, where river terrace material, alluvium, glacial sand and/or diamicton overlie impermeable solid geologies (e.g. Oxford Clay, London Clay, Ampthill and Kimmeridge Clay). All groundwater bodies have been defined such that little or no flow occurs between each defined aquifer type.

3.3 Water Framework Directive risk assessments

As part of the Environment Agency's River Basin Characterisation Project and in accordance with Article 5 of the WFD, an assessment of the risk of WFD-defined water bodies not achieving 'Good Status' has been made. A measure of confidence in each risk assessment is also made. The anthropogenic factors intended to be captured in such an assessment include the following:

- Morphological pressures – land reclamation, dredging and flood defence etc.
- Point source pollution – authorised discharges.
- Diffuse source pollution – nutrients, pesticides, sediments, acidification, urban pressures and mines/mine-waters.

Each of the above pressures or impacts is assessed for each water body within England and Wales. Each water body is then ascribed a specific level of risk (high, moderate, low, none) and an associated level of confidence (high, moderate, low).

3.3.1 Morphological pressures

Influences on river morphology considered include substrate manipulation; bed and bank reinforcement; resectioning, straightening and realignment; flow manipulation; impounding and construction; intensive use grazing; removal of natural barriers; modifications to sediment regime; and floodplain modification. Influences to lake morphology include bank construction and reinforcement; channelisation of inflows and outlets; lowering/draining; intensive macrophyte management; and modifications to sediment regime (UK TAG 2003). Assessment is made with respect to the impact these influences might have on river or lake morphology, including depth, structure and substrate of the river/lake bed, and structure of the near-shore/bank zone.

Databases used in the river risk assessment include National River Habitat Survey (RHS); Urban land use GIS (Environment Agency); and the Flood Defence Management System. Databases used in the lake risk assessment include: Ordinance Survey 1:10,000 maps and Land Cover 2000 maps. See the Environment Agency documents *R_Morphological Alteration_T_v1.0*, and *L_Morphological Alteration_T_v1.0* for detailed methodology (http://www.environment-agency.gov.uk).

3.3.2 Point source pollution

The risk to rivers from licensed point source discharges such as sewage works, industrial discharges and fish farms were assessed with respect to possible exceedance of Environmental Quality Standards (EQS) derived from relevant EC directives. Determinants used include nutrients (nitrogen and phosphorous), sanitary effluents (ammonia as nitrogen, BOD ATU), metals and pesticides. See Environment Agency document *rtc_pt_source_t_v4* for a more detailed list of determinants, data sources used in analysis and analysis methodology (http://www.environment-agency.gov.uk).

3.3.3 Diffuse source pollution

Several types of diffuse pollution pressures on surface and groundwater bodies are considered, including phosphorus and nitrogen nutrients, agricultural pesticides and sheep dip, mines and mine-waters, urban discharges, sediment delivery and acidification. Additional pressures on groundwater bodies include chlorinated solvents and dangerous substances other than pesticides.

3.4 General quality assessment data

The Environment Agency's General Quality Assessment (GQA) data is designed to provide an accurate assessment of chemical and biological water quality of the defined water bodies.

The water chemistry GQA assigns one of six grades (A to F) to each water body with reference to chemical measurements representative of the most common types of pollution (National Rivers Authority 1994; Environment Agency 1998). The measurements taken include dissolved oxygen (% saturation), biochemical oxygen demand (mg/l), nitrate (mg NO_3/l), and ammonia (mg N/l). The worst determinant value is used to set the water quality grade (where A = very good; B = good; C = fairly good; D = fair; E = poor; F = bad). Statistical confidence measurements are used to assess the predictions of change in water quality between surveys that took place in 1990, 1995, 2000 and 2002.

A similar grading scheme is used for biological quality assessment (A to F) and describes the difference between the expected and observed macro-invertebrate community within each water body. The River Invertebrate Prediction and Classification System (RIVPACS) is used to predict the number of taxa expected at any site if the environmental quality is good (Wright *et al.* 1986; Wright 2000). The BWMP (Biological Monitoring Working Party) system is then used to determine the number of observed taxa (National Water Council 1981; Institute of Freshwater Ecology 1995). The comparison between observed and predicted conditions is then represented by an Ecological Quality Index (EQI) for each water body. A less than expected number of taxa is representative of a general fall in ecological quality, due to organic or toxic pollution, or physical disturbance to river habitats. Estimations of changes to conditions between surveys in 1990, 1995, 2000 and 2002 are again made.

3.5 Digital terrain model

Based on the Ordinance Survey 50-m grid interval Digital Terrain Model (DTM), and digitised river network data (Moore 1983), the CEH DTM exhibits a 0.1 m vertical resolution (see Morris and Flavin 1992). Derived maps of inflow or outflow drainage directions, and contributing catchment area are also available.

3.6 Flood estimation handbook

The Flood Estimation Handbook (FEH) gives guidance on rainfall and river flood frequency estimation in the UK. The FEH also provides methods for assessing the rarity of notable rainfalls or floods. The associated datasets from the creation of the handbook provide a number of variables relating to river flow characteristics that may be used within this study. These include topographic descriptors of the catchment and stream network within defined catchments derived from a hydrologically referenced DTM, see Table 3.4 (Morris and Heerdegen 1988; Bayliss 1999). For related procedures and supporting theory, see Robson *et al*. (1999).

Table 3.4 River channel and catchment descriptors derived using the FEH

Abrev.	Units	Description
ALTBAR	m	Mean catchment altitude
ASPBAR	Degrees	The mean aspect of direction of all slopes in the catchment
ASPVAR	None	The invariability of slope direction
DPLBAR	km	The mean of the distances measured between each DTM node and the catchment outlet
DPLCV	km	The covariance of the distances measured between each node and the catchment outlet
DPSBAR	m/km	The mean of all the inter-nodal slopes for the catchment
LDP	km	The longest drainage path

3.7 Low flows 2000

The Low Flows 2000 (LF2000) system is a decision support tool designed to estimate river flows at ungauged sites and to aid the development of catchment and regional water resources. The core of Low Flows 2000 is the CEH universal feature database model. Point data with complex relational structures such as abstraction licences, and time series data such as flow records, are available. A low flow module allows estimation of natural and influenced flow statistics at any river reach in the United Kingdom. Catchment boundaries are automatically generated based on either a DTM or a constrained assignment of grid cells to river reaches. Estimates of mean flow are generated from a generalised soil moisture accounting model. The model operates on a daily time step and predicts long-term average annual runoff. Annual and monthly natural flow duration curves are predicted for ungauged catchments based on the flow regimes of catchments identified as being hydrogeologically similar to the ungauged target catchment. Monthly mean flows may also be predicted. The impacts of artificial influences are incorporated on a river reach basis. The structure of the river network also facilitates the aggregation of reach-scale impacts to the catchment scale and the derivation of residual flow diagrams. The system simulates the impact of surface water and groundwater abstractions, discharges and reservoir operation. For description of the modelling procedures and program, see Holmes *et al*. (2002a, 2002b, 2005).

3.8 Hydrology of soil types

The Hydrology of Soil Types (HOST) project produced a classification of 969 UK soil series into classes of similar hydrological response (Boorman *et al*. 1995). The classification system was based predominantly on conceptual models of processes taking place within the soil and substrate, where one of the following three conditions exists:

- soil with impermeable or semi-permeable layer within 1 m of the surface;
- soil on permeable substrate with shallow water table at <2 m depth;
- soil on permeable substrate with groundwater at >2 m depth.

Within the above context, 11 different soil groups were formed, ranging from permeable non-consolidated soils to less permeable gleys and peats. These groups were further subdivided, based on variation in geology and substrate properties, into the resulting 29 HOST classes. Physical properties described for each class include base flow index (BFI), standard percentage runoff (SPR), depth to aquifer and likely changes in permeability. The HOST datasets are used as dominant class grids at the 1 km^2 scale.

3.9 Land cover map 2000

The Land Cover Map 2000 (LCM2000) dataset is derived from analysis of spectral reflectance data from Earth observation satellites (e.g. Landsat 7) on a grid of approximately 25 m^2 cells. By segmentation of the obtained images, a representation of land parcels of different vegetation and land-cover patterns has been obtained (see Fuller *et al*. 2002). The data has been checked against field surveys of vegetation in 569 x 1 km^2 squares across the UK.

LCM2000 describes land-cover data at three levels: 16 target classes; 26 target subclasses (including an unknown class) and 72 target subclass variant classes. The 25 m spatial resolution raster data provides 26 target subclasses as standard; a 1 km summary then provides 16 target classes. The data used in this study is that derived from the 1 km subclass class grids consisting of 26 defined land-cover classes. In order to reduce the number of classes, the vegetation types have been grouped into five land-cover classes: deciduous, coniferous, arable, grassland and upland (see Table 3.5).

Table 3.5 Land-cover types represented by LCM2000 data

Land-cover class	LCM2000 1 km^2 aggregate classes
Deciduous	Broad-leaved and mixed woodlands
Coniferous	Coniferous woodlands
Arable	Cereals, horticulture, non-rotational arable
Grassland	Improved, set-aside, neutral, calcareous, acid, bracken, fen, marsh and swamp
Upland	Dense and open dwarf shrub heath, deep peat, montane habitats, bare ground
Urban	Continuous, suburban, rural development areas

3.10 River habitat survey

The River Habitat Survey (RHS) dataset provides information at the river reach scale. The database includes information surveyed from 1994 to 2003. Variables of particular interest include slope; height of, and distance from, source; hydrometric area; altitude; flow category; channel form (culverted, artificial, reinforcement, dug, dammed); valley form (shallow, vee, gorge, concave, floodplain); flow type (white water, step pool cascade, riffle pool, laminar, static, impounded); width; depth; and embanked height.

There are approximately 15,000 RHS sites in the UK. Their distribution is partially random, but also reflects the distribution of specific projects that have required more detailed assessments. A high number of RHS sites per water body will lead to a higher confidence in the true nature of the river channel morphology. Where only a few RHS sites are available, the confidence is much lower. Because of the variability in the spatial coverage of the RHS dataset, it will be used primarily to help validate estimations of HZ type at specific locations, and for Tier 2 locally scaled estimations of HZ type.

3.11 Intelligent river Network

The Intelligent River Network is a GIS system in ArcView developed for the automated extraction of map information from a 1:50,000-scale river network of Great Britain. Typical information extracted from the river network is altitude of site and source, distance to source, local slope, mouth and stream order characteristics. It was developed by CEH Dorset as part of the freshwater ecology research programme.

4 Typology rule definitions

In order to assign axes classifications (and hence the resulting HZ typology) to any SWB, a database of defining variables and processes that control the nature of the HZ was compiled for all SWBs (see Appendix A). This included information relating to the key process-controlled and descriptive variables described below.

Original axis	New axis	Defined by
Sediment	Sediment supply	Erodibility of surfaces within the SWB catchment, determined using land use, and the erosivity within the SWB catchment, determined by slope and rainfall
Stream power	Stream power	Mean flow and local slope
Sediment	Sediment thickness	Available sediment and river power
Sediment	Sediment geochemistry	Geochemistry of underlying geology and transported sediments
Sediment	Sediment permeability	Permeability of transported bed sediments – determined using the size and range of sediments
Geology	Subsurface permeability	Permeability of underlying geology

To represent the processes and data sources at the SWB catchment scale, each SWB catchment was characterised in terms of its channel and its catchment. Figure 4.1a illustrates the distinction between SWB channel and SWB catchment. Defining variables for each water body are described relative to both these land units. For example, SWB catchment land-cover type is described as the percentages of land cover that occur within the SWB catchment. By contrast, SWB (channel) geology is described by the geology type over which the stream channel most frequently passes. This approach allows the use of information derived for both in-channel and out-of-channel processes. It must be noted that each water body will also be affected by processes occurring within its contributing upstream area as illustrated in Figure 4.1b. In particular this will have implication for fine sediment budgets between upstream and downstream catchments.

4.1 Catchment connectivity

The characteristics of the HZ within a SWB will be related to processes and conditions within the SWB as well as those within upstream SWBs. The latter is the contributing catchment for each SWB.

For the purpose of classifying the HZ it was assumed that, at the timescales being considered, finer sediment is easily transported. Thus the fine sediment within the SWB will be related to the processes and conditions within the entire contributing catchment to the SWB. Coarser sediments are assumed to be relatively static (over the scale of a SWB) and related to processes and conditions within the SWB.

For the analysis of fine sediment it is necessary to develop a methodology to allow the impact of upstream SWBs to influence the HZ for the selected SWB. Two methodologies were proposed:

cascade and independent. Within the cascade methodology the conclusions from the upper catchment are ‘fed’ into the lower catchment continuing down the catchment. The independent methodology considers the entire upstream catchment as a whole and a similar analysis to that undertaken for the individual SWB is completed for the entire upstream catchment.

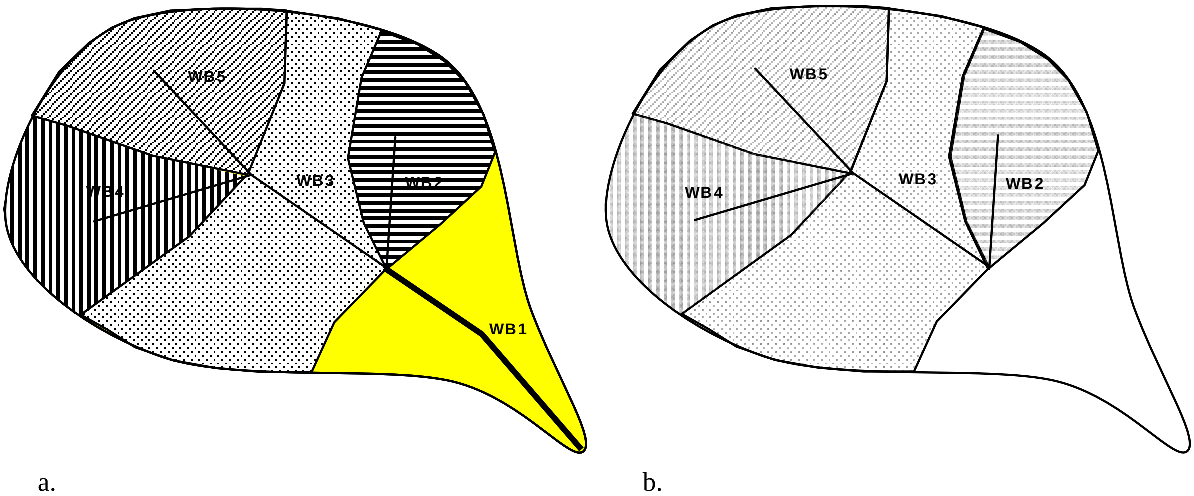


Figure 4.1 (a) Illustration of water body catchment river channel (WB1) and water body catchment area (yellow),
(b) contributing upstream area of WB1 (WB2; WB3; WB4; WB5)

The advantage of the cascade method is that it considers the contribution from upstream catchments in a more process-driven way. The disadvantage of the cascade approach is that any errors in upstream assessments will be propagated downstream through the SWB catchments.

The advantage of the independent methodology is that the final HZ typology will be immediately transparent, that is to say all the results leading to the assignment of the typology to the SWB will be presented. The disadvantage of the independent methodology, particularly in large catchments, is that the location-specific nature of sediment sources and how these relate to erosive and transporting processes will be lost.

The cascade approach was used within the development of the final typology.

4.2 Sediment supply

Sediment supply from the SWB catchments is described in terms of coarse sediment (>1 mm) and fine sediments (≤1 mm). The amount of each type of sediment is initially considered separately as the processes involved in their erosion and transportation will be different.

4.2.1 Fine material supply

Figure 4.2 illustrates the process by which the sediment supply from a SWB catchment was initially defined.

This was based on a number of assumptions relating to the dominant sources and processes which affect the presence of each type of sediment. It was assumed that fine sediment is derived from two sources, the SWB catchment surface and the SWB corridor. The first relates to sediment eroded from the catchment surface. This is controlled by the erodibility of the surface, a function of land use, and the erosivity, a function of rainfall and slope. The drainage density was also included to represent the connectivity, and therefore potential for sediment transport to the SWB, of the river network. In addition, it was assumed that sediment derived locally, that is adjacent to the SWB corridor, should be considered separately as an additional source.

Delivery of fine sediment to the SWB was represented by sediment derived from the SWB catchment (left box), and sediment derived from within the SWB corridor itself (right box). SWB catchment sediments were described as a function of available sediment within the catchment (based on the erodibility of different land-use types) and the average erosivity within the catchment (based on average slope and average annual rainfall). In a similar way, sediment available from the area directly adjacent to the river corridor was described as a function of the percentage area of erodible land that lies within the river corridor.

The resultant sediment supply represents a relative value of sediment supply that can be used within the subsequent analysis.

The total fine sediment supply to the SWB channel is described as a function of the sum of the sediments produced within the catchment and the sediments produced within the near-channel areas. The relative importance of each of these sediment-producing areas may be different within each catchment depending on catchment topography, and vegetation and soil type distribution. A SWB-specific weighting function, dependent on drainage density, was therefore applied to the ratio of catchment and river corridor derived sediments in order to reflect the different balance of sediments from each source area.

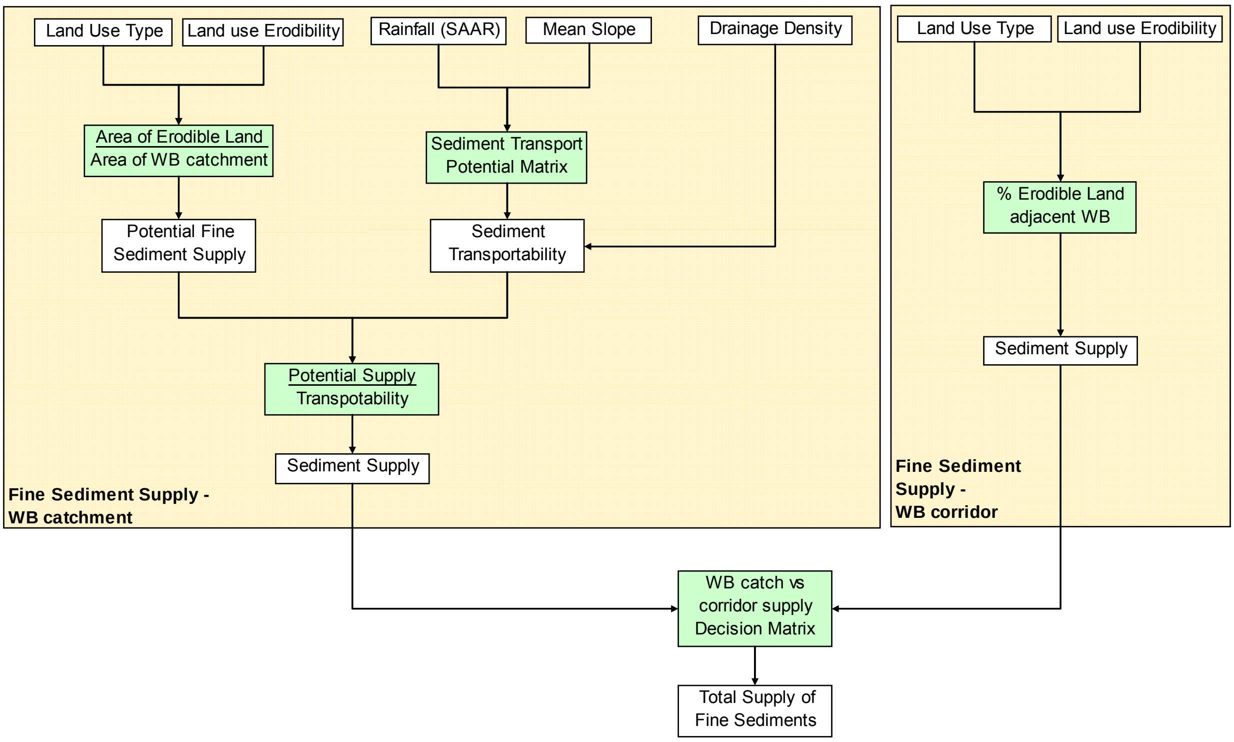


Figure 4.2 Initial conceptual model for production of water body fine sediment

Figure 4.3 presents the predicted fine sediments for the contributing catchment when both the SWB catchment and corridor are considered and when just the SWB catchment is considered. The strong relationship between the two indicates that there is redundancy within the model when both sources of fine sediment are included. The fine sediment supply to the river channel is therefore described as a function of land-use erodibility, catchment-specific erosivity, and the size and drainage density of a SWB catchment.

It is possible that this contributing fine sediment supply may be simply due to the fact that larger catchments are likely to have a larger area from which fines may be supplied. However, testing of the relationship between SWB contributing catchment size and the fine sediment supply verified that the magnitude of sediment supply is not purely a function of SWB contributing catchment size, and that the erodibility, erosivity and drainage density provide additional information about the sources and processes providing fine sediment within the SWB.

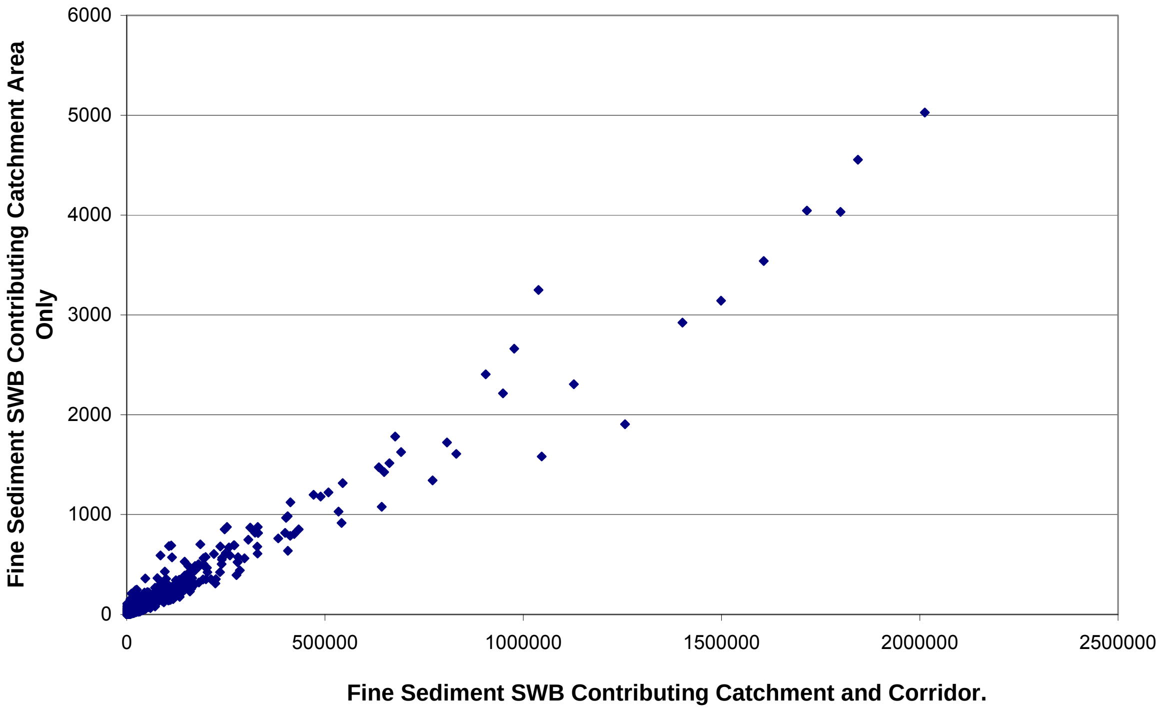


Figure 4.3 Comparison of the contributing catchment fine sediment predicted when both sources (SWB contributing catchment area and contributing catchment corridor) or just the SWB contributing catchment area are considered

Potential sediment supply

As described above, the erodibility of the surfaces within the SWB catchment are defined as a function of land use. Using the CEH LCM2000 GIS coverage map, arable and coniferous aggregated land-use types (see Appendix B for further description of these classes) were considered to be significant producers of fine sediment within the SWB catchment (see discussion on land-use impacts in Interim Report 1). For any SWB catchment, the potential amount of fine sediments that may be delivered to the SWB channel will be described as a function of the total area of erodible land-use types (coniferous and arable). Figure 4.4 shows distribution of slope–SAAR (Standard Average Annual Rainfall) classes. The slope class was assumed to be dominant in the combined classification.

Potential sediment transport

SWB catchment averages of SAAR and slope (as derived from LF2000) were categorised into low, moderate and high classes as defined in Table 4.1 and Table 4.2 respectively. The SAAR and slope classes were then combined to generate an erosivity weighting between 1 and 3 (see

Table 4.3). This provides a measure of the likelihood that available sediment will be eroded from the catchment surface.

Table 4.1 Rainfall class data table

Rainfall class	SAAR (mm/year)
Low	<800
Moderate	800–1500
High	>1500

Table 4.2 Slope class data table

Slope class	Slope (degrees)
Low	<3
Moderate	3–7
High	>7

Table 4.3 Erosivity weighting as defined by slope and rainfall (SAAR)

	SAAR		
Slope	Low (1)	Moderate (2)	High (3)
Low (1)	1	1	2
Moderate (2)	2	2	2
High (3)	2	3	3

Drainage density represents the potential to transport eroded material from the surface to the SWB. A low drainage density catchment for example, would be less likely to transport sediment to the SWB channel than a high drainage density catchment.

Table 4.4 illustrates example erosivity scores (1, 2 or 3), associated with each drainage density class in order to describe the likelihood that eroded soil particles will be transported to the main river channel. Potential to transport sediment from the catchment surface to the SWB channel is therefore expressed as a function of slope, SAAR and drainage density such that:

$$T_S = \left(\frac{E_S}{SAAR} \right) + E_{DD} \qquad \text{Equation 1}$$

where T_S is sediment transportability, E_S is erosivity weighting with respect to slope, *SAAR* is SAAR score and E_{DD} is erosivity weighting with respect to slope.

Table 4.4 Erosivity weighting as defined by drainage density

Erosivity weighting	Drainage density (km/km^2)
Low (1)	<1
Moderate (2)	1–2
High (3)	>2

Figure 4.5 illustrates the distribution of the calculated sediment 'transportability' as defined by slope, SAAR and drainage density (values range from 2 to 6). Analysis of the sensitivity of calculated sediment transportability to class boundaries defined for slope, SAAR and drainage density was completed. All boundaries were found to be relatively insensitive. While the

magnitude of the total sediment supply was variable, the relationship between the fine sediment supply for each SWB was insensitive (see Appendix D),

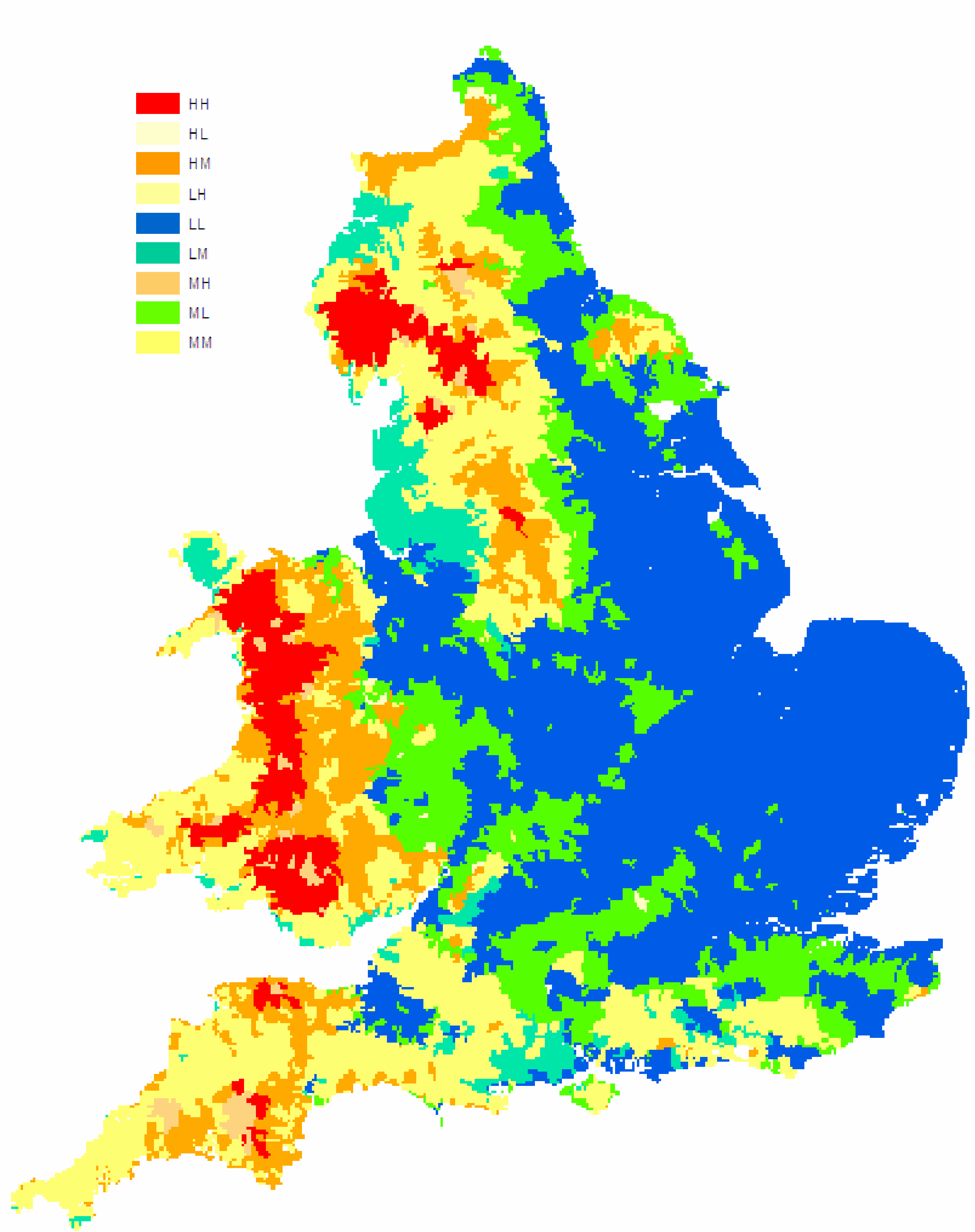


Figure 4.4 Erosivity classes for SWB catchments in England and Wales – letters in key represent parent slope and SAAR classes (low, medium, high)

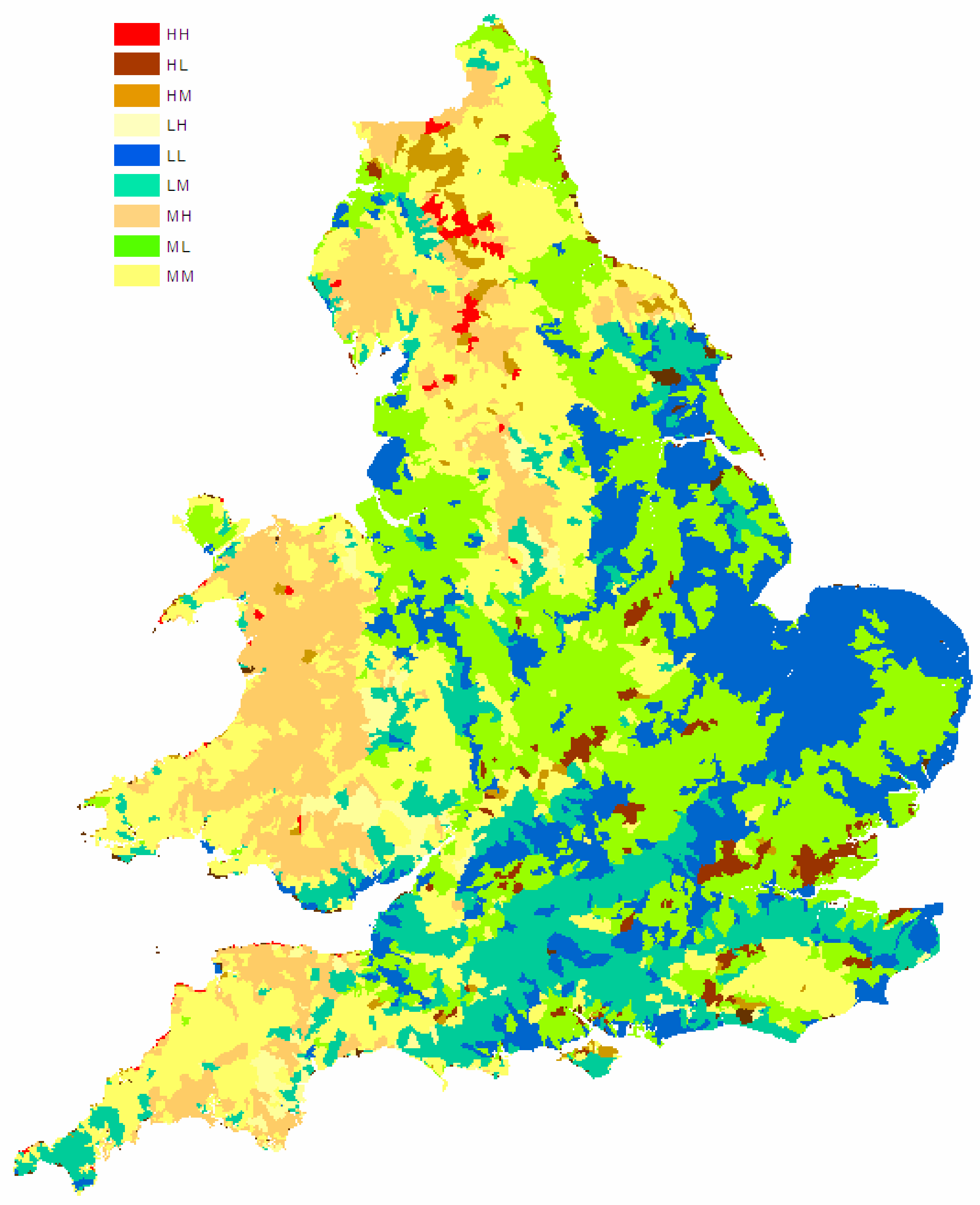


Figure 4.5 Combined slope/SAAR and drainage density defined erosivity classes – letters in key represent transportability scores (e.g. HH = 6, MM = 4, LL = 2)

Total sediment supply

The total sediment supplied to the SWB is described as the ratio between the potential sediment supply from the SWB catchment, and the potential to transport that sediment within the catchment (Figure 4.6).

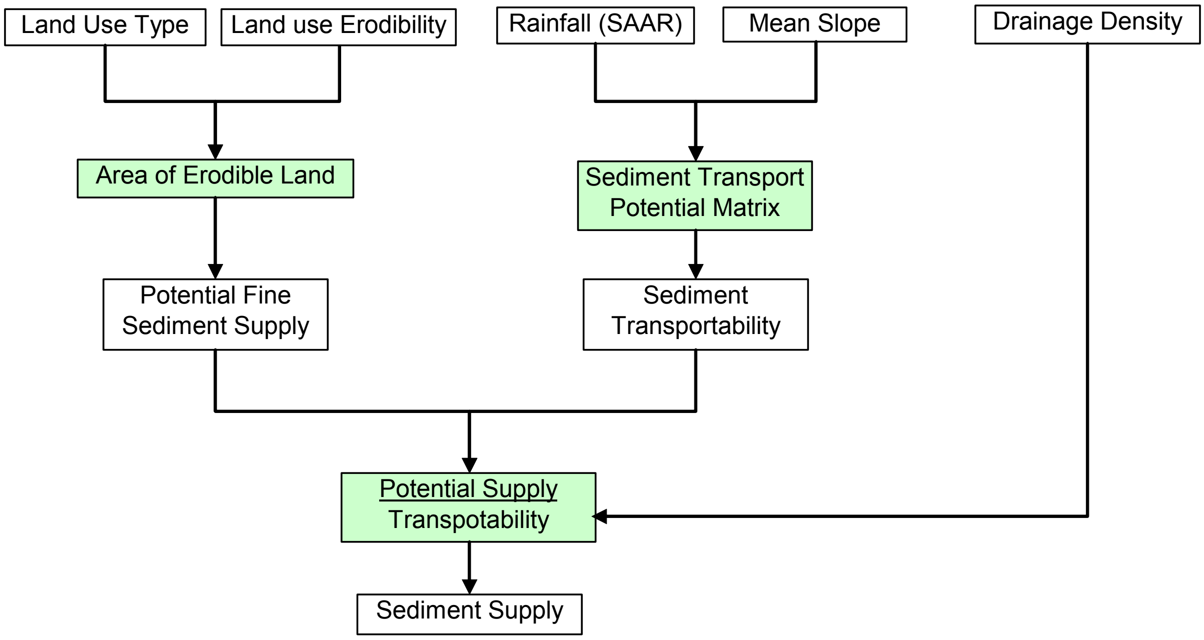


Figure 4.6 Total SWB sediment supply

While arable, coniferous and urban land use will enhance the prevalence of channel bed fines, the influence of urban land use is a Tier 2 consideration. The influence of organic soils on the type of sediment produced in a catchment is not represented.

The effect of lakes is a Tier 2 consideration because of the unique character of each lake feature (i.e. management of water resources). There will, however, be some impact on sediment delivery, so it is an important consideration at the smaller scale (reservoirs, delivery from upstream areas, impoundment). Similarly, regulated rivers are likely to have greater quantities of channel bed fines, as fewer extreme flows are likely to occur to transport them. This will also be a Tier 2 consideration.

4.2.2 Coarse material supply

Coarse sediments found in the HZ within SWBs are assumed to be derived predominantly from pre-existing coarse deposits. It was assumed that the presence of coarse sediment is a function of the sediment that is present locally, which itself is a function of the extent and type of drift along the SWB river corridor.

The extent of coarse sediment available within any SWB is thus determined using the BGS 1:50,000 drift geology map. In order to use this data, the length of SWB channel intersecting each drift geology type is first determined. Each drift geology type is then referenced in terms of the sediment particle sizes defined for that drift type (see Appendix B). It is assumed that sediment particle sizes within a particular drift type are equally present (i.e. if a drift type contains four different particle sizes then each will represent 25% of the drift). The percentage of each particle size within each SWB is calculated. The eight size categories (referenced from 1 to 8) are then aggregated into the classes small (1, 2, 3) medium (4, 5) coarse (6, 7), boulders (8) and bedrock (9), and resulting percentages for each SWB are calculated.

It should be noted that for certain areas of Wales and the North East there was no coverage of the BGS 1:50,000 drift map. In these cases the 1:625,000 drift map was used. It is noted within the typology database where this is the case.

In addition to coarse sediment supplied from drift deposits, a number of rock types are identified as contributing to specific sediment class size supply. For example, chalk and sandstone rock types are assumed to contribute flint pebbles (particle size 6) and sand-sized (particle size 4) sediment to SWB HZs respectively. The total coarse sediment supply available is thus described as a combination of both drift geology and specific solid geology types (see Figure 4.7).

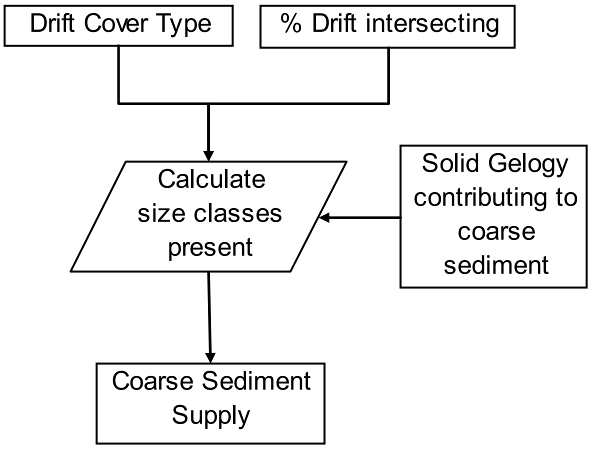


Figure 4.7 Schematic representation of coarse sediment supply calculation

Grassland, upland and deciduous vegetation classes are less likely to generate fines so a coarser channel bed deposit may be expected. Similarly, glacial deposits are likely to result in coarser channel- bed sediment.

The information from this sediment axis will be used with the power axes in order to develop a conceptual understanding of the fine sediment thickness and the permeability of the substrate.

4.3 Stream power

The power axis will be used to represent the average stream power of the SWB. Together with information on the sediment supply, this will be used to predict sediment thickness and provide input to the likely sediment permeability. The power classification will be used to represent an estimation of average sediment transport conditions of the SWB relative to available transportable sediment as defined in Section 4.2. Only sediment transport mechanisms that move suspended sediment (including fine to medium sized sands) will be considered (i.e. sediment size classes 1–3 as defined in Appendix B). Bedload is not relevant at the SWB scale (i.e. there is assumed to be no transport between SWBs within the time period being considered). Fines (size classes 1–2) derived from the solid or drift geology will also, in general, not be considered as transportable. As these fine sediments will affect the permeability of deeper sediments they are assumed to be held within the matrix of larger sediments.

4.3.1 Physical processes

A number of methods of representing stream power (and its subsequent effect on sediment load) were investigated. Stream power can be used as a measure of the energy at the stream bed and can therefore be expressed as a function of slope (Bagnold 1977), such that:

$$W = Q.s.\rho.g \qquad \text{Equation 2}$$

where W is stream power, Q is stream flow (m^3/s), s is channel slope, ρ is the density of water (kg/m^3) and g is acceleration due to gravity (m/s^2).

If this is considered per unit area of stream bed, then power can be expressed as a function of slope:

$$W_S = \left(\frac{Q.s.\rho.g}{w} \right) = \tau.v \qquad \text{Equation 3}$$

where W_S is specific stream power, w is stream width (m), τ is shear stress per unit area (N/m) and v = mean velocity (m/s).

In assessing the amount of transportable sediment that will settle on the river bed, the ability of flowing water to move sediment can therefore be assessed relative to a critical sheer stress acting on sediment particles. Critical sheer stress is the down-slope component of the weight of moving water that is exerted on sediment particles lying on the river bed, and is proportional to the depth and slope of the flowing water body. The force needed to move sediment can also be expressed as a function of stream velocity at the river bed, such that:

$$V_{crit} = k.W^{1/6} \qquad \text{Equation 4}$$

where V_{crit} is the velocity threshold over which a sediment particle will move, W is weight of the sediment particle and k is a proportionality constant.

Threshold velocities required to move sediment particles (quartz) of different sizes have been determined by Hjulstrom (1935). Figure 4.8 shows the thresholds between different values of bed-velocity determined for the processes of erosion, transport and sedimentation to take place for different sized sediment particles. These can be used to indicate the extent of erosion, transport or deposition within any SWB where reliable estimates of bed velocity can be made.

Estimates of the mean velocity were completed for each SWB using a regional regression equation based on the mean flow and flow percentile. Figure 4.9 shows the frequency distributions of SWB average velocities (as a proxy for the bed velocity), relative to the Hjulstrom velocity thresholds for sand-sized sediment particles.

Velocity estimations were made at Q5, Q30 and Q95 in order to represent the range of variability likely to be found within each SWB. Calculation of mean velocities at each percentile indicated that there was little variability between sites, with almost all sites falling within the same category (deposition, transport, erosion) for each sediment type, and for all of the year. This is probably a product of using averaged stream velocity instead of bed velocity.

Indeed, the main disadvantage of using this method would be that accurate estimations of near-bed velocity are very difficult to achieve, as realistic measures of stream depth are needed. In addition, no account is made of turbulence at the bed, which may lead to underestimation of the amount of sediment in transportation. In reality, it is likely that stream depth and hence stream-bed velocities vary considerably within a single SWB, and capturing such variability would again be problematic.

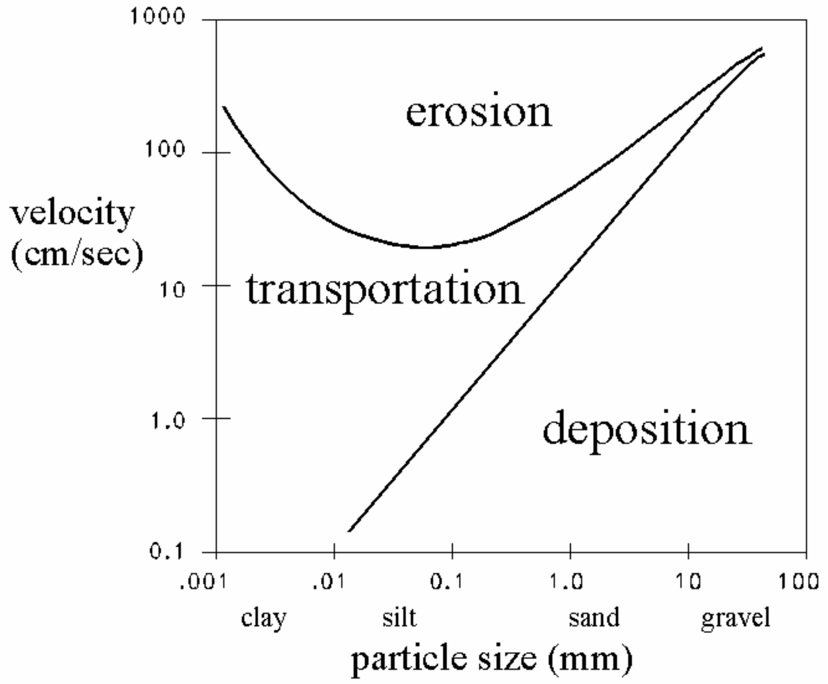


Figure 4.8 Hjulstrom diagram illustrating thresholds of sediment erosion, transportation and deposition for differently sized particles

While using velocity would allow a more deterministic approach to estimating the main processes, deposition transportation and erosion present within each SWB, the results show that the dataset cannot provide the information required for this method to be reliable. A more pragmatic approach was therefore developed.

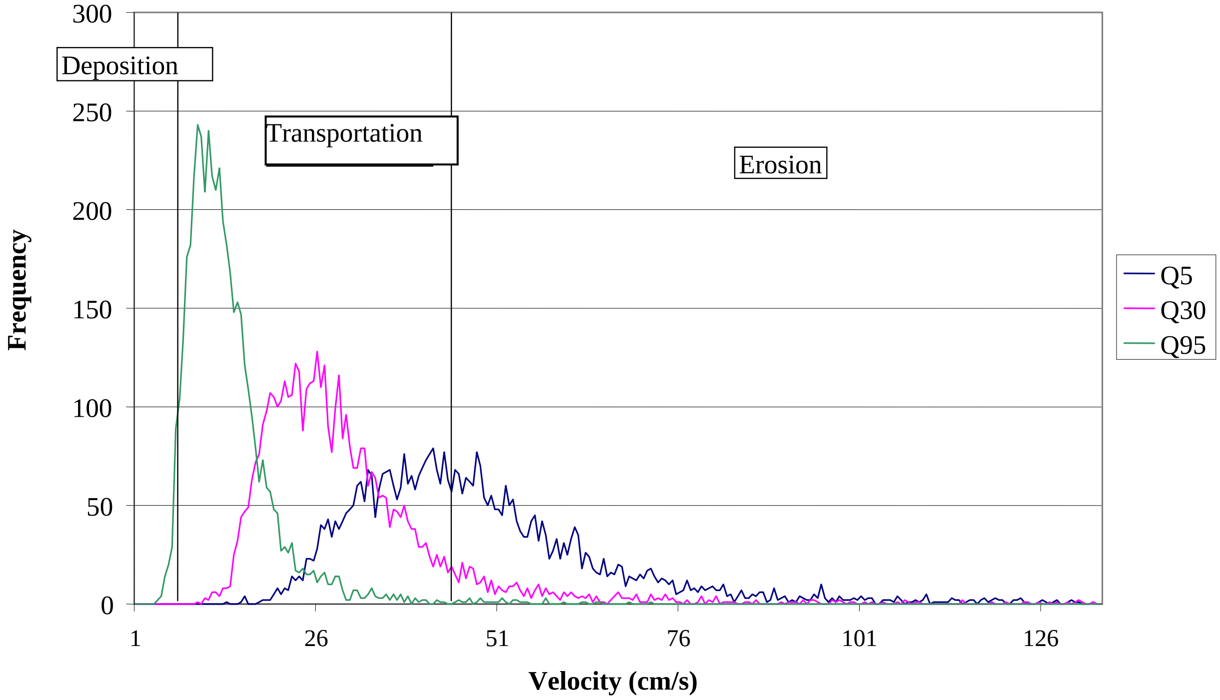


Figure 4.9 Hjulstrom sediment transport and deposition thresholds for sand-sized sediment

4.3.2 Relative representation

The aim within this study has been to predict relative rather than actual amounts of in-stream sediment. A number of FEH and LF2000 variables known to be representative of the transportive power of SWBs were suggested as surrogate values of stream power. These are listed in Table 4.5.

Table 4.5 Surrogate variables that can be used to represent relative differences in SWB stream power

Variable	Description and use
DPSBar	Catchment steepness index: the steeper the catchment, the higher the stream power
FARL	Lake attenuation index: flow attenuation will tend to reduce stream power
BFI	Base flow index: may be important in characterising rivers of specific catchment geology (e.g. chalk streams) where non-flashy flow regimes do not regularly clean out the channel
DPLBAR and LDP	Mean drainage path length and Longest drainage path: comparison of these two variables allows representation of catchment shape. For example, when DPLBAR and LDP are close, the catchment will be susceptible to high magnitude events
Q5/Area	A measure of flood generation potential: the larger the ratio, the greater the stream power
SAAR	High rainfall, wetter catchments exhibit greater stream power

In order to use available variables that most reflect the physical processes occurring within the SWBs, stream power will be represented as a function of discharge (thus representing stream velocity and channel dimensions) and stream slope (thus representing shear stress), Equation 5.

$$Power_{class} = f(dischrge, slope) \qquad \text{Equation 5}$$

For the above calculation the discharge was the mean annual flow, as defined for each water body. If LF2000 information was available the influenced mean flow was used; where this was not, an estimate of the natural mean flow, derived from a runoff grid, was used. Where this is the case it is noted within the typology database. River slope was calculated using the average percentage increase in elevation between 50-m grid squares within the boundaries of the SWB river corridor. Other surrogates, such as the average slope within the catchment area, and the elevation change within the SWB corridor, were also tested; however, the average percentage increase in elevation provided the best correlation when compared with measures of slope obtained from gauging station data.

4.4 Sediment thickness

Sediment thickness is assumed to be related to both the power within the SWB (i.e. the ability of the SWB to transport sediment) and the sediment supply (i.e. the amount of sediment which is delivered to the SWB). The balance between these will provide an indication of the relative sediment thickness. This methodology is only appropriate for the estimation of fine sediment thickness, and an estimate of the coarse sediment thickness will not be made.

Where stream power is adequate to support transport of the sediment load imposed by erosive processes, all sediment inputs to the SWB will be transported as opposed to being deposited. Where stream power is insufficient, sediments will be deposited on the stream bed. A critical power threshold will separate the two modes, which is dependent on the relative magnitude of power needed to transport the sediment delivered into the stream channel, and the actual power available with respect to discharge and slope conditions (as described above). Bull (1979) offers explanation of the differing states of fluvial systems with respect to such a critical power threshold. Where actual stream power is higher than the critical stream power threshold in upstream sections of a river (high gradient, low sediment load), no sediment deposition occurs. By contrast, downstream sections of rivers (low gradient, high sediment load), are characterised by critical stream power thresholds higher than actual stream power available, and therefore sediment will tend to be deposited. In mid-catchment sections of the river, the ratio between the critical power threshold and actual power available will be more dynamic, as it will be more sensitive to locally scaled changes in both sediment supply and stream gradient.

The ratio of relative stream power (as predicted for the power axis) to sediment (as predicted by the sediment supply axis) is therefore used to signify the type of processes that will dominate each SWB, and hence the relative abundance of fines that will be found deposited at the surface layer of the HZ. Note that this will only provide a relative depth for each SWB.

4.5 Sediment permeability

The permeability of sediments that make-up the HZ will be a product of *in situ* sediments into which the stream has been cut, represented by the drift, and the transported sediments that have been deposited over a period of years, represented by the additional fine sediment supply.

The sediment permeability axis was therefore separated into two distinct classifications. The first classification uses the drift information to provide an indication of the permeability based on the types of drift within the SWB. The second classification combines this information with that obtained from the fine sediment thickness axis which represents an additional supply of fine material.

The first classification provides an indication of the underlying substrate’s permeability. Where fines exist they are assumed to fill interstitial gaps in the more permeable substrate, such that it becomes less permeable at depth. The second classification provides an indication of the permeability of the exposed substrate. If there is a large supply of fines to the catchment then the permeability will be dominated by the mobile layer of fines; where there are fewer fines, this will represent the drift layer. It is assumed that fines within the upper drift layer will be winnowed out where the power within the stream is sufficient, thus providing a more permeable exposed substrate layer.

The underlying permeability of the rock was not considered as this will be included as part of the subsurface permeability axis.

4.6 Subsurface permeability

Rather than using the WFD groundwater typology map as originally proposed, the 1 km^2 HOST map was used to obtain catchment-averaged BFI estimates for each water body. This will act as a more process-orientated indicator of average SWB connectivity with the underlying geology. The resulting BFI number will then be scaled to an appropriate permeability class.

4.7 Sediment geochemistry

In order to determine the geological characteristics of the HZ for a single water body, the geochemical properties of the dominant geological cover need to be determined. This was done by assessing the percentage cover of each of the geochemical properties (see Table 4.6).

Table 4.6 Geological occurrence data table

Geochemical property type	% cover
Absent	0
Present	<5
Subdominant	5–50
Dominant	>50

The approach used for classification of geochemical properties of geological formations (including superficial deposits) and river-bed sediments considers selected geochemical properties of sediments or rocks that attenuate pollutant migration (normally by retardation due to sorption processes). At the first (Tier 1) assessment of HZ properties, broad scale data and assumptions are used to develop a classification at water body scale. At further more detailed tiers (focusing on specific reaches) more detailed data can be applied to generate a more accurate prediction of HZ attenuation capacity.

The formulation of classes for geochemical properties of cation exchange capacity (CEC), fraction of organic carbon (f_{oc}) and total inorganic carbon (TIC) are described below. They represent the main geochemical controls on pollutant retardation in the subsurface. The approach is described fully in Smith and Lerner (2007).

4.7.1 Fraction of organic carbon

The quantity (and type) of organic carbon in a sediment affects the apparent velocity by which organic pollutants migrate through an aquifer or sediment. Organic molecules often partition into or onto other organic compounds in preference to remaining in aqueous solution. The degree to which an organic molecule partitions from aqueous to organic medium, its hydrophobicity, is described by a partition coefficient, K_{oc}, which represents the ratio of mass in organic to aqueous media at equilibrium conditions. In geological media, a distribution coefficient, K_d, describes partitioning between water and media possessing only a fraction of organic carbon.

At low pollutant concentrations it is often assumed that the distribution coefficient can be represented by a linear isotherm, which is often approximated by:

$$K_d = K_{oc}.f_{oc}$$

where K_{oc} is the organic carbon partition coefficient and f_{oc} is the fraction of organic carbon in the sediment.

The effect of sorption processes is to slow the movement of a pollutant through an aquifer. The increased flow velocities can be described by a retardation factor, R_f, where:

$$R_f = 1 + \left(\frac{K_d.\rho}{n}\right) = 1 + \left(\frac{K_{OC} \cdot f_{OC} \cdot \rho}{n}\right) \quad \text{and} \quad u = v.R_f$$

where ρ is the bulk density (of sediment) – assumed = 2000 kg/m^3; n is porosity (of sediment) – assumed = 0.3; u is pollutant velocity and v is water velocity.

For the purpose of this exercise, the properties of a number of common organic groundwater pollutants have been examined. An assessment was undertaken to determine the amount of aquifer organic carbon (f_{oc}) that would cause retardation of each pollutant (in a single pollutant plume) by a factor or 5, 50 and 500 (i.e. the necessary f_{oc} to achieve an R_f equal to 5, 50 and 500).

The most common industrial organic pollutants in groundwater systems include the chlorinated ethenes associated with industrial degreasing and dry-cleaning activities, and BTEX compounds derived from releases of petroleum hydrocarbons. Organic pesticides are also common in groundwater, albeit at normally much lower concentrations. For the purpose of this exercise a selection of chlorinated ethenes have been evaluated. This group has been selected because they are (a) common pollutants and (b) have intermediate hydrophobicity between weakly sorbed pollutants such as phenol and very strongly sorbed substances such as the PAHs.

The relationship between f_{oc} and R_f has been calculated for compounds with K_{oc} values of 126, 364, 424 and 2000 l/kg respectively. TCE has a K_{oc} value of 126 l/kg and PCE 364 l/kg (Mackay *et al*. 1993). Xylene has a K_{oc} of 424 l/kg and naphthalene has a K_{oc} of 2000 l/kg. A retardation factor, R_f of 5, 50 and 500 is achieved for each of the four modelled pollutants when there is a sediment f_{oc} value as summarised in Table 4.7.

Table 4.7 Calculated f_{oc} required to achieve selected R_f values for a range of organic pollutants

	K_{oc}			
R_f	**126 l/kg (TCE)**	**424 l/kg (xylene)**	**364 l/kg (PCE)**	**2000 l/kg (naphthalene)**
5	0.0048	0.002	0.0016	0.0003
50	0.058	0.025	0.020	0.0036
500	0.59	0.25	0.21	0.037

On the basis of this evaluation, it is suggested that the division of f_{oc} attenuation categories is based on the results for PCE sorption (see Table 4.8).

Table 4.8 Fraction of organic carbon classification table

Attenuation class	f_{oc} value	Organic carbon (%)
Low organic sorption potential	<0.002	<0.2%
Moderate organic sorption potential	0.002–0.02	0.2–2%
High organic sorption potential	0.02–0.2	2–20%
Extremely high organic sorption potential	>0.2	>20%

4.7.2 Cation exchange capacity

Charged ions will sorb onto mineral grains with an opposite electrostatic charge, subject to the availability of an exchange site and the ability to exchange with an ion with a lesser affinity for the sorption site. In the subsurface environment this normally involves the sorption of positively charged ions onto negatively charged clay mineral surfaces. The potential for sorption of cations on a mineral surface is measured as a CEC, having units of equivalents per unit mass. In geological applications CEC is normally described in milliequivalents per 100g (meq/100 g) or kg (meq/kg) of sediment.

Most cation-based pollutant plumes are complex mixtures, such as landfill leachate. CEC is a complex process that requires the competitive effects of multiple cations to be considered. In order to simulate the behaviour of a multi-species plume the Environment Agency's cation exchange in landfill liners worksheet (Smith 2001) has been modified to calculate effective R_fs for each cation in a complex plume comprising 14 cations (see Table 4.9). The worksheet simulates cation transport following solutions in Apello and Postma (1993) and is described in detail in Smith (2001). It has been assumed that the plume has a composition equivalent to the mean concentration of each cation measured in numerous landfill leachate plumes, and reported in DoE (1995). Assumed cation concentrations for this calculation are shown in Table 4.10 (sediment density = 2000 kg/m^3, sediment porosity = 0.3).

On the basis of this analysis, it is suggested that the mean of the lead and cadmium cation exchange behaviours, which are the most hazardous substances present (to human health) are used to derive classes for significance of CEC processes. However, current laboratory lower reporting limits for CEC are around the 2–3 meq/100 g level. Therefore, the lower threshold is increased to 5 meq/100 g to overcome practical difficulties of assessing against 'less than' values. Attenuation classes are shown in Table 4.11.

Table 4.9 Calculated CEC (meq/100 g) required to achieve selected R_f values for a range of cations in a landfill leachate plume

	Cation			
R_f	Mg^{2+} (or Cu^{2+})	Cd^{2+}	NH_4^+	Pb^{2+}
5	3.4	2.2	10	1.2
50	42	27	120	15
500*	(430)	(270)	(1300)	(150)

* CEC values required to produce R_f values greater than 500 are greater than observed values found in geological media, and are shown in parentheses for completeness.

Table 4.10 Assumed cation concentrations

Cation	Concentration (mg/l)	$K_{Na/i}$	β cation
Na^+	2000	1	0.129
NH_4^+	1000	0.25	0.330
K^+	800	0.2	0.152
Rb^+	0.1	0.1	0.000
Fe^{2+}	350	0.6	0.038
Mn^{2+}	15	0.55	0.002
Mg^{2+}	250	0.5	0.091
Ni^{2+}	0.2	0.5	0.000
Cu^{2+}	0.1	0.5	0.000
Ca^{2+}	750	0.4	0.257
Cd^{2+}	0.02	0.4	0.000
Zn^{2+}	3.5	0.4	0.001
Sr^{2+}	2	0.35	0.000
Pb^{2+}	0.2	0.3	0.000

Table 4.11 Cation exchange capacity classification table

Attenuation class	CEC (meq/100 g)
Low cation exchange potential	<5
Moderate cation exchange potential	5–20
High cation exchange potential	>20
Extremely high cation exchange potential	No class defined

4.7.3 Total inorganic carbon

The acid buffering capacity of an aquifer is largely dependent on the $CaCO_3$ content of the aquifer minerals and cements. To determine acid buffering capacity thresholds (as expressed as total inorganic carbon, TIC), the following assumptions are made:

- A spillage of 50,000 litres of 1M HCl represents a reasonable worst-case acute industrial acid spill.
- A plume is generated that is 2 m thick and 5 m wide (plume cross-section of 10 m^2).
- The aquifer has a porosity of 0.3, and the acid–base reaction is instantaneous and as follows:

$$2HCl + CaCO_3 \leftrightarrow CaCl_2 + H_2O + CO_2$$

- However, the reaction efficiency is only 10%, due to limited exposure of mineral ($CaCO_3$ surface within sediment grains).
- An aquifer/sediment has a high buffering capacity if it is capable of neutralising a 50,000 litre 1M HCl spill within 10 m. Criteria for low buffering capacity are set at incomplete buffering within 100 m, and moderate buffering is plume buffering between 10 and 100 m from the spill location.

Using a similar approach to calculate the TIC to limit an acid plume within 10 and 100m respectively gives the criteria listed in Table 4.12. On the basis of these calculations, acid buffering attenuation classes are shown in Table 4.13.

Table 4.12 Calculated TIC and calcium carbonate required to buffer a 50,000 litre 1M HCl plume within 10 and 100 m of aquifer

Plume length (m)	TIC		$CaCO_3$	
	(g-C/kg)	(%)	(g-$CaCO_3$/kg)	(%)
10 (high buffer)	15	1.5	125	12.5
100 (low buffer)	1.5	0.15	12.5	1.25

Table 4.13 Total inorganic carbon classification table

Attenuation class	TIC (%)
Low acid buffering potential	<0.2
Moderate acid buffering potential	0.2–2
High acid buffering potential	>2
Extremely high acid buffering potential	No class defined

A series of attenuation classes based on sediment/aquifer organic sorption, cation exchange and acid buffering capacity have been derived that broadly describe the environmental significance of those processes in a hypothetical aquifer environment. Three classes are defined for CEC and TIC, while a fourth class is defined for f_{oc}, to provide a better description of the sorption potential of very organic rich materials, such as peat and other similar superficial deposits. The proposed pollutant attenuation classes are given in Table 4.14.

Table 4.14 Nett attenuation classification table

Attenuation class	f_{oc} value (fraction)	CEC (meq/100g)	TIC (%)
Low attenuation potential	<0.002	<5	<0.2
Moderate attenuation potential	0.002–0.02	5–20	0.2–2
High attenuation potential	0.02–0.2	> 20	>2
Extremely high attenuation potential	>0.2	No class defined	No class defined

If drift geology is present, then this should be taken account of in preference to solid geology (note – the assumption is made that where it is indicated on the map, drift will be significantly thick).

5 Mapping of hyporheic zone classification axes

The final classification of the HZ for each SWB is based on the characteristics of the SWB relative to the axes outlined above. These are:

- Sediment supply
- Power
- Sediment thickness
- Sediment permeability
- Subsurface permeability
- Sediment geochemistry.

Once the final dataset had been collated the results were used to derive preliminary classifications for each of the axes, generally into three categories, low, moderate and high. The boundaries for the different classes were determined by assessing the distribution of values within the dataset (although it was not thought appropriate to ensure equal numbers of SWB within each category) and by visually examining the spatial distribution of the variable. There was little field data against which to check the classification boundaries of each axes; however, the preliminary results for the sediment permeability axis were developed using the substrate data from the RHS database and descriptions of the HZ classification from site visits within the Severn catchment. The spot check data, in which substrate observations were noted, was extracted from the RHS database. This provides a description of the substrate at ten points along the RHS survey. The information was disaggregated, in a similar way to the drift data, to provide proportions of particle sizes at each RHS survey point. Where more than one RHS survey existed within a SWB this information was aggregated to provide an average for the SWB.

The resultant maps of each axis classification illustrate the spatial patterns associated with each axis. The information from each of these axes is then used within the final HZ typology.

5.1 Sediment supply

The fine sediment supply is considered separately to the supply of coarse material. The total fine sediment supply is calculated for the contributing catchment for each SWB. These values were then classified into low, moderate and high supply (Table 5.1). Note that the total fine sediment value is a dimensionless value and is used as a relative measure of sediment supply (see Figure 5.1).

Table 5.1 Classification for total fines sediment supply

Supply	Total fines sediment supply value
Low	<=5
Moderate	<=50
High	>50

For coarse sediment the percentage of drift present within the catchment was used. Since only coarse material was being considered, only particle sizes greater than silt were considered. Table 5.2 present the boundaries for this classification. Figure 5.2 illustrates the spatial distribution of the classes within SWBs. It should be noted that these results are presented here for completeness. The classification of sediment supply of coarse material is not used to provide an indication of the thickness of sediment, as the fine sediment supply axis is, and the information is unlikely to be included within the final HZ typology.

Table 5.2 Classification for coarse sediment supply

Supply	% drift
Low	<50
Moderate	>=50
High	>=80

5.2 Power

The power for each SWB was classified as low, moderate or high, Table 5.3. Power, in this case, is a relative value, which allows the comparison of power within different SWBs but does not represent absolute stream power. The spatial distribution of the classes within SWBs is presented within Figure 5.3.

Table 5.3 Classification for power

Class	Power
Low	<2
Moderate	>=2
High	>=20

5.3 Sediment thickness

The classification for sediment thickness is based on the power/fines ratio, that is the ratio of the ability of the SWB to transport fine sediment and the quantity of sediment that is supplied. The thickness of fine, mobile, sediment will be greater at lower values of power/fines than where this value is high. This value represents the relative fines sediment thickness and is not an absolute value. The depth of coarse sediment cannot be estimated, as information on the depth of the drift is unavailable.

The boundaries for the fine sediment thickness were estimated using a sample of RHS catchments and the Severn catchment data, analysing the power/fines ratios at which fines become the dominant feature of the substrate. This is presented in Table 5.4. Figure 5.4 presents the spatial distribution of classes for SWBs.

Table 5.4 Classification for sediment thickness

Supply	P/F *1000 ratio sediment thickness
Low	>100
Moderate	>50
High	<=50

5.4 Sediment permeability

As outlined within Section 4.5, the sediment permeability was split into two classifications: the first in which only the drift information is used, the second in which the fine sediment supply is also considered.

For the first classification, using the drift information, each SWB was categorised into low moderate or high permeability according to the particle sizes that were present within the SWB, based on the BGS mapping of drift geology. This considered both the size and range of sediments present. Where both fines (impermeable) and coarse material (permeable) were present it was assumed that the overall permeability would be controlled by the presence of fines, reducing the permeability. The categories of sediment sizes, and how these relate to the permeability of the substrate are presented in Table 5.5.

Table 5.5 Classification for sediment permeability

Permeability	Size classes
Low (L)	Peat, clay, silt
Moderate (M)	Sand, gravel
High (H)	Pebbles, cobbles, boulders
Bedrock (B)	Bedrock

If there was more than 50% of any one aggregated grain size class present, then the permeability class relating to this sediment type was assigned. If no permeability class had more than 50% present, then all those classes the contributed greater than 15% were considered.

Table 5.6 presents the resulting assigned permeability associated with the presence of the permeability classes (L, M, H, B) present within each SWB. A 'Y' indicates the presence of sediments with low, moderate, high or bedrock permeability within each SWB.

Table 5.6 Resultant sediment permeability based on sediment size classes present

Permeability class present (Y)				
L	M	H	B	Resultant permeability
			Y	B
		Y		H
		Y	Y	H
	Y			M
	Y		Y	M
	Y	Y		M
	Y	Y	Y	M
Y				L
Y			Y	L
Y		Y		M
Y		Y	Y	M
Y	Y			L
Y	Y		Y	M
Y	Y	Y		M
Y	Y	Y	Y	M

The spatial distribution of the drift permeability is presented within Figure 5.5. It should be noted that the bedrock present within south Wales is more a feature of the fact that the 1:625,000 drift map was used for these SWBs rather than a true representation of the drift in this area. The 1:625,000 map shows far less detail than the 1:50,000 map used for other SWBs.

The second stage of the permeability assessment is to take into account the additional fines introduced to the SWB. The amount of fine sediment introduced to the system is based on the power/fines ratio. An additional power factor was also introduced. If the additional fines supply was low, and the power was greater than 2, then the permeability of the substrate was considered to be higher than if the fines supply was low and the power was less than 2. As explained previously, this attempts to represent the winnowing of fines (present within the drift layer) within the upper layers of the substrate. The resultant permeability associated with combining the fine sediment thickness and drift permeability classification is presented within Table 5.7 and represents the exposed substrate permeability (Figure 5.6).

Table 5.7 The exposed substrate permeability associated with combining fine sediment thickness classification, drift permeability classification and power

Fine sediment thickness classification	Drift permeability classification	Resultant permeability if power is less than 2	Resultant permeability if power is greater than 2
H	B	L	L
H	H	L	L
H	L	L	L
H	M	M	M
L	B	M	H
L	H	M	H
L	L	M	H
L	M	M	H
M	B	M	M
M	H	M	M
M	L	M	M
M	M	M	M

5.5 Subsurface permeability

The subsurface permeability is classified according to the value of BFI for each SWB. Table 5.8 presents the boundaries for the classification. The spatial distribution of the permeability is presented within Figure 5.7.

Table 5.8 Geological permeability class

Permeability	BFI
Low	0–0.4
Moderate	0.4–0.6
High	0.6–1

5.6 Sediment geochemistry

The WFD river networks were intersected with the 1:50,000 solid geology maps (or 1:625,000 where necessary) to obtain the length of river associated with each solid geology lexicon or rock description. The attenuation capacity (low, medium and high) of geological media (using the 1:625,000 lexicon descriptions) for each of CEC, f_{OC} and TIC were estimated using field data where possible. The 1:50,000 lexicon was then mapped to these rock descriptions. There were 2220 different 1:50,000 lexicon classes, hence the classification was only completed for the lexicon classes with the largest surface areas within the UK. All classes that cumulatively account for up to 60% of the UK were mapped to the 1:625,000 rock descriptions. Where possible other lexicon classes were also mapped.

The attenuation classes were then mapped to the WFD rivers, which had previously been intersected with the solid geology. As a result, the length of river for each of CEC, f_{OC} and TIC with low, medium or high attenuation was found. Figures 5.8, 5.9 and 5.10 present the attenuation classes for CEC, f_{OC} and TIC respectively.

Since it was not possible to assign all the lexicon classes to attenuation classes there are some water bodies that are unclassified. Within future processing it may be possible to assign these with the same attenuation as the majority of surrounding water bodies, since there are clear geographical trends. However, at this stage it was thought important that the location of missing data was retained, and any validation efforts focused on water bodies with actual geochemical data.

While it would have been preferable to also consider the drift geology in order to assign the attenuation capacities, information on the geochemistry of drift deposits was not available at a national scale. The inclusion of the geochemistry of drift deposits would therefore be part of a Tier 2 investigation.

The mapped SWB categories are mostly as expected and reflect what is known to exist. Intuitively the Coal Measures outcrop in the Wigan–Bolton–Burnley area would be expected to have a high f_{OC} class. The bedrock at this point maps onto the Lower Westphalian Coal Measures (at 1:625,000 scale), which initially had an f_{OC} class of moderate. This was subsequently changed to high (to reflect the geochemistry of similar geological deposits elsewhere), and the f_{OC} classes were recalculated.

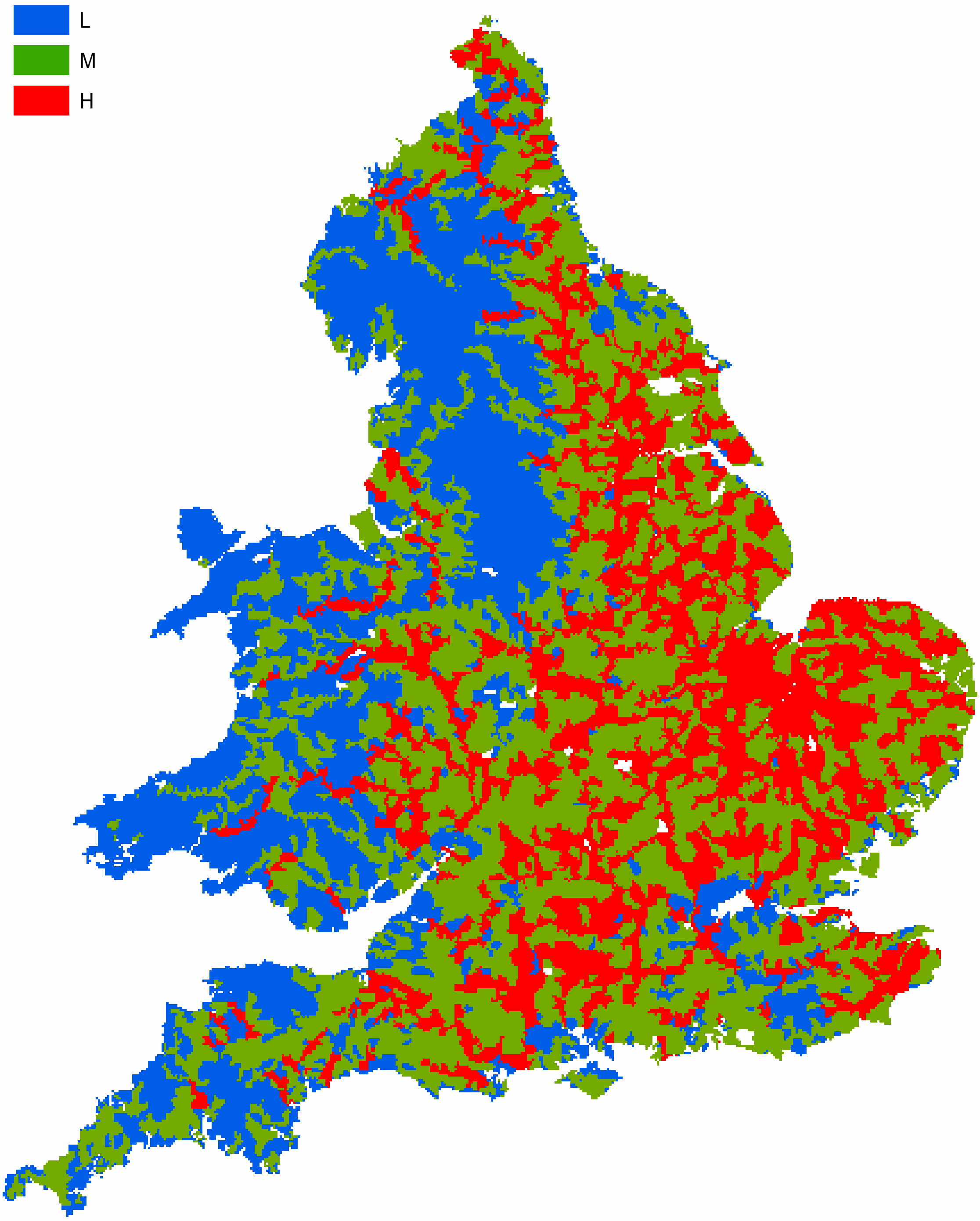


Figure 5.1 Distribution of fine sediment supply classes

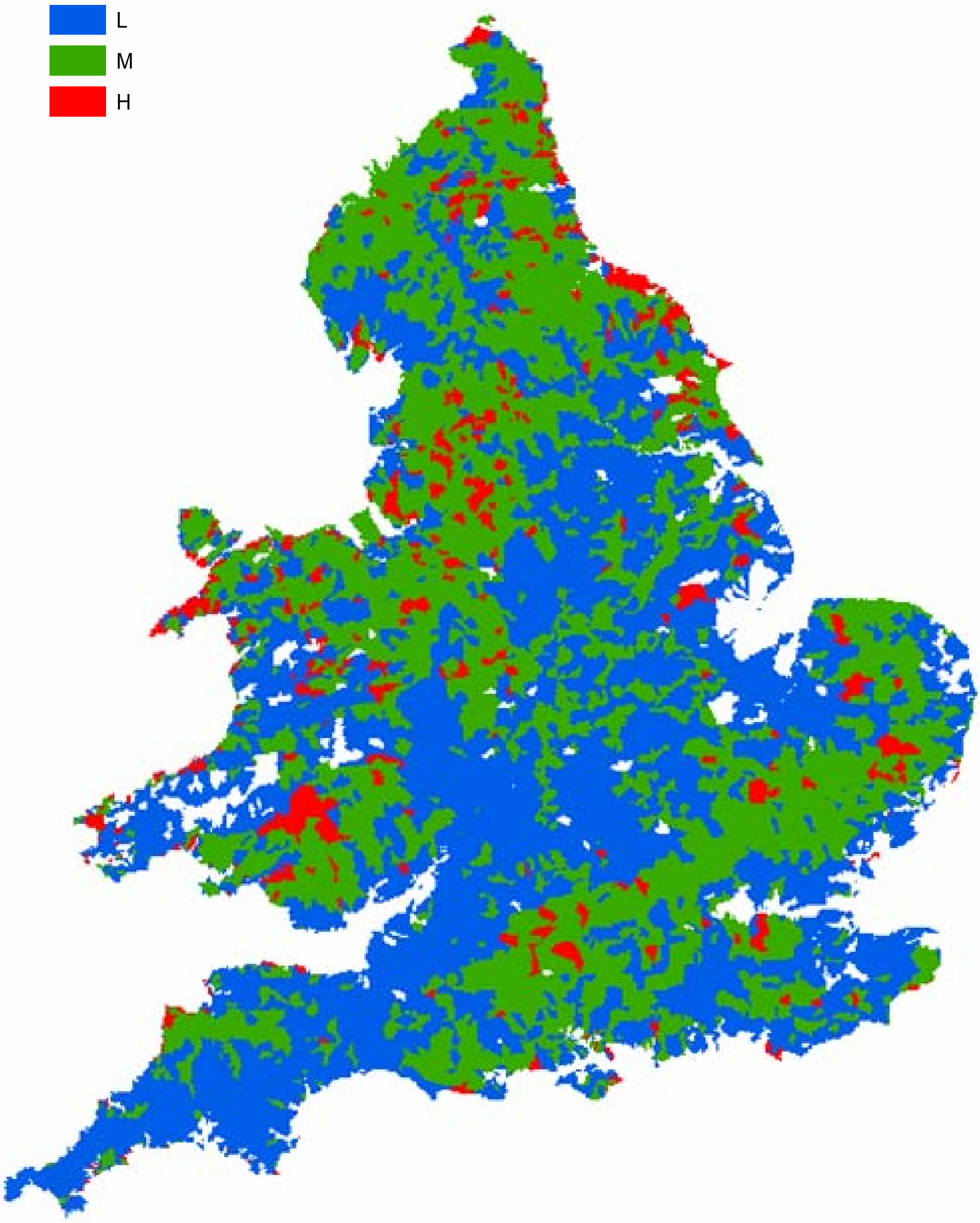


Figure 5.2 Distribution of coarse sediment supply classes

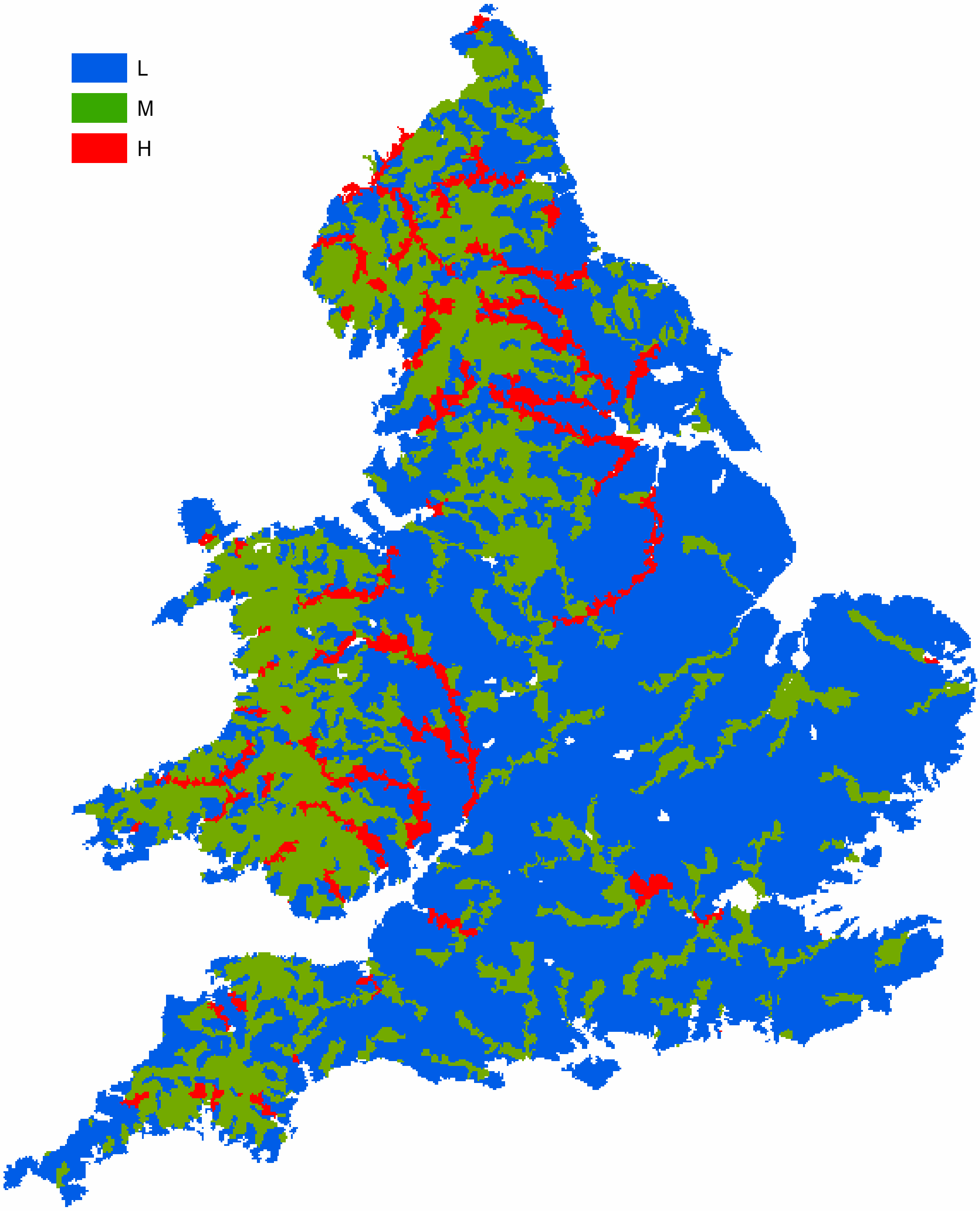


Figure 5.3 Distribution of stream power classes

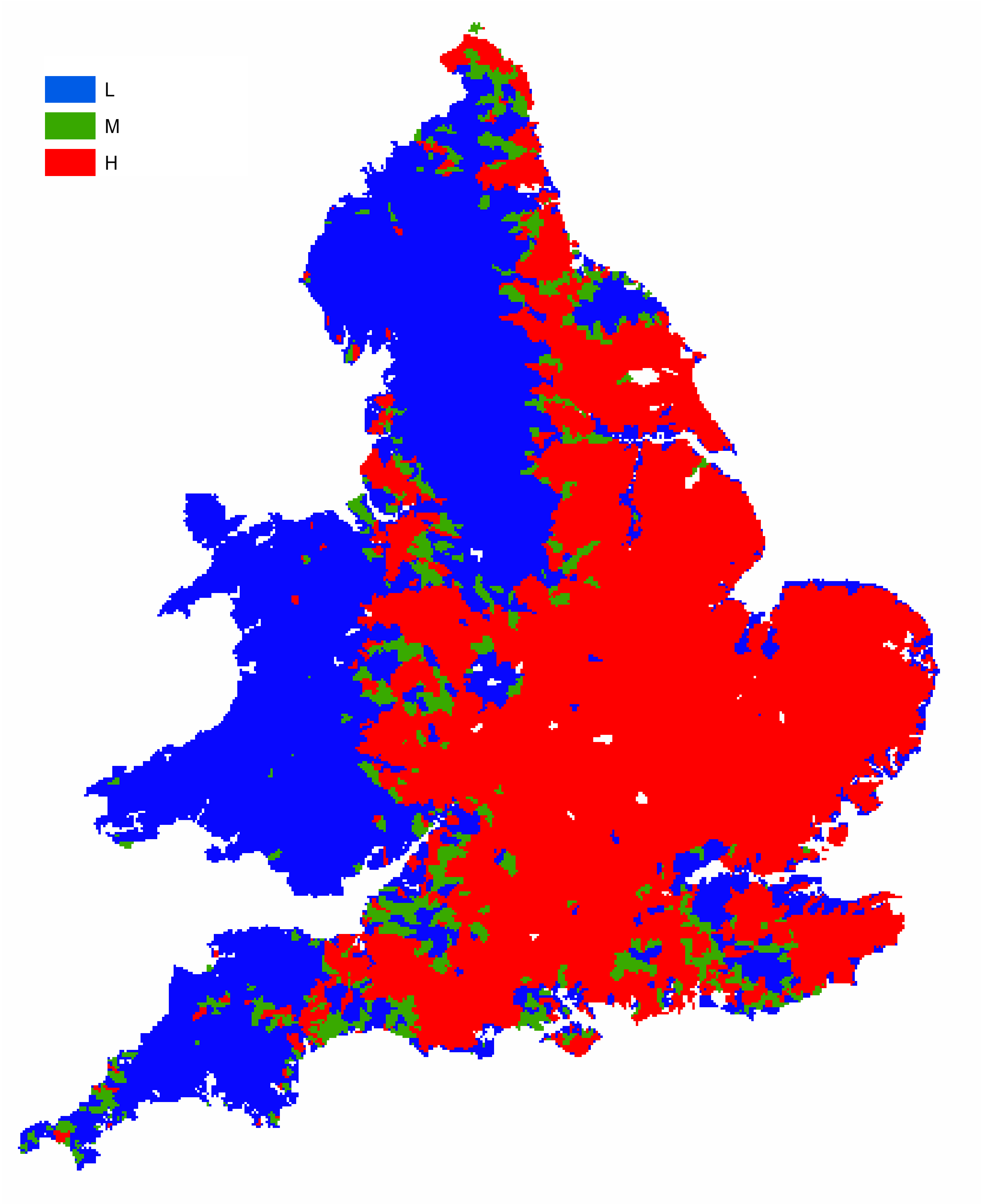


Figure 5.4 Distribution of fine sediment thickness classes

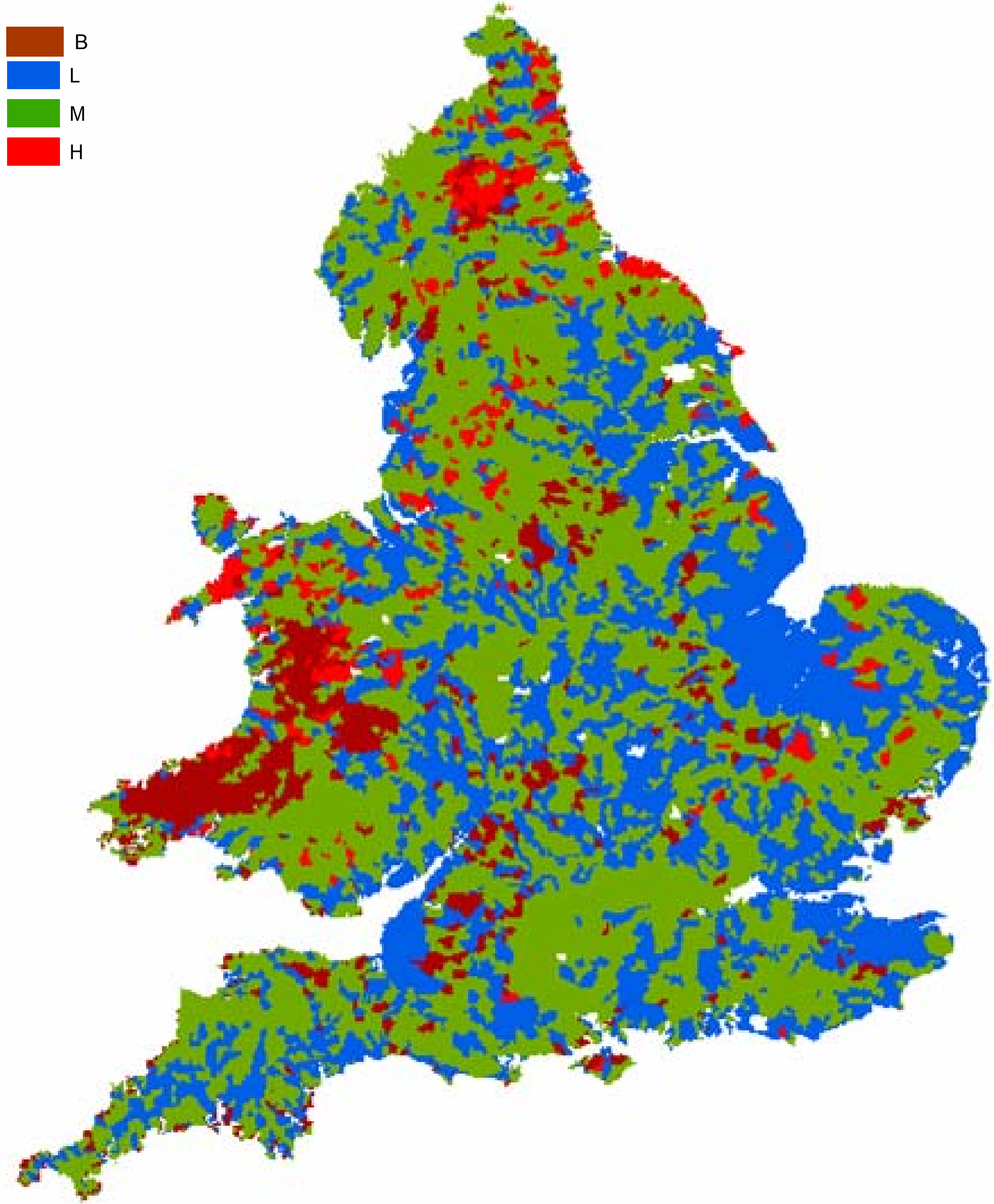


Figure 5.5 Distribution of drift-derived permeability classes

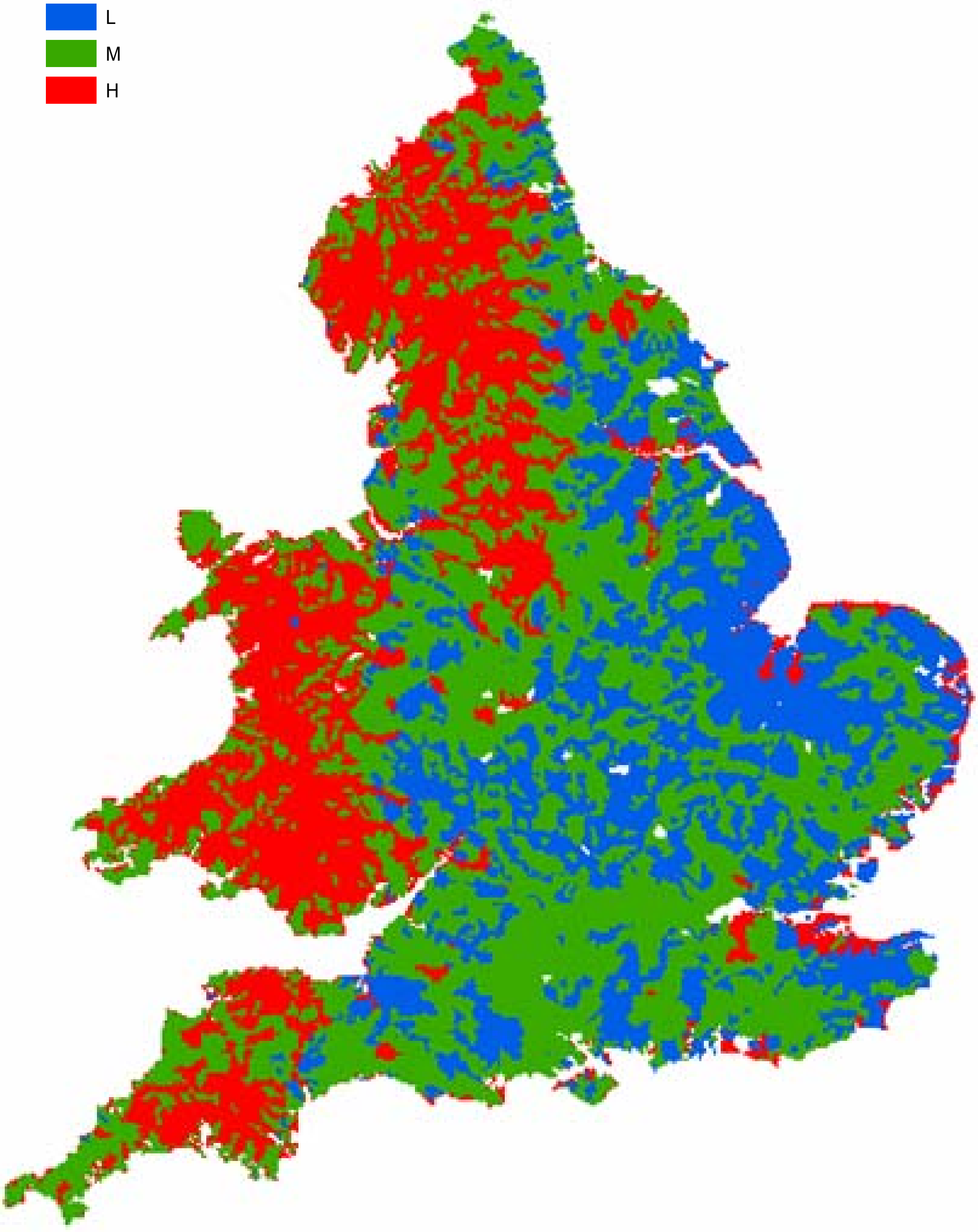


Figure 5.6 Distribution of exposed substrate permeability classes

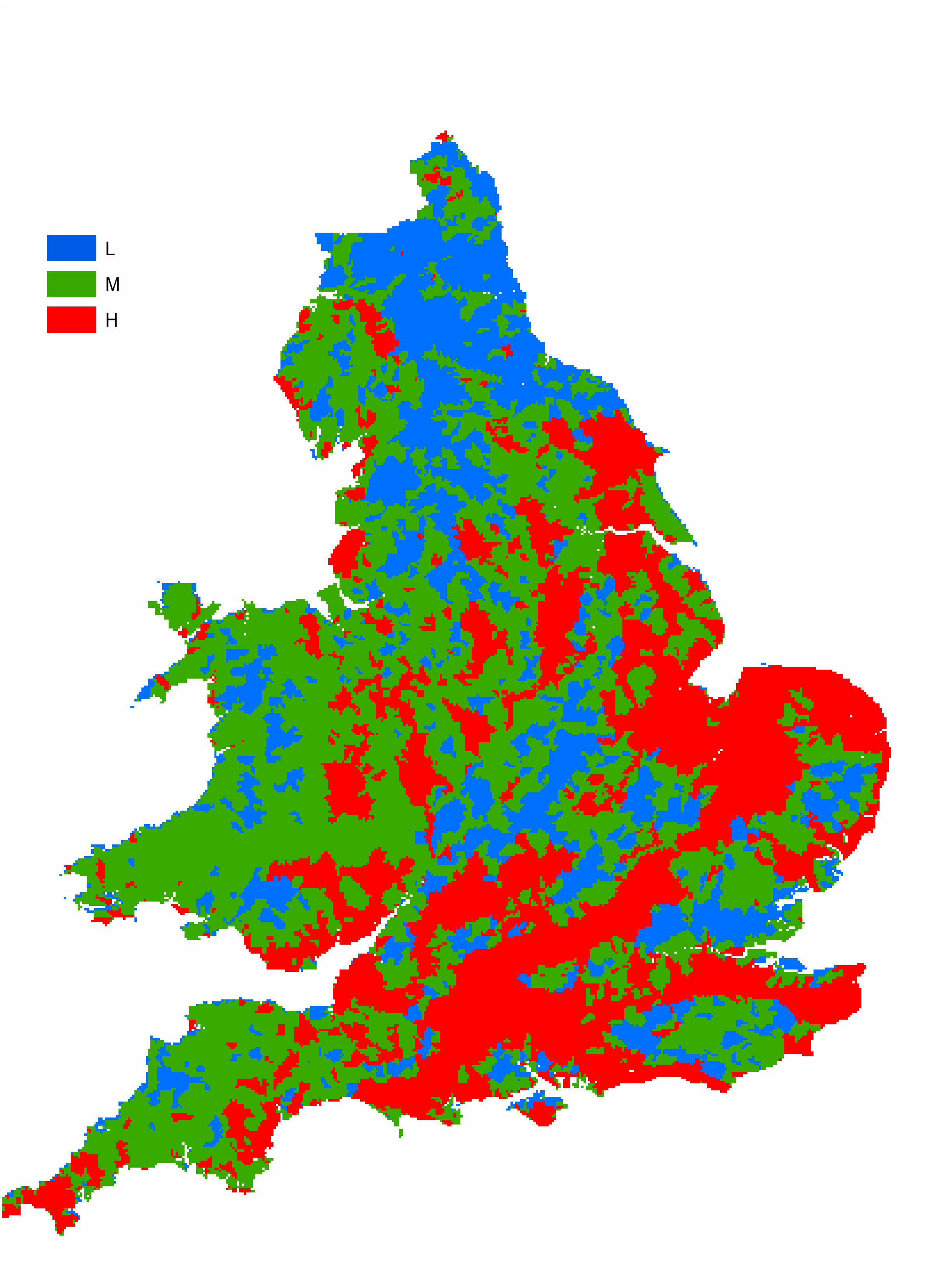


Figure 5.7 Distribution of subsurface permeability classes

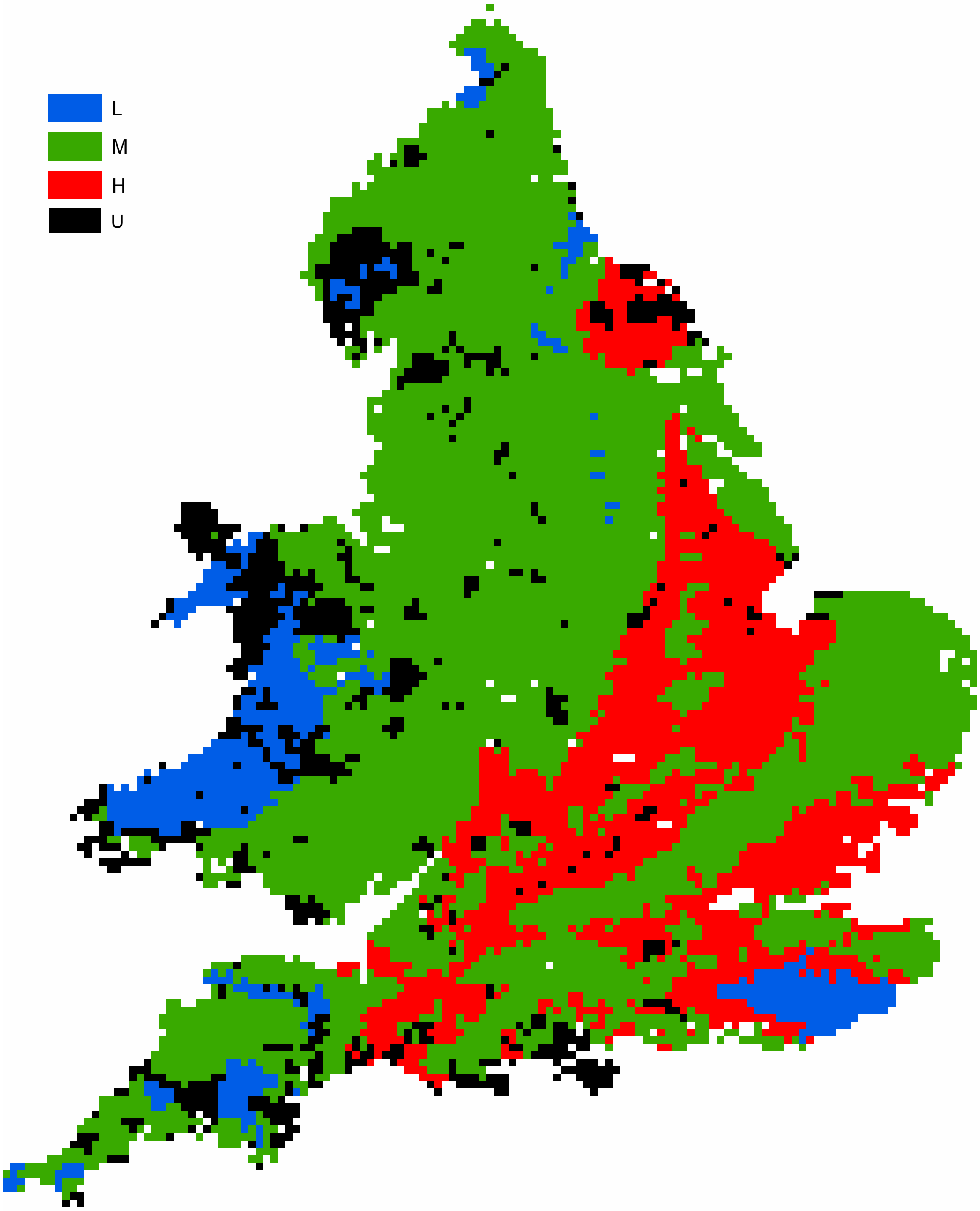


Figure 5.8 Attenuation classes for each WFD SWB for CEC

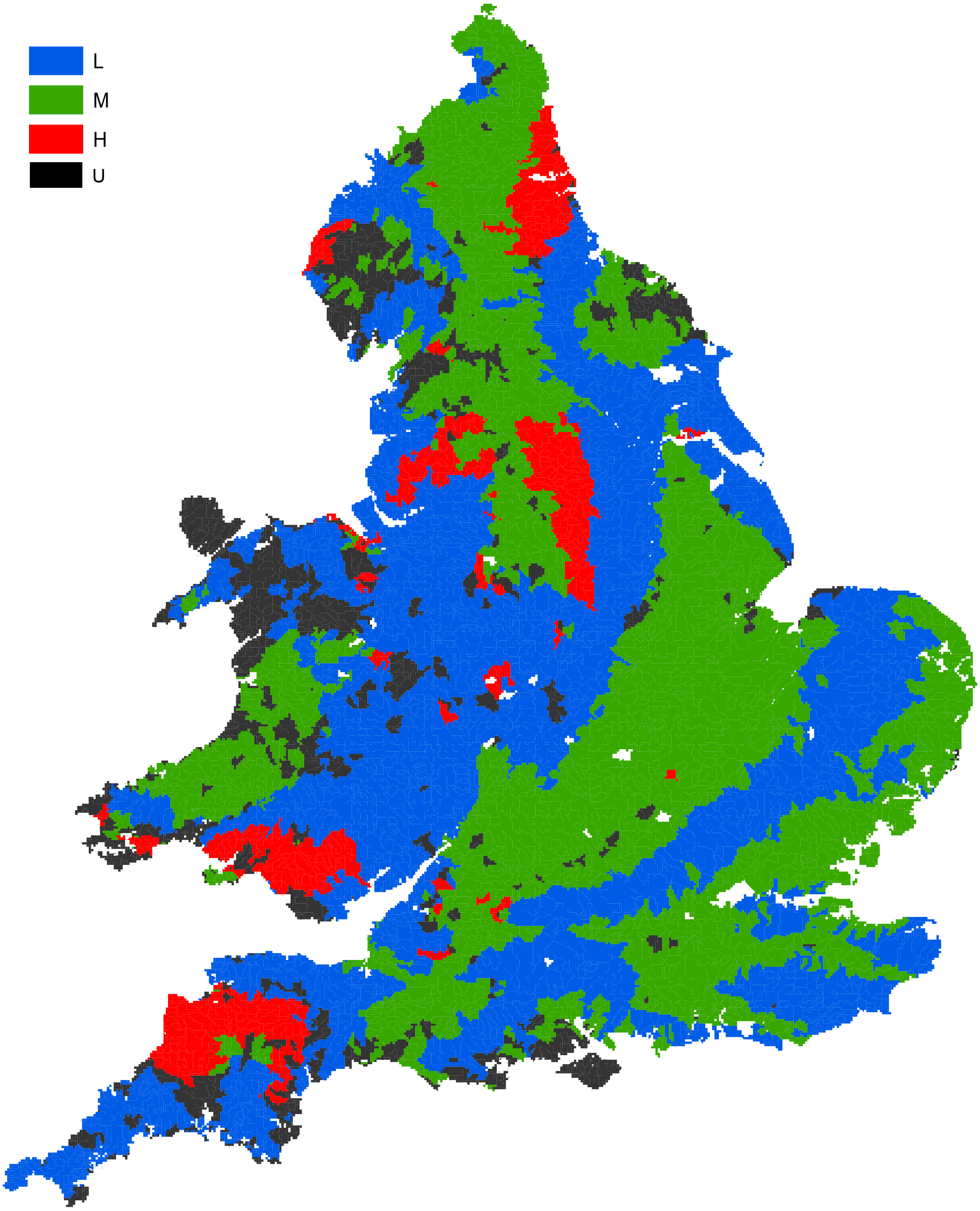


Figure 5.9 Attenuation classes for each WFD SWB for f_{OC}

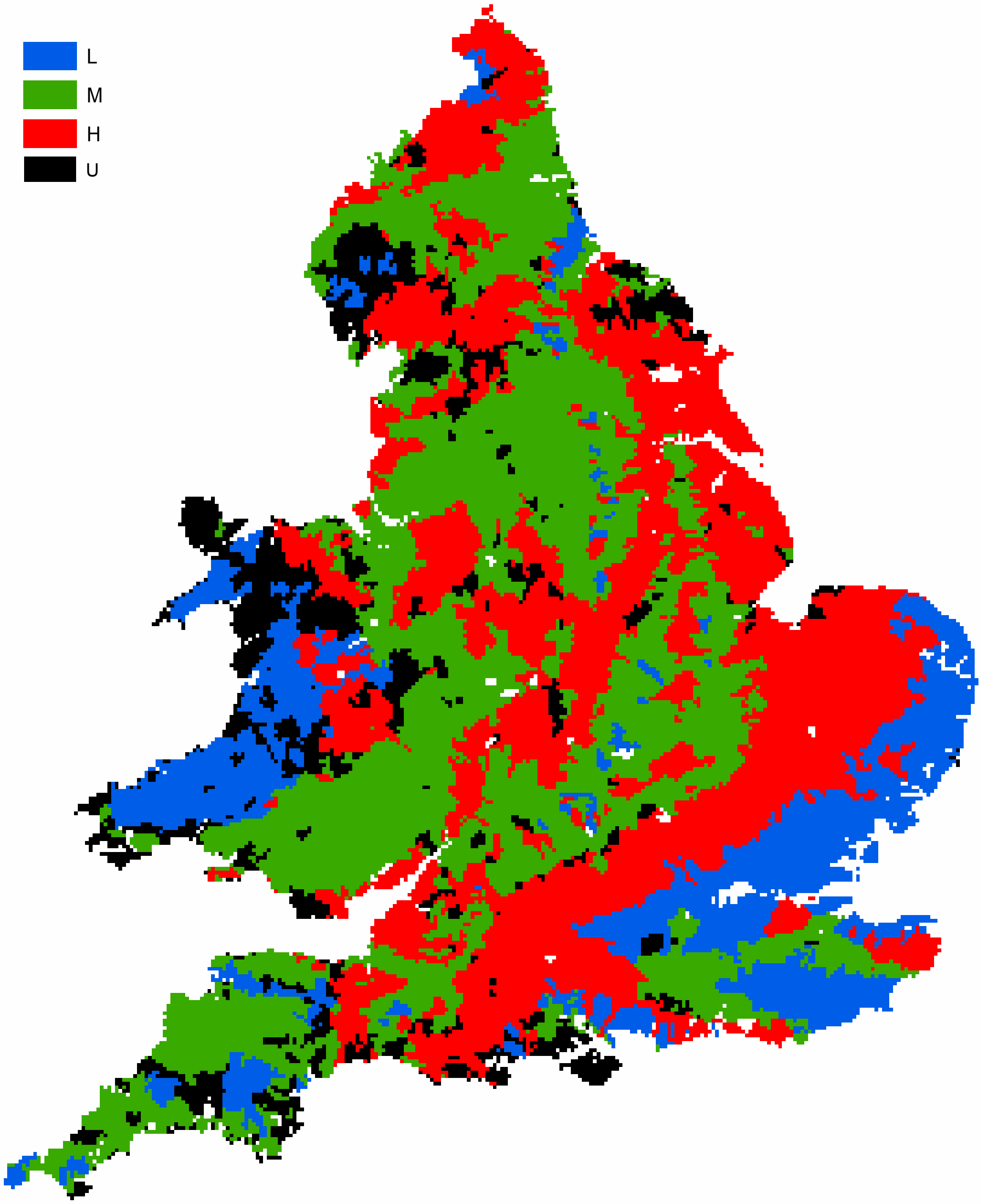


Figure 5.10 Attenuation classes for each WFD SWB for TIC

6 Hyporheic zone classification

The four axes used within the HZ classification are sediment thickness, sediment permeability, subsurface permeability and geochemical attenuation capacity. Each SWB has been assigned a class: low (L), medium (M) or high (H) for each axis. Geochemistry has an additional class of unclassified (U). Out of a possible 108 combinations of these classes, only 58 are found within the dataset that represents the water bodies in England and Wales. Figure 6.1 presents the percentage of SWBs within each of these class combinations. Figure 6.2 presents the location of these combinations for all SWBs within the UK dataset for which data was available.

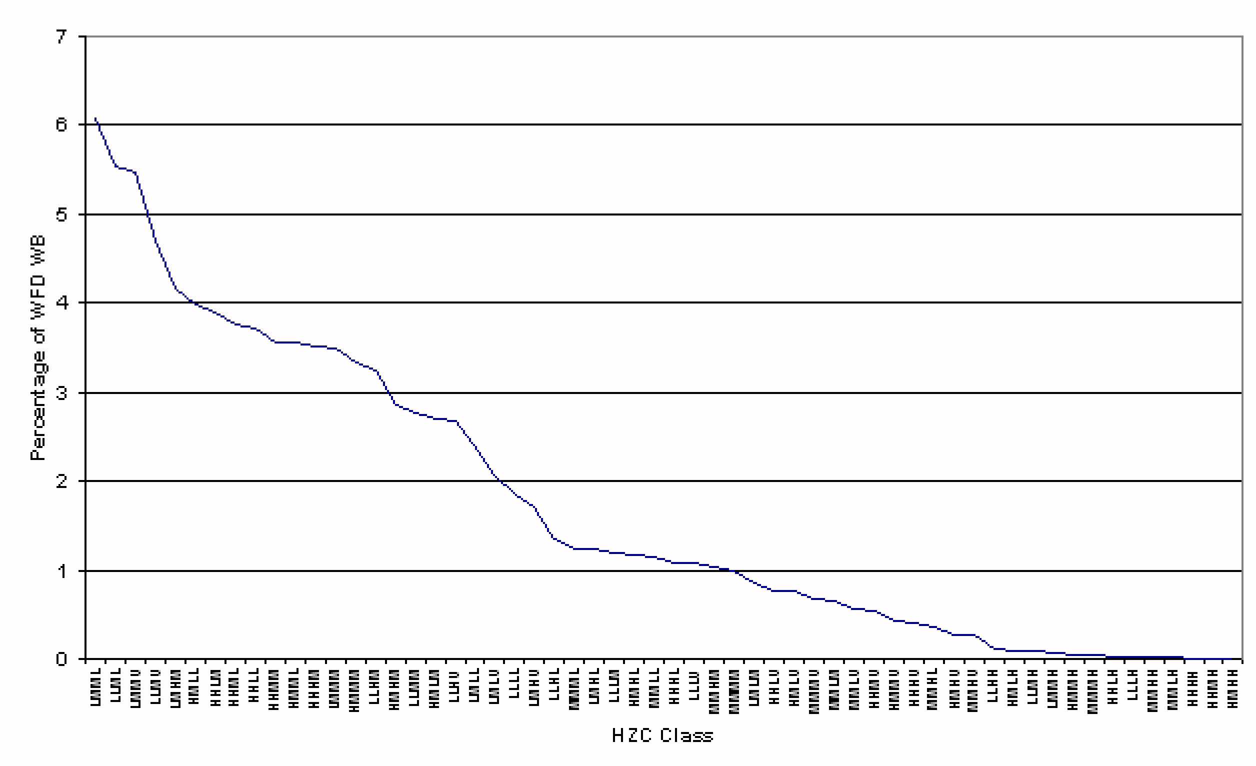


Figure 6.1 The percentage of SWBs within each HZ class (class abbreviations represent sediment thickness, sediment permeability, subsurface permeability and geochemistry respectively)

There were several ways by which the number of classes could be reduced in order to simplify the spatial distribution of SWB attenuation capacity. Several different methods were trialled. These were all based on the use of scoring systems. For this purpose it was assumed that a high classification for ‘sediment thickness’ axis for a SWB might be associated with a high attenuation capacity (due to increased residence time and/or reactive surface to attenuate pollutants passing through the sediment). Conversely, it was assumed that a high classification on the ‘permeability’ axis for a SWB represents a low attenuation capacity, due to decreased residence time in the sediments for reactive processes to occur.

The scores associated with each axis class are presented within Table 6.1. Where the geochemistry was unclassified this was not included within the scoring system. The scores for each axis were then summed (where the geochemistry was unclassified the total score was weighted to account for there being fewer values). This process produced attenuation scores of between 4 and 12 (to obtain a more meaningful number, 3 was subtracted from the total so that values ranged between 1 and 9).

Figure 6.3 presents the resulting HZ attenuation capacity classification using the simple scoring system in which all axes were summed. This system assumed that all the axes were of equal importance.

Within Figure 6.3, the sediment permeability and subsurface permeability axes have been combined. The lower class of the two axes was used for the classification of each SWB.

Table 6.1 Attenuation capacity scoring system associated to each axis classification

Axis attenuation class	Attenuation score
Low	1
Medium	2
High	3
Unclassified	-

6.1 Validation

Data from RHS spot checks and from field visits within the Severn catchment were used to validate the dataset. This available data was only suitable for comparison of the sediment permeability axis, and represents the exposed substrate permeability. Figure 6.4 presents the permeability determined, using the same process as that for drift, for RHS data.

Table 6.2 presents a comparison with substrate descriptions, and the assumed permeability associated with them, on the River Severn.

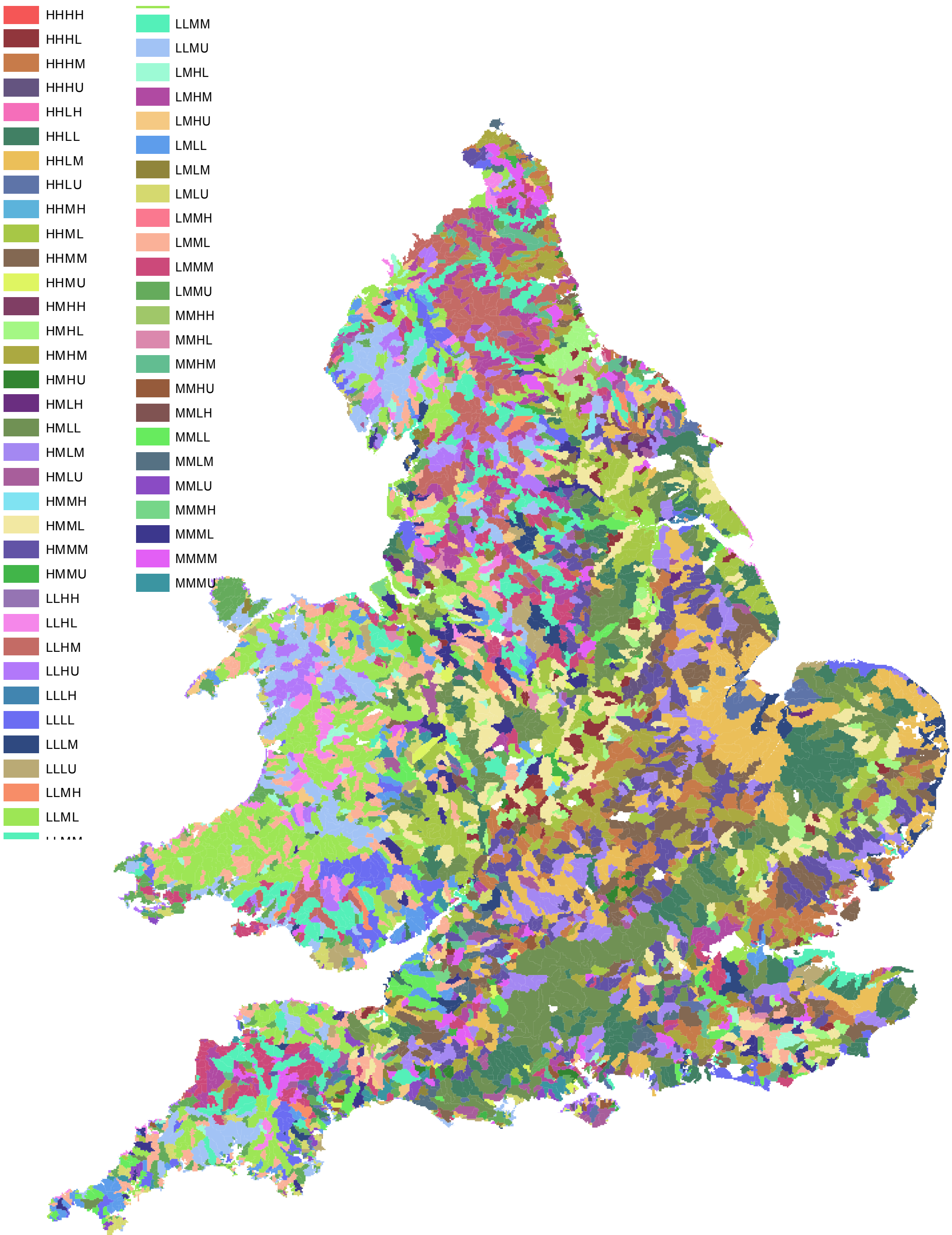


Figure 6.2 The 58 final HZC classes. In order, the classes represent sediment thickness, sediment permeability, subsurface permeability and geochemistry

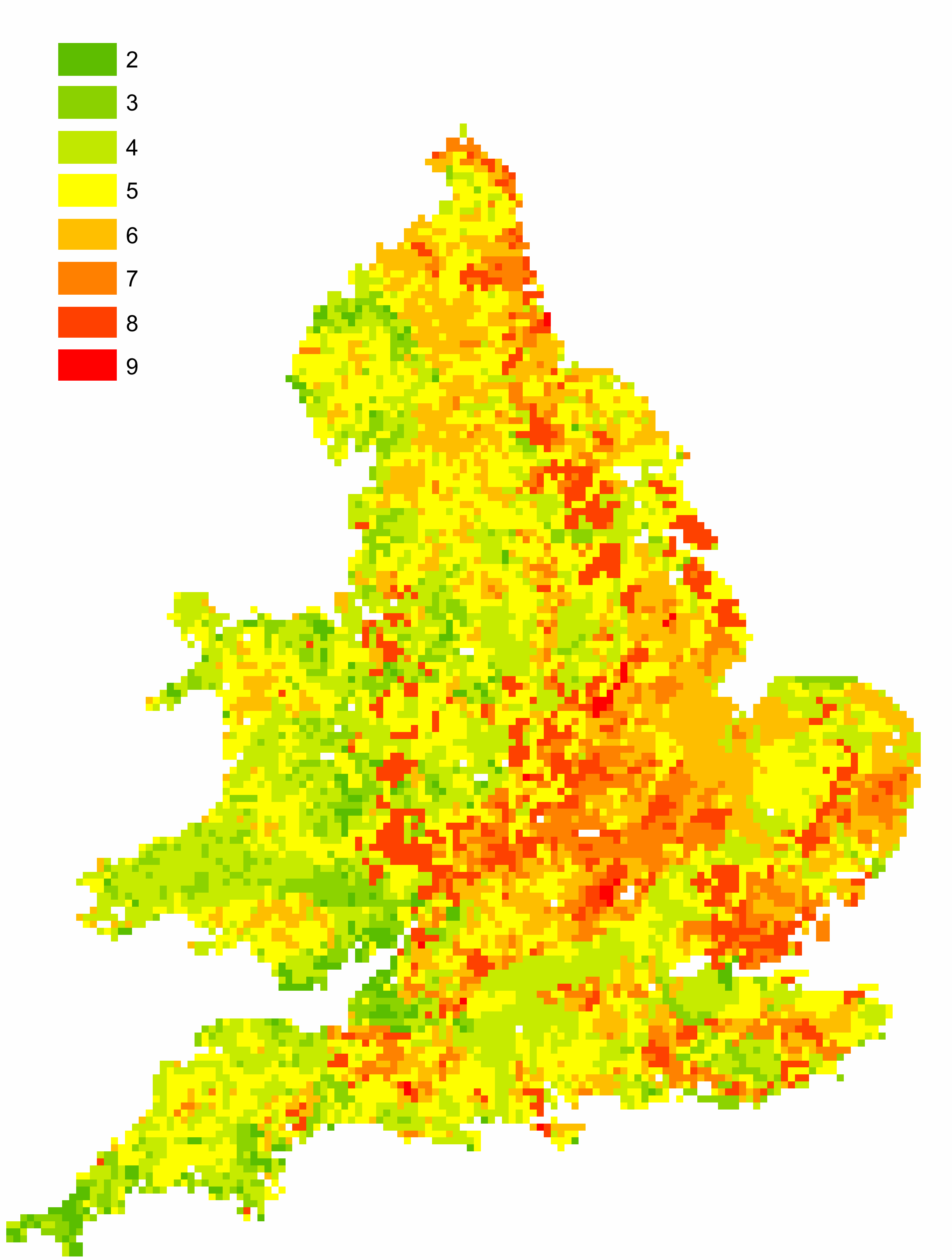


Figure 6.3 HZ classification using attenuation capacity scoring system for each axis class (highest attenuation is 9)

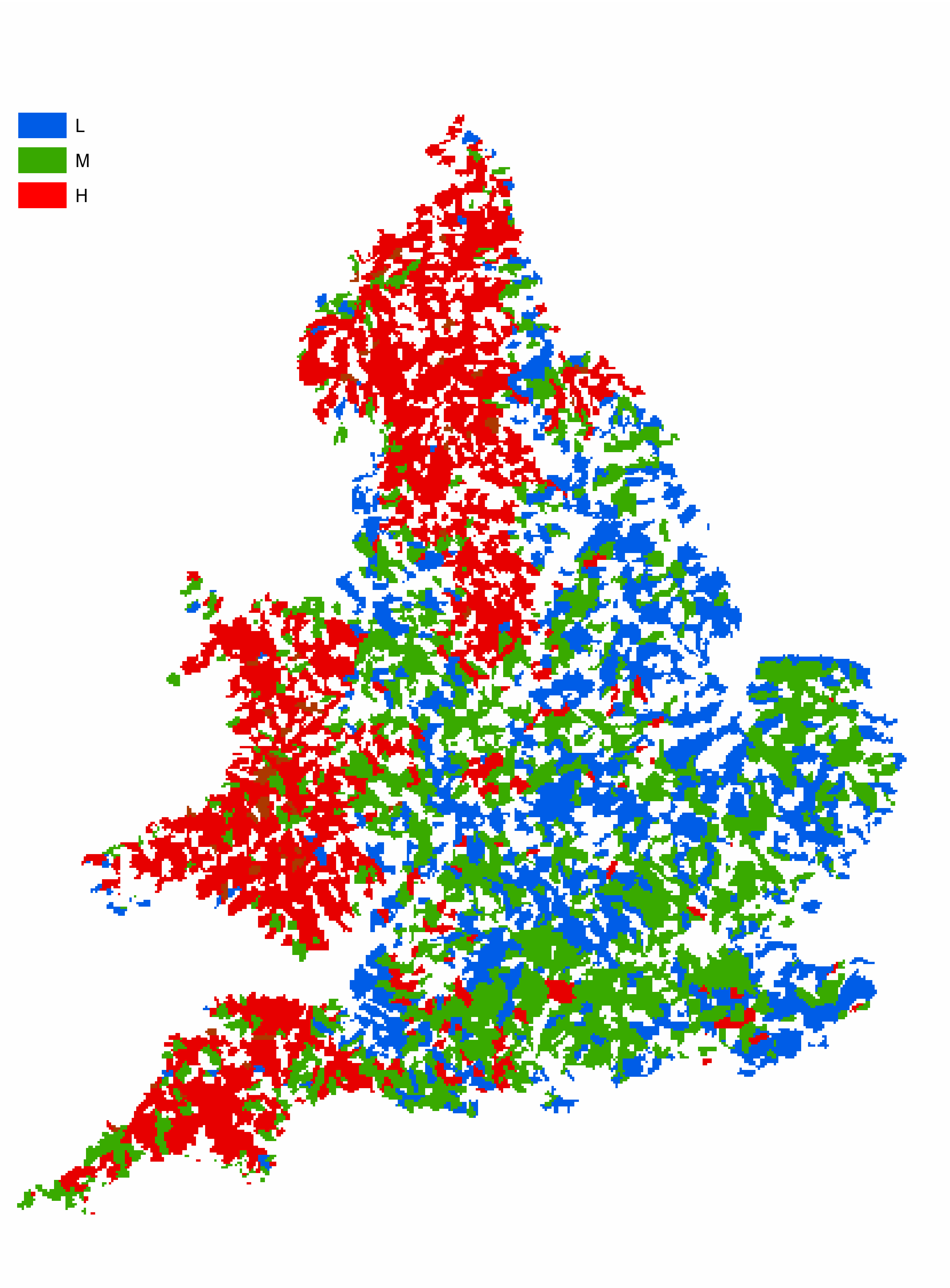


Figure 6.4 Distribution of sediment permeability classes using the RHS dataset

Table 6.2 Comparison of observed bed sediment descriptions from the Severn catchment with predicted HZ classifications axes and RHS data

Observed sediment properties			**HZ classification predictions**						**RHS observations**
Description of HZ	Inferred permeability	Sediment thickness	SWB EA ID	Fine sediment supply	Power	Fine sediment thickness	Inferred permeability – drift	Inferred permeability – sediment and fines	Inferred permeability
Sand, with gravel horizons, dominant sand bed	M	0.2–1 m	GB109054049310	M	M	L	M	H	H
Gravel, medium sand to cobbles	M	0.5–2 m	GB109054050240	M	L	H	M	M	
Cobbles to gravel	M	1–>2 m	GB109054049145	H	H	M	L	M	L
Fine sand to silt	L	>3 m	GB109054049144	H	H	H	L	L	L
Fine-grained silty sand	L	>3 m	GB109054039760	H	H	H	L	L	
Silts and plastic clay	L	>3 m	GB109054044404	H	H	H	L	L	

7 Summary

This report describes a methodology used to derive a hyporheic zone 'type' for each WFD-defined surface water body within England and Wales. The resulting compendium represents a first approximation of the likely nature of the river-bed sediments within any of the defined SWBs, based on available data. While validation work using field data collected within the River Severn shows a good correlation with the nature of the hyporheic zone predicted by the classification scheme/compendium, it is suggested that further field validation is needed to validate the compendium over a wider range of river types. It is envisaged that such work may take place simultaneously with sub-SWB-scale investigations to assess the variability of the hyporheic zone within a SWB. Such investigation may incorporate the use of Tier 2 level data to explain the reason for any such variability.

It is concluded that the information provided within this report may be used in combination with the Arc GIS shape files in order to provide more detail about the nature of each hyporheic zone class ascribed to each SWB. A summary of the methodology used in the derivation of each classification axis is given in Appendix E in order to facilitate transparency of the methods used and repeatability.

Postscript

Subsequent to the completion of this report additional statistical analysis of water quality data and the HZ classification scheme has been completed. Readers may wish to read:

Environment Agency, 2008. *Nitrate in groundwater and rivers: Degradation at the groundwater – surface water interface?* Environment Agency Science Report SC030155/SR10.

and

Smith, JWN, Surridge, BWJ, Haxton TH, Lerner DN. 2008 (subm.). Pollutant attenuation at the groundwater – surface water interface: A classification scheme and statistical analysis using national-scale nitrate data. *Journal of Hydrology*.

Appendix A: Summary of data and descriptive variables

Table 1 Summary of databank holdings

Name	Definition	Held	Resolution/format	Categories and units	Variables
Bedrock and Drift Geology	Bedrock Geology (England and Wales) Drift Geology (England and Wales)	BGS	1:625 000 ESRI Shape file 1:625 000 ESRI Shape file	97 classes 14 classes + 1 unknown	Inference of geomorphology and permeability Inference of geomorphology and permeability
WFD Typologies for Surface Water Bodies	▪ River catchment water body ▪ River stretch water body ▪ Lake water body ▪ Groundwater	EA	▪ Polygons Shape files ▪ 1:50,000 polylines ▪ Polygons Shape files ▪ Polygons Shape files		Rivers: Geology, Modified, Artificial, Ecoregion, Size, Altitude Lake: as above plus depth, groundwater, rivers Groundwater: Horizon, Aquifer
WFD Risk Assessments	▪ River/lake/groundwater	EA	▪ Joinable databases	Level of risk with confidence measure	Point source/Diffuse pressures: Nutrients, Polutants, Urban, Sediment, Metals, Morphological
National General Quality Assessment (GQA) data	▪ Biology ▪ Chemistry	EA	▪ 1:250 000 Shp polyline ▪ 1:250 000 Shp polyline	Catchment and reach scale	Flow type (C, D, R, T) Flow (1–10) Biol. grades A to F [pollution, taxa] Chem. grades A to F [Dissolved Oxygen; Ammonia; BOD]
CEH Digital Terrain Model (DTM)	50 m height and flow direction grid. 1:50,000 river network has been incorporated in most areas	CEH	▪ 50 m ▪ Vertical resolution?	Elevation Flow direction	Calc. of altitudes, altitude difference, average slopes, contributing area etc.
Flood Estimation Handbook (FEH)	Estimates of FEH descriptors. See additional table	CEH	50 DTM. Catchment basis		▪ Used within EA regularly ▪ Bulk estimates already derived?
Low Flows 2000 (LF2000)	Flow statistics and catchment characteristics, derived from DTM overlaying HOST, RUNOFF grid	CEH	1 km resolution; catchment scale. DTM at 50-m resolution. Flow statistics at 17 points on flow duration curve. Monthly runoff	Area + shape files BFI HOST proportions SAAR, potential evaporation, runoff. Monthly and annual Flow duration curve stats, m^3s^{-1} Long term	▪ In format, batch processing can do whole country. Already have WFD data points ▪ Used by other EA functions ▪ Many variables
Hydrology of Soil Types (HOST)	Developed to integrate the soil properties of site, classified to group soils/substrates of similar hydrological pathways	CEH	▪ Dominant HOST category. 1 km ▪ HOST proportions. 1 km	30 categories	
Land Cover Map 2000 (LCM2000)	Land-cover data including information on urban areas and inland waters. Aggregated vegetation types based on 72 vegetation classes placed into 22 broad habitat classes	CEH	Vector data: Raster data: 25 m resolution or aggregated 1 km resolution (dominant class or percentage cover)	Vector data: 26 subclasses or 72 subclass variants Raster data: 26 subclasses	Inferences can be made about related mechanical/erosive properties of different land cover
River Habitat	Survey database containing large	CEH	Most sites were randomly		Many variables

Name	Definition	Held	Resolution/format	Categories and units	Variables
Survey (RHS)	amounts of information including measured hydraulic variables, habitat and flow types, as well as map-based variables, distance from source etc.	EA	selected (number per km). There were then a number of non-random sites introduced, mainly large rivers etc. Time resolution from 1994 onwards. Few sites have been revisited. Around 13,000 sites	Qualitative information	
GB Lakes Database	Database giving the centroid location of all lakes >0.5 hectare Also information on surface area, catchment area	EA	All lakes >0.5 hectare	Areas in hectares	Surface Area Catchment Areas
Climatology datasets	Standardised Period Average Annual Rainfall Potential Evaporation Monthly resolution data grids	CEH	1 km grid SAAR measured in mm	SAAR (mm) Variability throughout year PE	
WFD national influence dataset	Quantities, impacts of abstractions, discharges impoundments for average year, and licensed quantities for all influences. Matched to river network	CEH EA	Long-term monthly values. In m^3 per month	Influence volumes, impact volumes	Calc of sewage treatment works inputs (quality) and quantity. Derive ‘natural’ and ‘actual’ conditions

Table 2 In-channel factors influencing sediment supply:
Key: Silt-gravels in normal font, *Fine sediment shown in italics*

Importance	Influence	Why of interest?	Information required
1	Bed material	Affects permeability of bed	Presence/absence/dominance and spatial variation of silt, sand, gravel, pebbles, boulders, bedrock
1	Glacial outwash legacy	Affects depth of sediments – Large quantities of gravel sediments deposited in rivers as a result of glacial outwash events Affects grain size distribution of HZ	Location of headwaters in UK relative to glacial extent
2	Bank material	Readability	Presence/absence/dominance and spatial variation of silt, sand, gravel, pebbles, boulders, bedrock
2	Bank vegetation	Limits sediment supply	Vegetation type Presence of grazing animals
2	Restoration	Has the HZ been artificially thickened?	Volume of gravel added
2	*Channel bank stability*	*Direct sediment supply*	*Extent and severity of bank erosion* *Channel bank vegetation coverage* *Channel bank protection*
2	*Position in long profile*	*Fine sediment increases downstream* *Depth of unconsolidated material increases downstream*	*Distance from source*
2	*Reservoirs*	*Trap fine sediment. Downstream reduction in fines. Cleaner gravels*	*Reservoir shape, depth, volume, operation regime*
2	*Engineering structures*	*Trap fine sediment. Downstream reduction* *Complex impact. Local accumulation of sediment. May reduce downstream supply. However, flow peaks may be attenuated, which may reduce downstream sediment transport*	*Type of weir or flume* *Maintenance and operation regime*
2	*Point discharges*	*Treated sewage effluent is a source of fine organic sediment* *Combined sewer overflows (CSOs) are a source of fine organic sediment*	*Effluent discharge volumes and locations* *Numbers of CSOs and estimated discharges*
3	Dredging	Reduces thickness of HZ Disturbs HZ	Date dredged Volume of material dredged per m^2 of river bed Depth of dredging Where extracted to? (e.g. top of bank)
3	Bank protection	Limits sediment supply	Type of protection Hard or soft engineering
3	*Tributary inputs*	*Source of fines. May be deposited in main channel especially where main river is regulated*	*Locations of tributary inputs*
3	*Gravel cleaning*	*Removal of fines*	*Frequency and locations of gravel cleaning*

Table 3 In-channel factors influencing sediment supply – data usage:
Key: Silt-gravels in normal font, *Fine sediment shown in italics*

Importance	Influence on sediments	Dataset	Related variables
1	Bed material	Drift geology	Drift sediment types – calc. percentage of each intersecting WB – test with RHS
1	Glacial outwash legacy	Drift map	Consideration of drift within WB, within WB catchment, and within larger catchment
2	Bank material	RHS, Drift geology	Tier 2
2	Bank vegetation	RHS	Tier 2
2	Restoration	River Restoration centre. Gravel added	Tier 2
2	*Channel bank stability*	*Geology dependent* *Drift map*	*Tier 2*
2	*Position in long profile*	*FEH, DTM*	*Distance from source* *Mean and variance of catchment slope and altitude* *Mean and variance of drainage path lengths* *Catchment area* *Altitude of WB site and source area*
2	*Reservoirs/lakes*	*Lakes typology map* *GB Lakes Database*	*Catchment area of lake/catchment area* *Area, volume, depth of lake* *Tier 2 consideration: lake or reservoir?*
2	*Engineering structure*		*Tier 2*
2	*Point discharges*	*LCM2000, LF2000*	*Urban extent from LCM2000/point source* *Organic sediments, sewage treatment works, CSO, road runoff*
3	Dredging		Tier 2
3	Bank protection	RHS, degree of modification	Tier 2
3	*Tributary inputs*	*River typology/DTM*	*Tier 2*
3	*Gravel cleaning*		*Tier 2*

Table 4 Out-of-channel factors influencing sediment supply:

Key: Silt-gravels in normal font, *Fine sediment shown in italics*

Importance	Influence on sediments	Why of interest?	Information required
1	Glacial legacy	Controls the availability of gravel sediments. Rivers located in previously glaciated areas may have large supplies of gravel sediments available near to the river channel. Controls depth and width of HZ	Location of site in UK relative to glacial activity
1	Valley side slope	Controls the supply of gravel sediments. Valley side slope provides a mechanism for transporting material into the channel	Slope of valley adjacent to river channel
1	*Land use*	*Importance for sediment supply:* *cultivated land>pasture>woodland*	*Proportions of each land use* *Ploughing dates* *Spatial coverage of each land use* *Spatial distribution of each land use*
1	*Vegetated buffer zones*	*Traps sediment on its way from field to river*	*Width of buffer zones* *Presence of field drains*
2	*Valley side slopes*	*Sediment delivery from slopes is more efficient when slopes are steep*	*Gradients of valley slopes*
3	*Developments*	*Increases supply of fine sediment*	*Dates of major developments*
3	*Mass movement*	*Landslides may contribute large amounts of sediment to river*	*Map landslides*
3	*Urban extent*	*Surface runoff provides fine sediment contaminated with fines* *CSOs provide organic sediment* *Low baseflow encourages deposition of fines and growth of algae to trap sediment* *Flashy flow regime cleans bed periodically*	*Urban extent as proportion of catchment* *Combined sewer system* *Sewage effluent discharges*
4	Buffer zones	Limits transport of fines into river channel	Farming practices, detailed land use

Table 5 Out-of-channel factors influencing sediment supply – data usage:
Key: Silt-gravels in normal font, *Fine sediment shown in italics*

Importance	Influence on sediments	Dataset	Related variables
1	Glacial legacy	Drift map	Drift map – drift sediment types – calc. percentage of each intersecting WB – test with RHS
1	Valley side slope	DTM	Mean and variance of catchment slope and altitude Mean and variance of drainage path lengths Channel slope
1	*Land use*	*LCM2000*	*5 or 26 vegetation class range* *Intersecting channel and contributing from catchments*
1	*Vegetated buffer zones*		*Tier 2*
2	*Valley side slopes*	*DTM/RHS/FEH*	*Tier 2*
3	*Developments*		*Tier 2*
3	*Mass movement*	*Drift/geology maps*	*Drift map class; more recent events is Tier 2 consideration*
3	*Urban extent*	*LCM2000; FEH*	*Urban extent from LCM2000; URBXT; point source*
4	Buffer zones	LCM2000	Tier 2

Table 6 In-channel factors influencing power to erode:

Key: Silt-gravels in normal font, *Fine sediment shown in italics*

Importance	Influence on power	Why of interest?	Information required
1	Channel structure (cross-sectional shape)	Controls velocity Controls flow and conveyance Controls patterns of scour and deposition *Controls sediment transport*	Bankfull width and depth Geomorphological form, pools and riffles, runs, glides etc. Channel cross-sectional shape *Bed morphology, width, depth*
1	Channel slope and gradient	Controls velocity and shear stress	Gradient
1	Flood alleviation schemes	Storage of bypassing may attenuate or reduce peak flows Channel widening or deepening may decrease power Channel confinement may increase power	Quantity of reduction m^3s^{-1} Location of flood defence works
2	Roughness – form resistance	Controls velocity and shear stress	Geomorphological form, pools and riffles, runs, glides etc. Sinuosity Vegetation, biomass and type
2	Sinuosity	Controls velocity Controls patterns of scour and deposition *Controls patterns of erosion and deposition*	Channel sinuosity (channel length/valley length) *Sinuosity*
2	Reservoirs and lakes	Attenuates flows *Attenuates flow peaks. Greater potential for fine deposition if downstream source prevails*	Release frequency and magnitude *Shape, depth, volume, operational regime*
2	Vegetation	Controls velocity and shear stress *Reduces flow velocity and ability to transport sediment*	Spatial coverage, biomass, species *Spatial coverage*
3	Roughness – skin friction	Controls velocity and shear stress *Controls velocity*	Presence/absence/dominance and spatial variation of silt, sand, gravel, pebbles, boulders, bedrock *Channel substrate*
3	Floodplain connectivity	Allows spreading out of power to erode during floods	Flood extent map Location of flood defence works Stage–discharge relationship
3	*Position in long profile*	*Change in stream power along river course*	
3	Engineering structures	Backwater effects, increase power downstream, decrease power upstream	Presences of weirs, gauges and flumes

4	Discharges	Increase flows	Quantity and timing of discharge
4	Abstractions	Reduce flows	Quantity and timing of abstraction

Table 7 In-channel factors influencing power to erode – data usage:
Key: Silt-gravels in normal font, *Fine sediment shown in italics*

Importance	Influence on power	Dataset	Related variables
1	Channel structure (cross-sectional shape)	LF2000 RHS	Velocity function (flow) Tier 2 consideration – use width, depth, habitat
1	Channel slope and gradient	DTM	Mean and variance of catchment slope and altitude
1	Flood alleviation schemes	Assets database WFD dataset	Tier 2
2	Roughness – form resistance	RHS, RAPHSA models WFD River Typology	Tier 2 consideration – use width, depth, habitat
2	Sinuosity	DTM WFD River Typology	Tier 2
2	Reservoirs and natural lakes	WFD dataset GB Lakes Database *WFD typologies*	Operational regime Catchment area of lake/catchment area *Area, volume, depth of lake*
2	Vegetation	RHS	Tier 2
3	Roughness – skin friction	Drift geology	Drift sediment types – calc. percentage of each intersecting WB – test with RHS
3	Floodplain connectivity	1 in 100 year flood map	Fractional extent of flood map
3	Engineering structures		Tier 2
4	Discharges	LF2000 WFD dataset	Tier 2 – WFD initial characterisation
4	Abstractions	LF2000 WFD dataset	Tier 2 – WFD initial characterisation

Table 8 Out-of-channel factors influencing power to erode:

Key: Silt-gravels in normal font, *Fine sediment shown in italics*

Importance	Influence on power	Why of interest?	Information required
1	Flow regime	Controls magnitude and frequency of events *Controls ability to transport sediment*	Time series and derived statistics Flood frequency Flow duration curve
2	Valley slope	Affects transfer of potential to kinetic energy	Gradient of water body
3	Catchment size	Controls magnitude and frequency of events	Area
3	Rainfall	Controls magnitude and frequency of events *Characteristics determine flow regime*	Time series and derived statistics *Seasonality* *Frequency distribution*
3	Altitude	Affects transfer of potential to kinetic energy	Altitude of site Altitude of source Distance from source
3	Stream order	Estimation of stream size and power *Maturity*	Stream order *Order*
3	Urban extent	Affects magnitude and frequency of events	Urban extent
3	*Floodplain connectivity*	*Loss of in-channel power if bank overtopping occurs*	*Presence of embankments*

Table 9 Out-of-channel factors influencing power to erode – data usage:
Key: Silt-gravels in normal font, *Fine sediment shown in italics*

Importance	Influence on power	Dataset	Related Variables
1	Flow regime	LF2000 FEH	LF2000 (flow duration curves), FEH (Qmean, Qmed)
2	Valley slope	FEH, DTM	Mean and variance of catchment slope and altitude Mean and variance of drainage path lengths Channel slope
3	Catchment size	DTM WFD System A	Catchment area
3	Rainfall	SAAR	Average annual rainfall
3	Altitude	DTM/FEH	Altitude of site at source
3	Stream order	River typology	Tier 2
3	Urban extent	FEH	URBXT
3	*Floodplain connectivity*	*1 in 100 year flood map*	*Fractional extent of flood map*

Appendix B: Parameter descriptions

Table 1 CEH LCM2000 vegetation class components (for more information see Smith *et al*. 2001; Fuller *et al*. 2002)

Deciduous	Broad-leaved/mixed woodland
Coniferous	Coniferous woodland
Arable	Arable cereals Arable horticulture Arable non-rotational
Grassland	Improved grassland Set-aside grass Neutral grass Calcareous grass Acid grassland Bracken Fen, marsh, swamp
Upland	Dense dwarf shrub heath Open dwarf shrub heath Bog (deep peat) Montane habitats Inland bare ground
Urban	Suburban/rural development Continuous urban
Coastal	Supra-littoral rock Supra-littoral sediment Littoral rock Littoral sediment Saltmarsh
Water body	Water (inland) Sea/estuary

Table 2 Drift type with ascribed sediment size class

Rock ID	Rock Code	Drift Description	Size class Peat 1	Clay 2	Silt 3	Sand 4	Gravel 5	Pebbles 6	Cobbles 7	Boulders 8
1	BDGR	BOULDERS [GRANITE]								y
2	CATU	CALCAREOUS TUFA								
3	CLAY	CLAY		y						
4	CLGR	CLAYEY GRAVEL		y			y			
5	CLSA	CLAY AND SAND		y		y				
6	CLSI	CLAY AND SILT		y	y					
7	CLSS	CLAY, SILT AND SAND		y	y	y				
8	CSGR	CLAY, SAND AND GRAVEL		y		y	y			
9	CSSG	CLAY, SILT, SAND AND GRAVEL		y	y	y	y			
10	CZPS	CLAY, SILTY, PEATY, SANDY (UCDS)	y	y	y	y				
11	DGSS	DIAMICTON, GRAVEL, SAND AND SILT			y	y	y	y	y	
12	DMGR	DIAMICTON AND GRAVEL					y	y	y	
13	DMRC	DIAMICTON WITH CHALK RAFTS						y	y	
14	DMSG	DIAMICTON, SAND AND GRAVEL				y	y	y	y	
15	DMTN	DIAMICTON						y	y	
16	GRAV	GRAVEL					y			
17	GRSA	GRAVELLY SAND				y	y			
18	GRSM	GRAVEL, SAND AND MUD		y		y	y			
19	GRSS	GRAVEL, SAND AND SILT		y		y	y			

			Size class							
Rock ID	Rock Code	Drift Description	Peat 1	Clay 2	Silt 3	Sand 4	Gravel 5	Pebbles 6	Cobbles 7	Boulders 8
20	GSSC	GRAVEL, SAND, SILT AND CLAY		y	y	y	y			
21	GVFL	GRAVEL, FLINT-RICH					y	y		
22	GVLM	GRAVEL, LIMESTONE-RICH					y	y		
23	LMST	LIMESTONE						y		
24	MUD	MUD		y						
25	PEAT	PEAT	y							
26	PECL	PEBBLY CLAY		y				y		
27	PES	PEBBLY SAND				y		y		
28	POCM	PEAT, ORGANIC MUD AND CALCAREOUS MUD	y							
29	PTSI	PEAT AND SILT [EITHER DOMINANT LOCALLY]	y		y					
30	RFAU	ROCK FRAGMENTS, ANGULAR, UNDIFFERENTIATED							y	
31	SACG	SAND WITH CLAY AND GRAVEL		y	y		y			
32	SAGR	SAND AND GRAVEL				y	y			
33	SAND	SAND				y				
34	SASI	SAND AND SILT			y	y				
35	SDSH	SEDIMENT, SHELL			y					
36	SGRB	SAND, GRAVEL AND BOULDERS				y	y			y
37	SHEL	SHELLS/SHELL BED/SHELL PLASTER				y				
38	SHMD	SHELLY MUDSTONE				y				
39	SICL	SILTY CLAY		y	y					
40	SIGR	SILT AND GRAVEL			y		y			

Rock ID	Rock Code	Drift Description	Size class							
			Peat	Clay	Silt	Sand	Gravel	Pebbles	Cobbles	Boulders
			1	2	3	4	5	6	7	8
41	SILT	SILT			y					
42	SMUD	SANDY MUD		y		y				
43	SSCL	SAND, SILT AND CLAY		y	y	y				
44	SSGR	SILT, SAND AND GRAVEL			y	y	y			
45	TUFA	TUFA							y	

Table 3 Parameter ranges of identified variables within England and Wales

	Within WB					
ALTITUDE	MIN	MAX	RANGE	MEAN	STD	MEDIAN
Min	-5	3	0.00	0.3	0	0
Max	528.0	1078.0	1050	651.4	232	645
Mean	41	203	162	107.1	35	103.9
SD	57.9	182.2	148.8	105.3	32.9	105.6

	Within WB					
SLOPE	MIN	MAX	RANGE	MEAN	STD	MEDIAN
Min	1	1	0	1	0	1
Max	9	78	77	25.9	14.2	27
Mean	1	18	17	4	3	4
SD	0.2	11.8	11.8	3.3	2.2	3.0

	Within WB									
LF2000	LF2K_Area	diff_Area	BFI	MF_Nat	Q5_Nat	MF_Inf	Q5_Inf	m3PerYear	mperyear	runoffmm
Min	2	-0.15	0.17	0.009	0.025	0	0.0	285000	0.06	62
Max	9984	0.150	0.97	110	348	101	328.4	3464923392	3.48	3478
Mean	77	0.010	0.50	1.268	4.18	1.22	3.97	39997021	0.58	581
SD	341	0.044	0.2	4.451	14.36	4.18	13.5	140359677.2	0.44	438

	Within WB															
FEH	Area	SAAR	AltBar	DPSBar	bfihost	sprhost	dplbar	farl	ldp	urbconcraw	urbextraw	urblocraw	urbconc	urbext	urbloc	QMED
Min	2	526	2	2	0.17	2.50	0.10	0.00	-0.02	0.00	-0.002	-0.002	-0.002	0	-0.002	0.028
Max	7022	3242	655	437	0.99	60	13.95	1.00	270	0.95	0.52	0.95	0.953	0.518	0.953	440.0
Mean	67	983	161	82	0.51	35.6	0.85	0.98	15.7	0	0.02	0.32	0.318	0.02	0.318	14.6
SD	214.1	384.8	114.8	56.0	0.16	10.86	0.77	0.04	13.9	0.32	0.05	0.32	0.32	0.05	0.32	27.84

Figure 1 FEH dataset variables

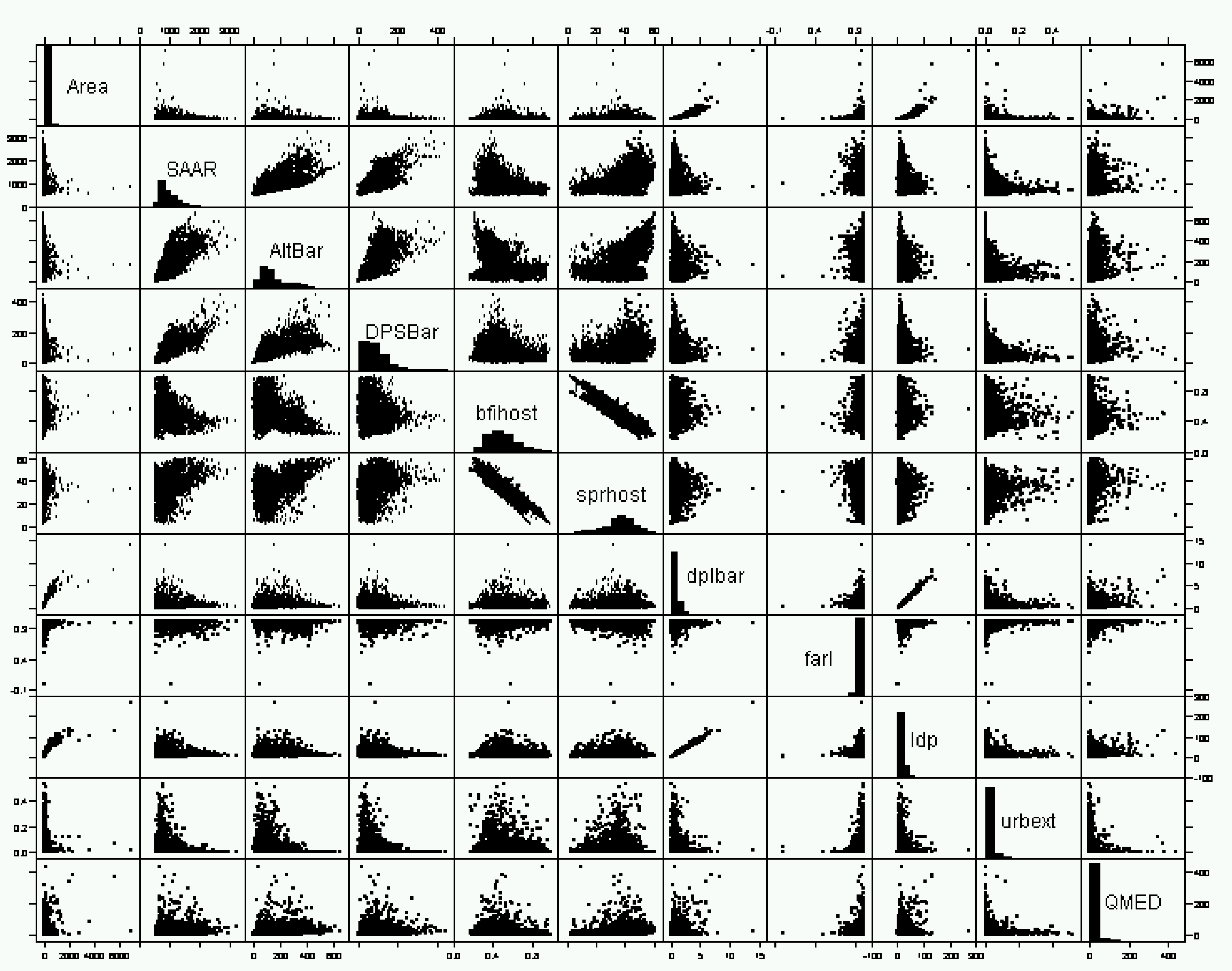


Figure 2 **LF2000 dataset variables**

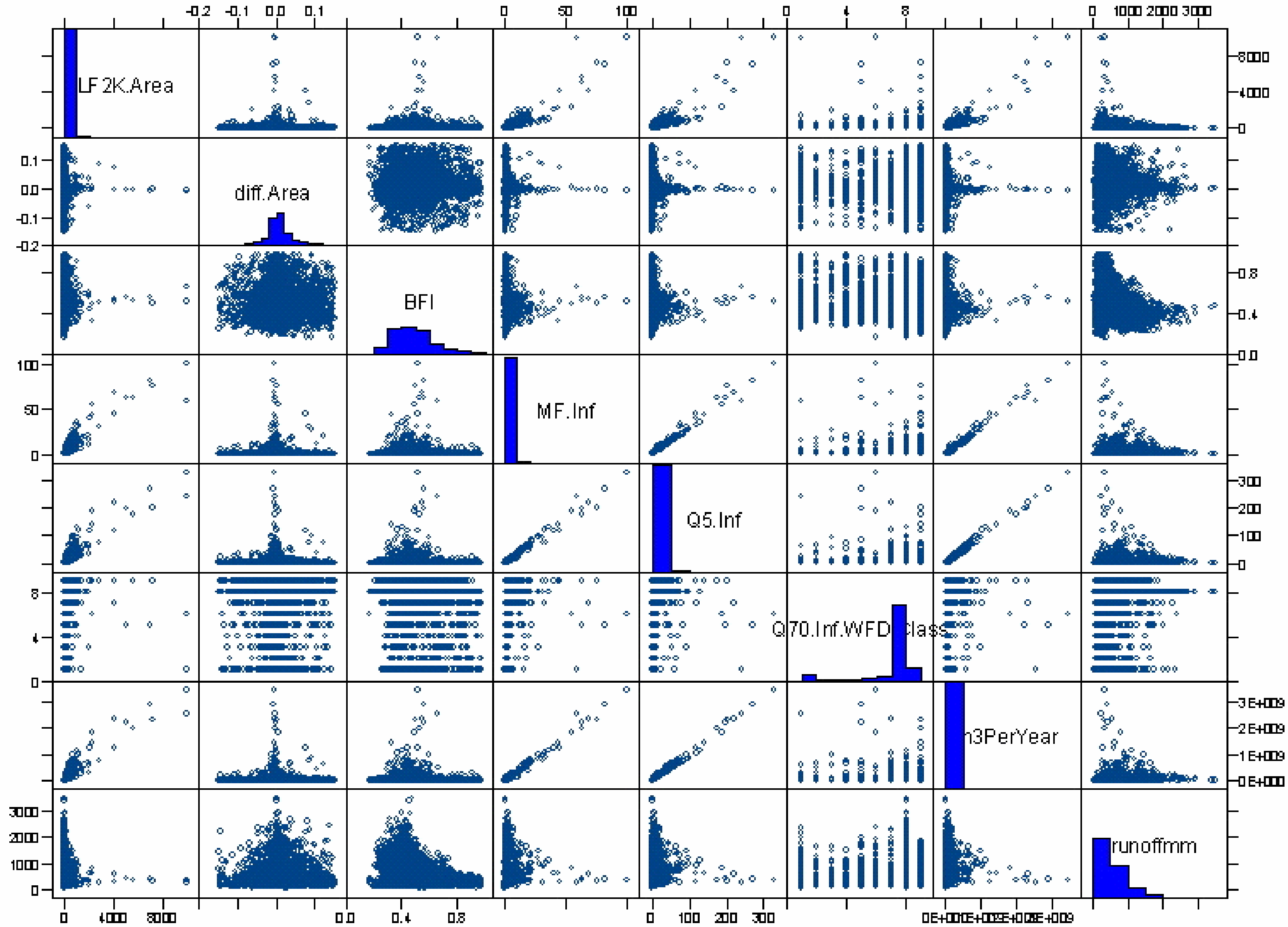


Figure 3 **Hydrological and structural catchment characteristics**

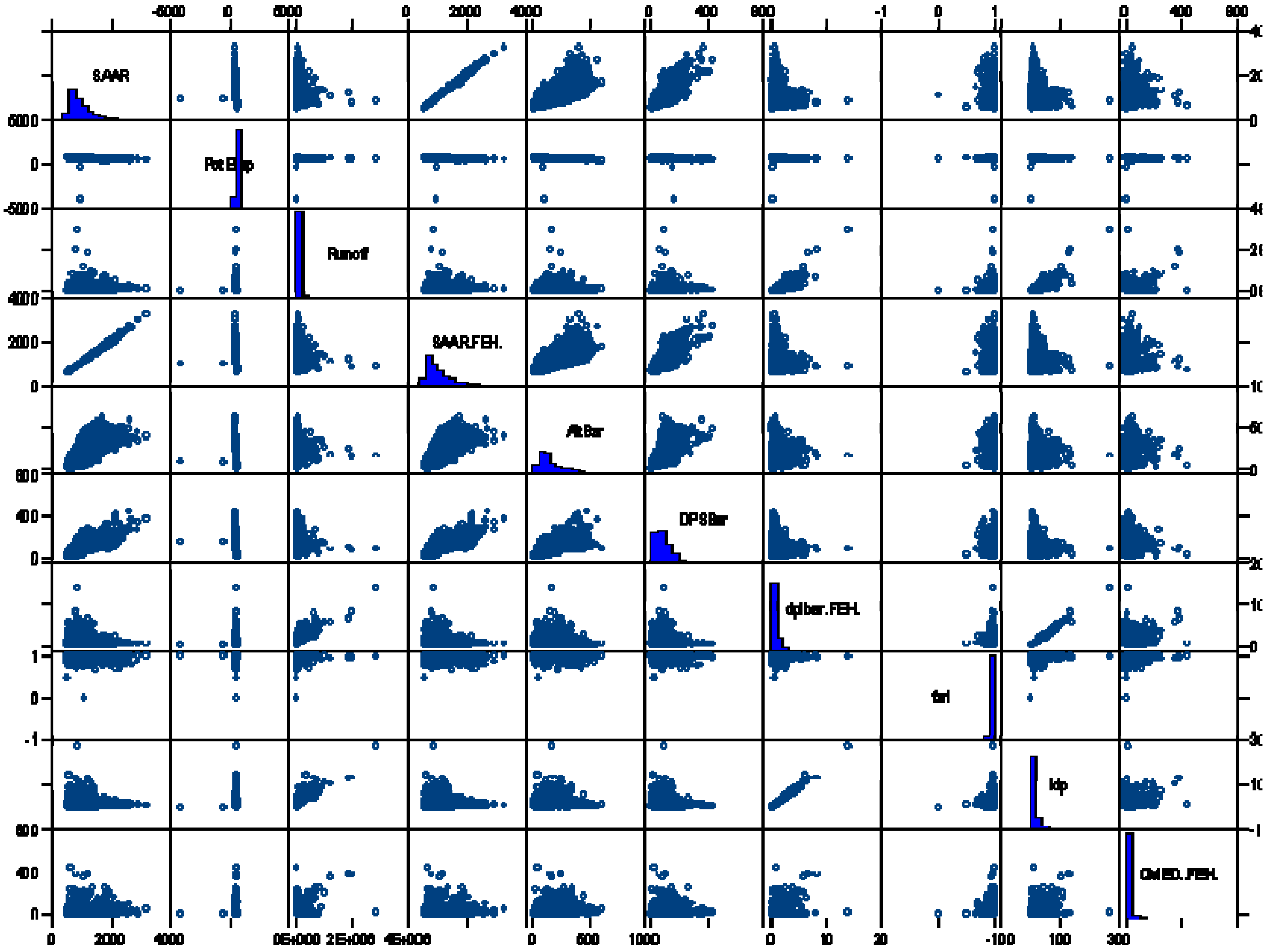
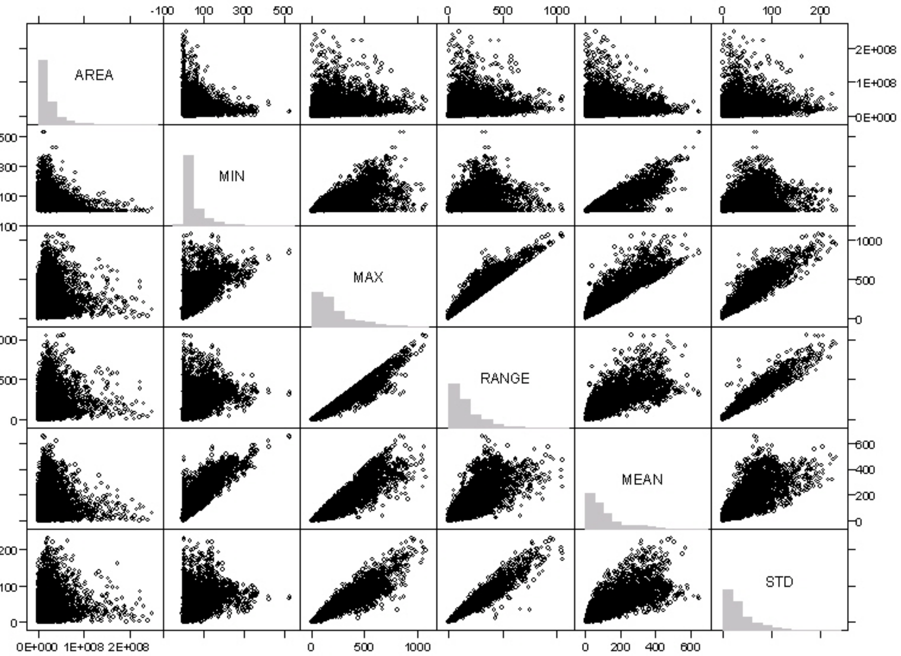


Figure 4 Altitude data

Within water body catchment



Upstream contributing areas

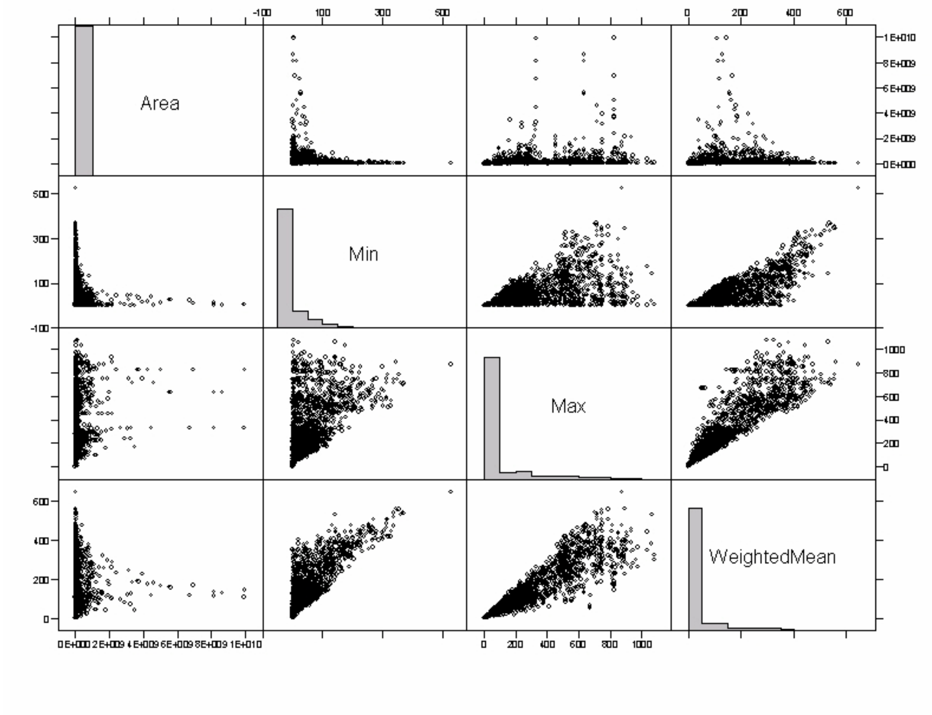
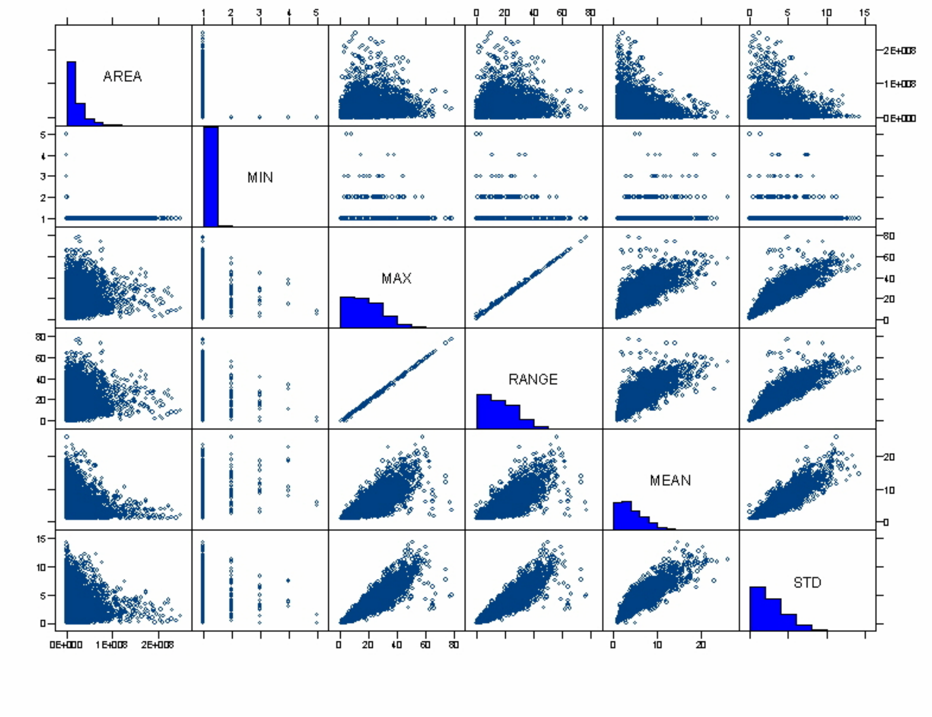


Figure 5 **Slope data**

Within water body catchment



Upstream contributing areas

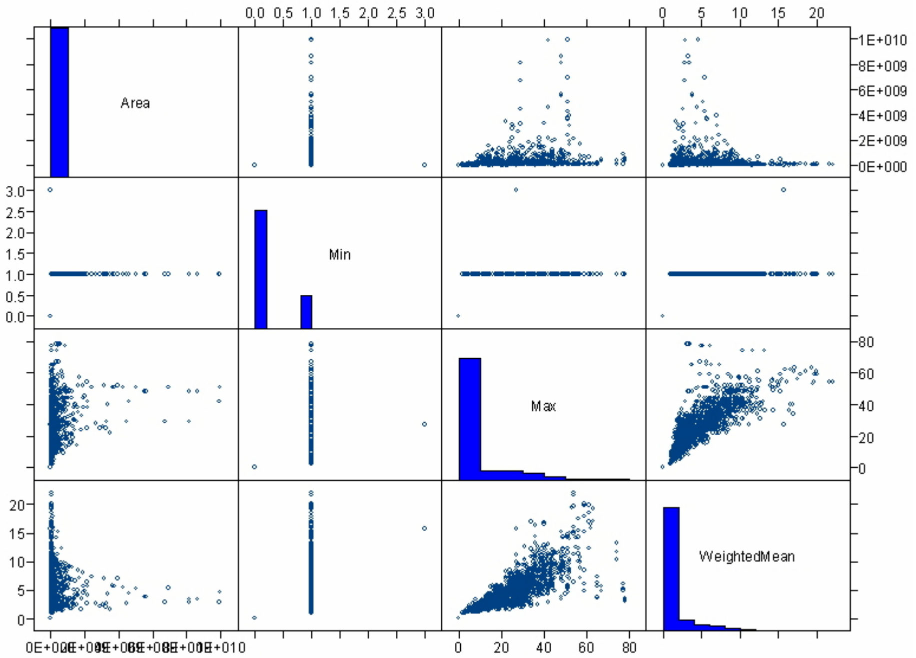


Figure 6 **LCM2000 – percentage land cover within catchment and upstream areas**

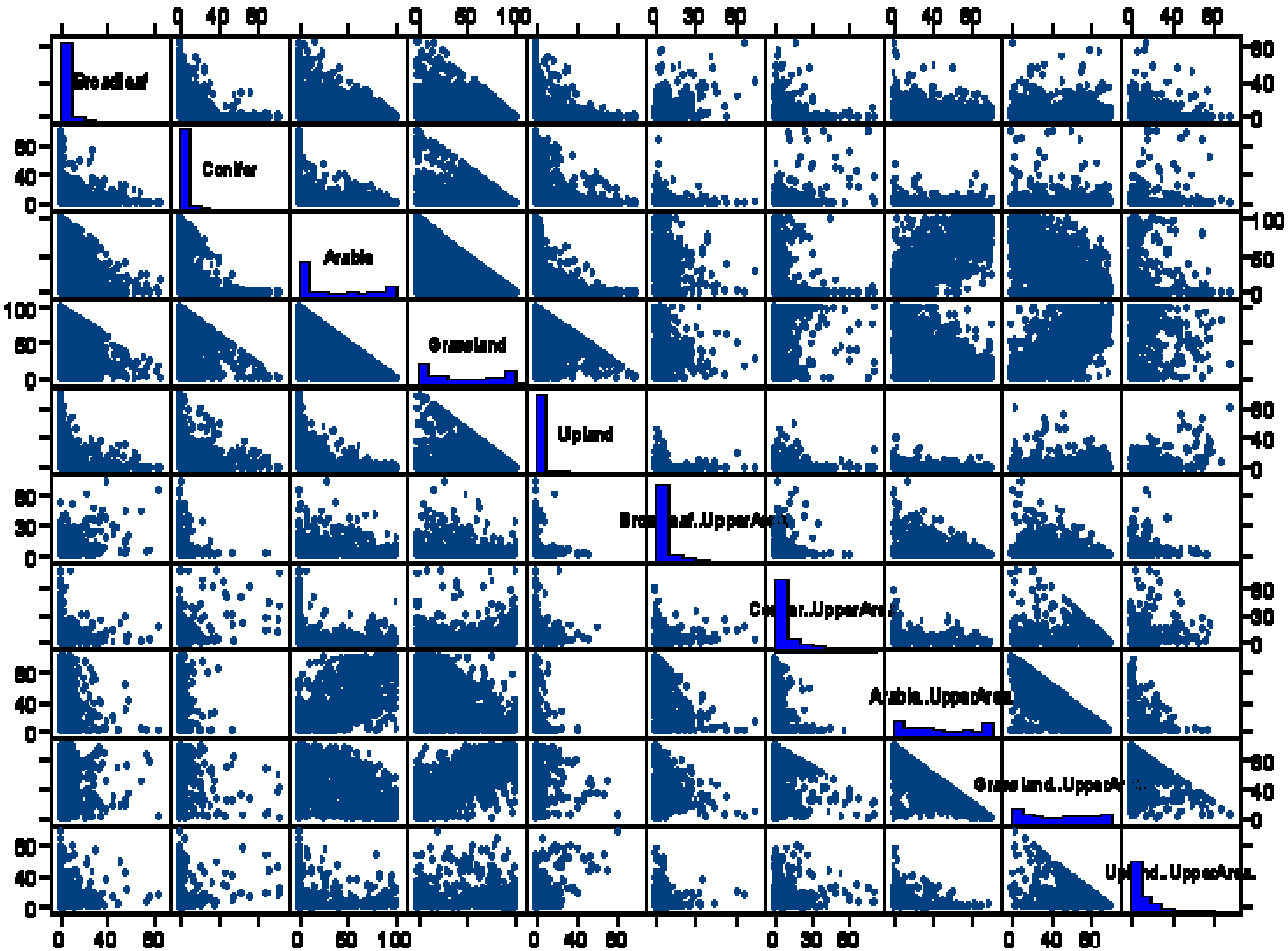


Figure 7 **LCM2000 – percentage land cover adjacent to channel and within catchment area**

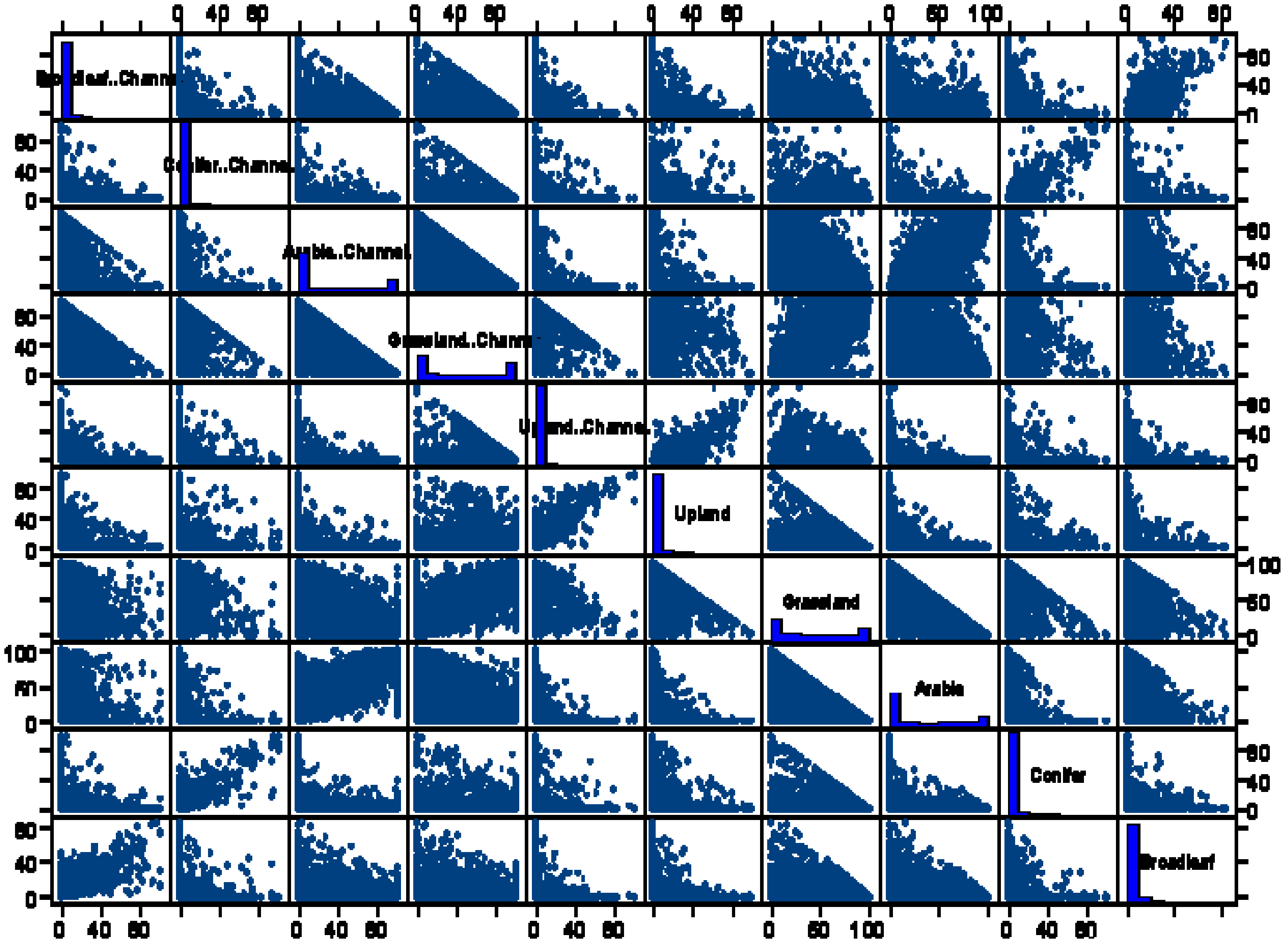


Figure 8 **BFI and downstream distance estimates from different datasets**

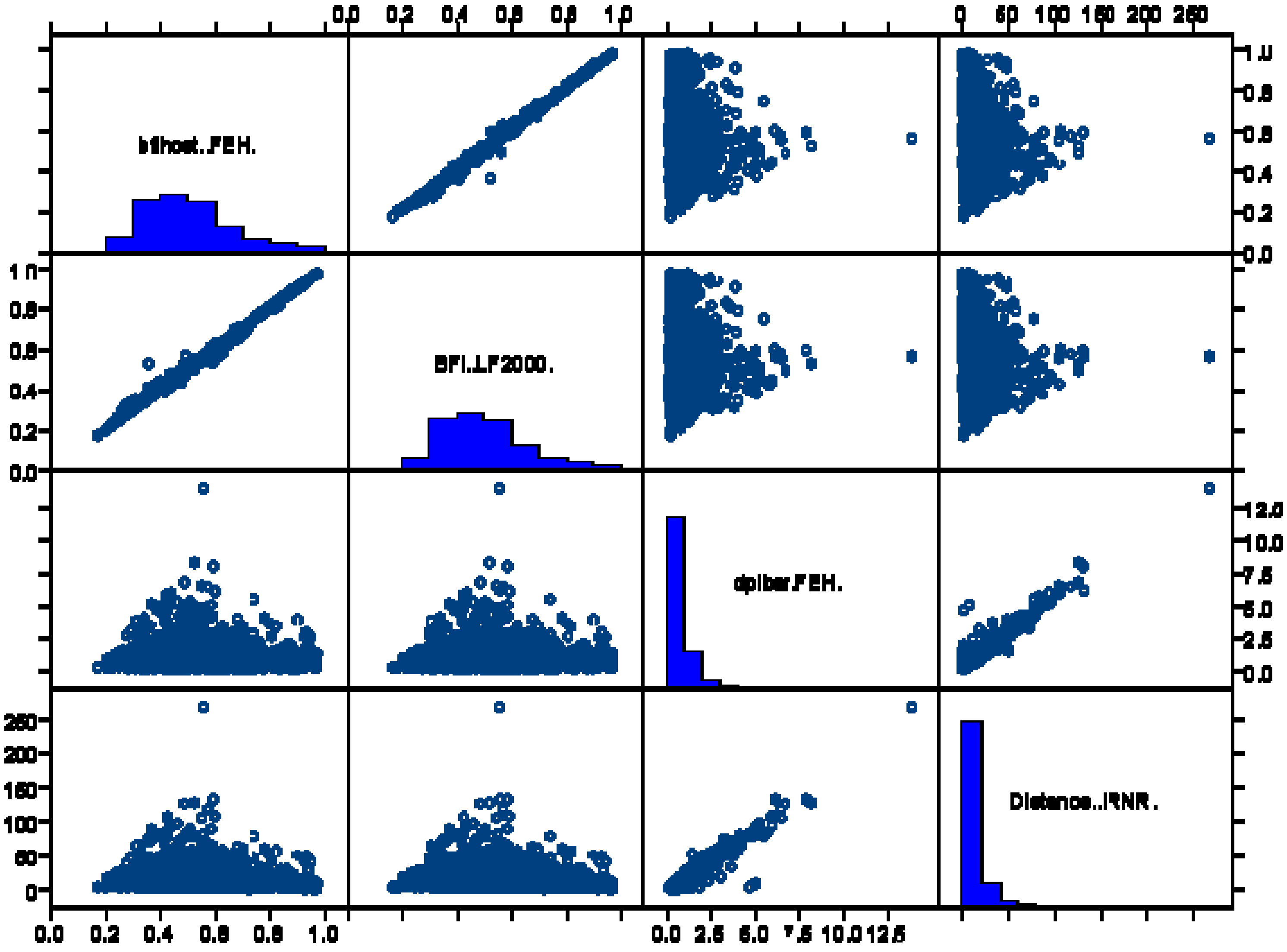


Figure 9 **Urban area estimations derived using different datasets**

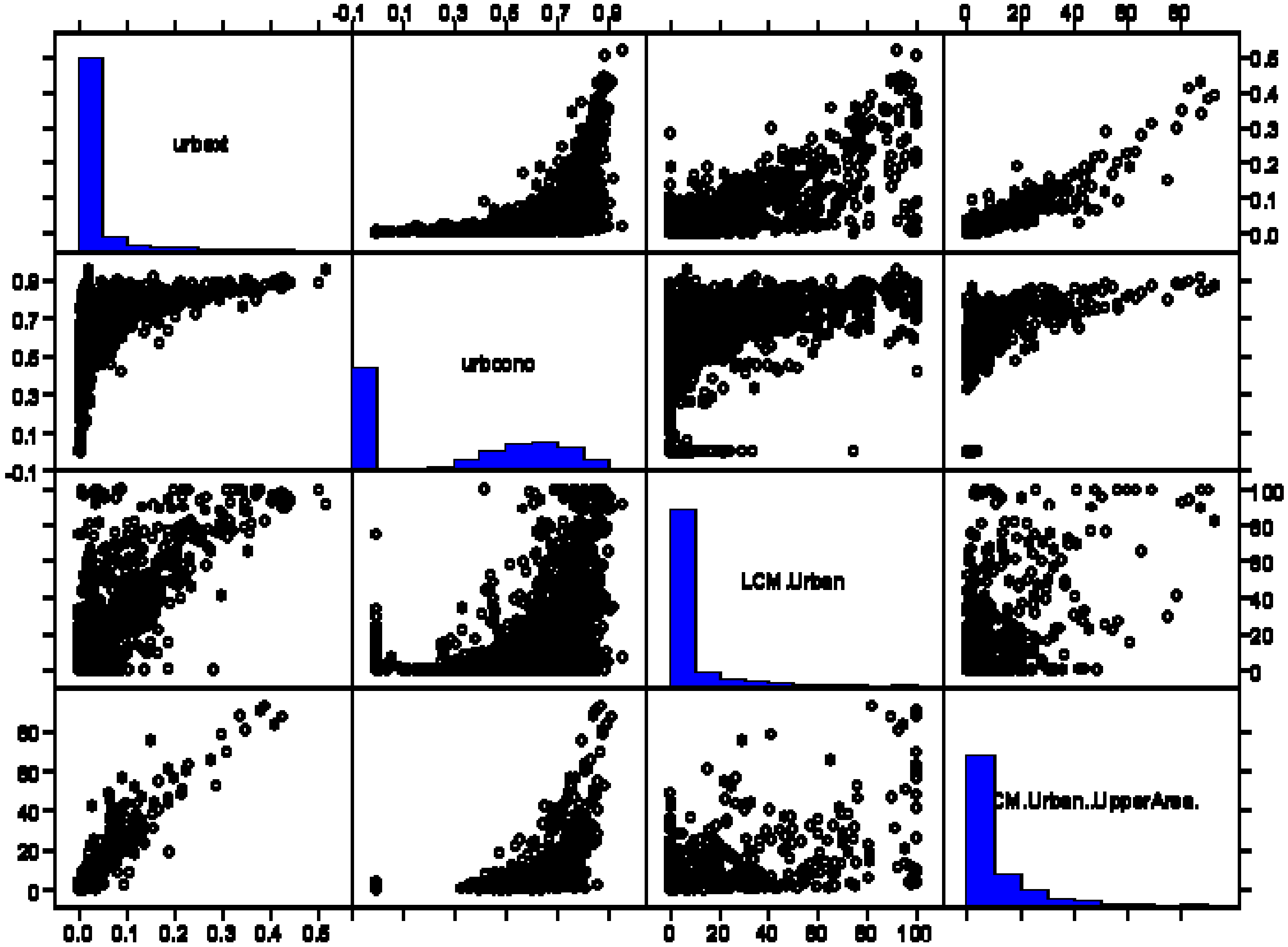


Figure 10 **Area estimations using different datasets**

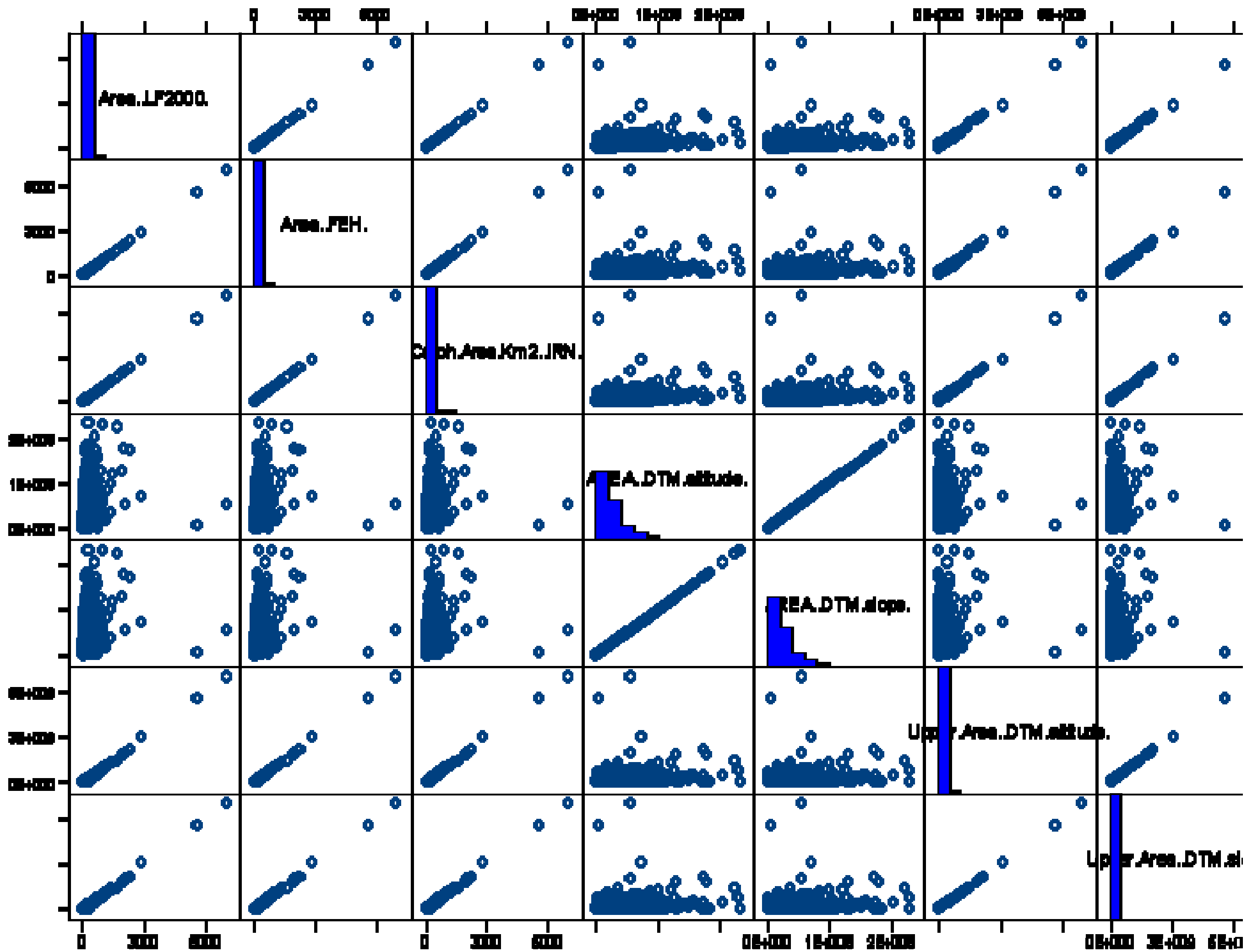


Table 4 Glossary of abbreviations used for variables within Flood Estimation Handbook (FEH) datasets

FEH variables	Description	Notes
AREA	Catchment area, should be the same as LF2000 (km2)	
FARL	Index of lake attenuation	
PROPWET	Index of proportion of time that soils are wet	Related to the proportion of time the soil moisture-drainage (SMD) threshold was exceeded, i.e. 0.84 indicates that the SMD values were exceeded for 84% of the time
ALTBAR	Mean catchment altitude, m above sea level	
ASPBAR	Index representing the dominant aspect of catchment slopes	
ASPVAR	Index describing the invariability in aspect of catchment slopes	
BFIHOST	Based flow index derived using the HOST classification	
DPLBAR	Index describing the catchment size and drainage path configuration (km)	Average length between nodes. Mean drainage path length. As such it indicates the drainage configuration
DPSBAR	Index of catchment steepness	
LDP	Longest drainage path (km)	e.g. Trent and Severn, 4330 and 4414 km^2. LDP values, Severn 216.8 km (sinuous), Trent 131.5 (fan shaped)
RMED-1H	Median annual maximum 1 day rainfall	
RMED-1D	Median annual maximum 2 day rainfall	
RMED-2D	Median annual maximum 1 hour rainfall (mm)	
SAAR	61–90 standard period average annual rainfall	
SAAR4170	41–70 standard period average annual rainfall	
SPRHOST	Standard percentage runoff – SPR derived using the HOST classification	
URBCONC	Index of concentration of urban and suburban land cover	Concentration URBCONC = sum of $INFLOW_{urb/suburban}$/sum of $_{inflow\ total}$ for each urban grid nodes, the number of adjacent nodes flow into, along the DTM drainage paths is computed
URBEXT1990	FEH index of fractional urban extent for 1990	URBEXT = URB_{ext} + 0.5($SURBURB_{EXT}$)
URBLOC	Index of location of urban and suburban land cover	URBLOC = $URBDIST_{MEAN}/DIST_{MEAN}$ Then adds the suburban and urban together in similar way to previous. Mean drainage path to all the Urban grid nodes as a fraction of the mean distance to all nodes within the SWB
C		Six parameters required for the depth duration model. Catchment average DDF values.

Table 5 Glossary of abbreviations used for variables within Low Flows 2000 (LF2000) dataset

LF2000 Variables	Description	Notes
WB Area	Area in km^2	
diff_Area	Difference between the LF2000 DTM area and the WB catchment area	
MF_Nat	Natural Mean Flow	
Q5_Nat	Natural Q5	
BFI	BFI estimated using HOST	
MF_Inf	Influenced Mean Flow	
Q5_Inf	Influenced Q5	
Q70_Inf	Influenced Q70	
Runoff (mm)	Runoff in mm	

Appendix C: Improvement of surface water body outlet X and Y co-ordinates

In order to retrieve data from the FEH and LF2000 datasets, accurate X and Y co-ordinates of catchment outlet points were required. From these, catchment boundaries were derived using the CEH DTM. The required catchment characteristics were then obtained by overlaying the derived catchment polygon (.shp file) over gridded datasets.

In 2002, as part of the initial WFD classification, the LF2000 dataset was used by CEH to derive natural and influenced flow statistics for all identified (at the time) SWBs. This amounted to 6019 sites (identified by a *PntRef* ID), for which 4480 successful searches were made. This information has been used as part of the HZ project. The DTM co-ordinates derived during this process were also used to derive the FEH statistics. Note, the *PntRef* ID used to identify catchments is unrelated to the WFD water body reference ID.

The initial WFD classification resulted in the production of an Access database. This presented the WFD water body reference ID; the X and Y co-ordinates (derived separately from those used within the LF2000 analysis); the natural and influenced mean flow; and the natural influenced Q95. In addition, an extra field allowed the provenance of the information presented to be recorded. For SWBs for which information was derived from LF2000, the tag 'LF2000' was used; for the remaining SWBs the tag 'ENTEC' (who led the initial project) was used.

Following this initial characterisation, the boundaries of a number of SWBs were revised, while others were split into a number of smaller basins. The SWBs that were split up, were primarily those representing the river corridors of large rivers such as the Severn and Trent. The revisions and splitting have caused a number of problems when trying to obtain information for these water bodies from the FEH and LF2000 datasets within the current project.

There are 8059 Environment Agency SWB polygons, of which 7186 have associated assigned WFD river typologies. This is a far greater number of water bodies than were initially described, with the result that only 6975 of this number existed within the initial WFD characterisation Access database. The difference between this number and those with river typologies relates predominantly to those catchments that have subsequently been split into a greater number of smaller catchments (Figure 1).

To use the existing LF2000 and FEH results (identified using the *PntRef* ID) it was necessary to relate the *PntRef* ID to the WFD water body reference ID, using the X–Y co-ordinates associated with each dataset. As these co-ordinates have been compiled using different methodologies (and possibly different scales), this was done using a nearest neighbour technique, with a number of checks incorporated. The final result was that out of the 7186 SWBs (with associated river typologies), only 4132 (58%) can be directly linked to LF2000 and FEH information using the method described.

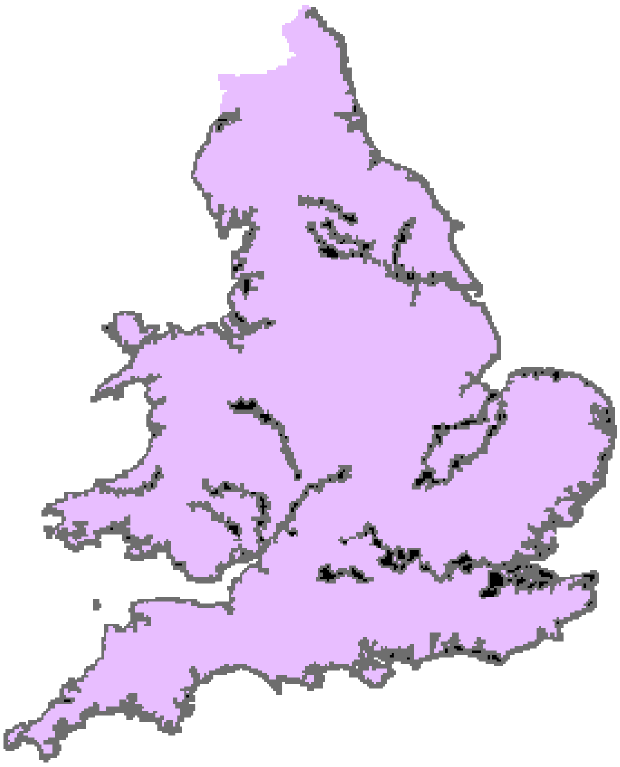


Figure 1 The location of large WFD water bodies which have been subsequently split into smaller water bodies. These are indicated in black

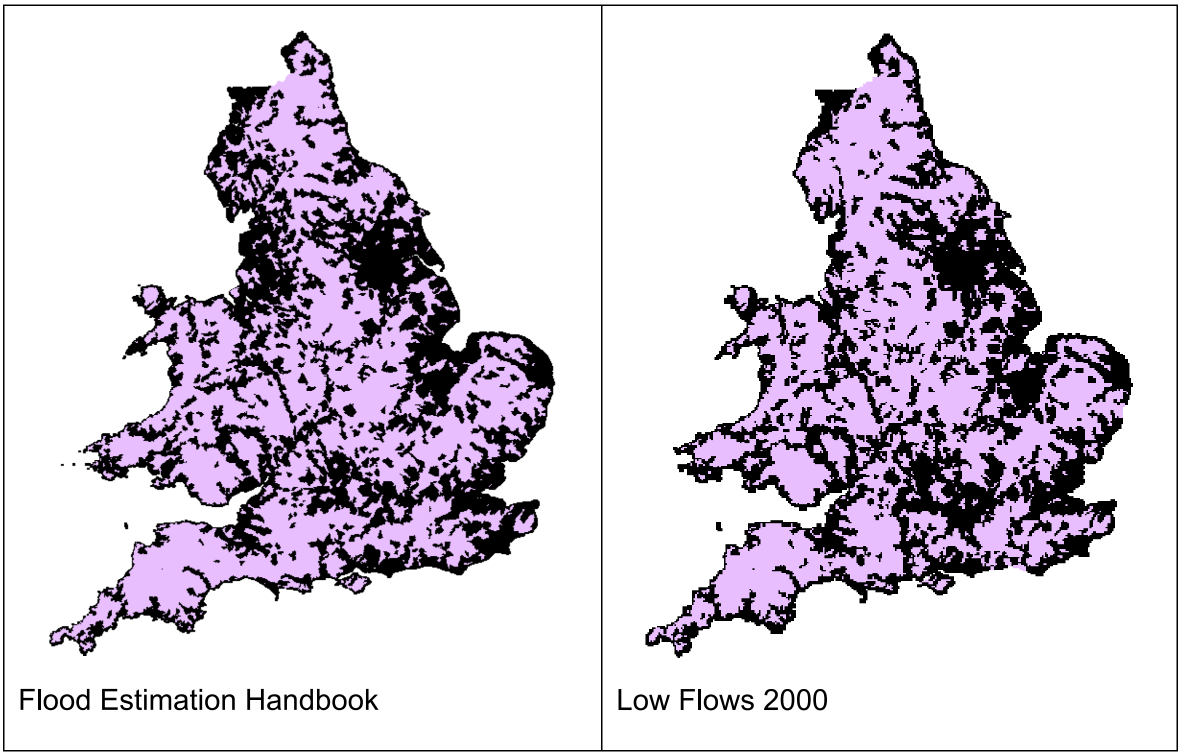


Figure 2 Spatial coverage of LF2000 and FEH datasets using original method – dark areas indicate missing data

In summary, the difficulties involved in trying to retrieve catchment characteristic data from the LF2000 and FEH were as follows:

- LF2000 required X and Y co-ordinates of the downstream point within a WFD water body catchment; these are used to derive a catchment boundary. For FEH, this must also coincide with the 50-m DTM grid outlet.
- WFD initial characterisation of defined SWBs initially used X and Y's provided by the Environment Agency to derive flow estimates from LF2000 – these were referenced using a *PntRef* ID.
- The Environment Agency database of flow statistics records each have a *EA_WB_ID* number and X and Y co-ordinates, but these are not co-incident with those used to derive LF2000 estimates.
- Since the initial characterisation, additional water body catchments have been created by dividing some of the larger water bodies. This means there are some river SWBs, mainly on larger river corridors (e.g. the Trent, Thames and Severn), for which information was not originally sought.

The low percentage of catchments for which acceptable LF2000 results have been obtained was therefore due to a combination of the above factors. However, all these factors were related to the fact that there is no definitive dataset which presents the WFD SWB ID, and the X–Y co-ordinates of the catchment outlet that can be accurately associated with the CEH DTM. The current spatial coverage of information available from the LF2000 and FEH was not sufficient for the desired use within this project. A short investigation into methods available for obtaining an improved co-ordinate set was therefore conducted.

The developed methodology used Arc GIS and the CEH DTM to identify which grid cell within any water body polygon has the longest inflow path (i.e. the grid cell through which the longest drainage path would pass if the DTM were used to derive a river network). The co-ordinates derived from this method were then used with LF2000 and FEH. The validity of the results obtained for each polygon were assessed by comparison of the LF2000 and FEH defined catchment areas with the catchment area calculated for the EA water body polygon. If the areas were within 15% of each other, the results from LF2000 and FEH were deemed as acceptable.

Results of using new method

The first table gives the total averages (of those which are within 15% of the expected area), the second looks at only catchments above 1 km^2 (we would not really expect to get good catchments below this) to see the percentages there.

Total number with area	7816	%
Number obtained previously	3770	48.24
Number obtained new	971	21
Total new	4741	60.66

Number over 1 km^2	6635	%
Number obtained previously	3770	56.82
Number obtained new	958	33.44
Total new	4728	71.26

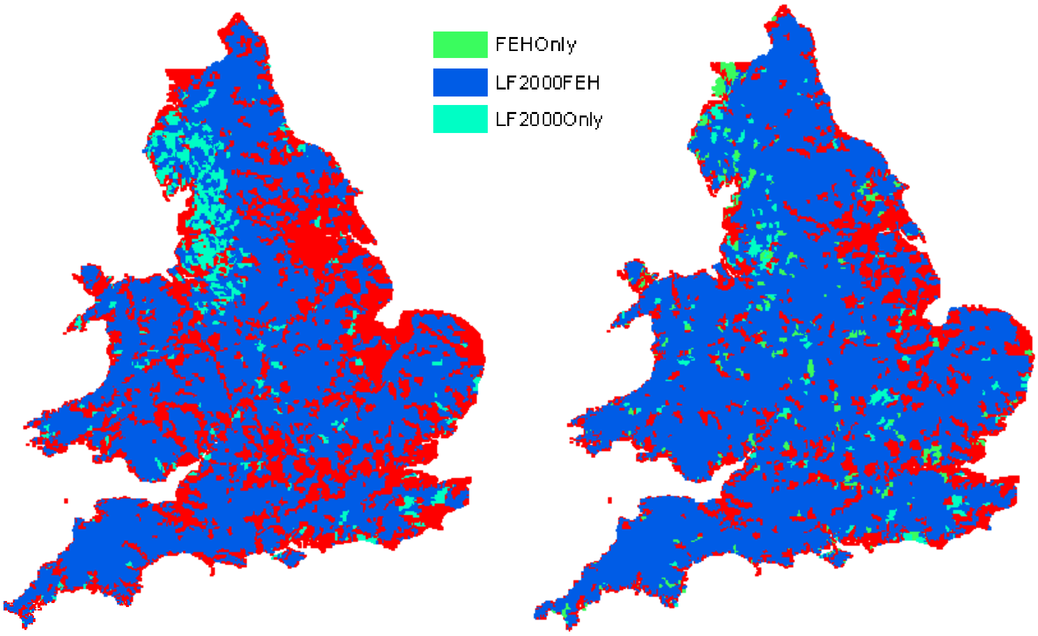


Figure 3 Comparison of FEH and LF2000 data coverage before and after introduction of new X–Y points (red areas indicate no data)

Appendix D: Sediment axis sensitivity analysis

Drainage density, SAAR and SLOPE class boundary variation

Model Runs:

a)	DD 1.0, 2.0	SAAR = 800, 1500 SLOPE 3, 7. (SLOPE dominant over SAAR)
b)	DD 1.0, 2.0	SAAR = 800, 1500 SLOPE 2, 8. (SLOPE dominant over SAAR)
c)	DD 1.0, 2.0	SAAR = 700, 1800 SLOPE 3, 7. (SLOPE dominant over SAAR)
d)	DD 1.0, 2.0	SAAR = 800, 1500 SLOPE 3, 7. (SAAR dominant over SLOPE)
e)	DD 1.0, 2.0	SAAR = 800, 1500 SLOPE 3, 7. (SLOPE dominant over SAAR)
f)	DD 0.5, 2.5	SAAR = 800, 1500 SLOPE 3, 7. (SLOPE dominant over SAAR)
g)	DD 1.5, 2.0	SAAR = 800, 1500 SLOPE 3, 7. (SLOPE dominant over SAAR)

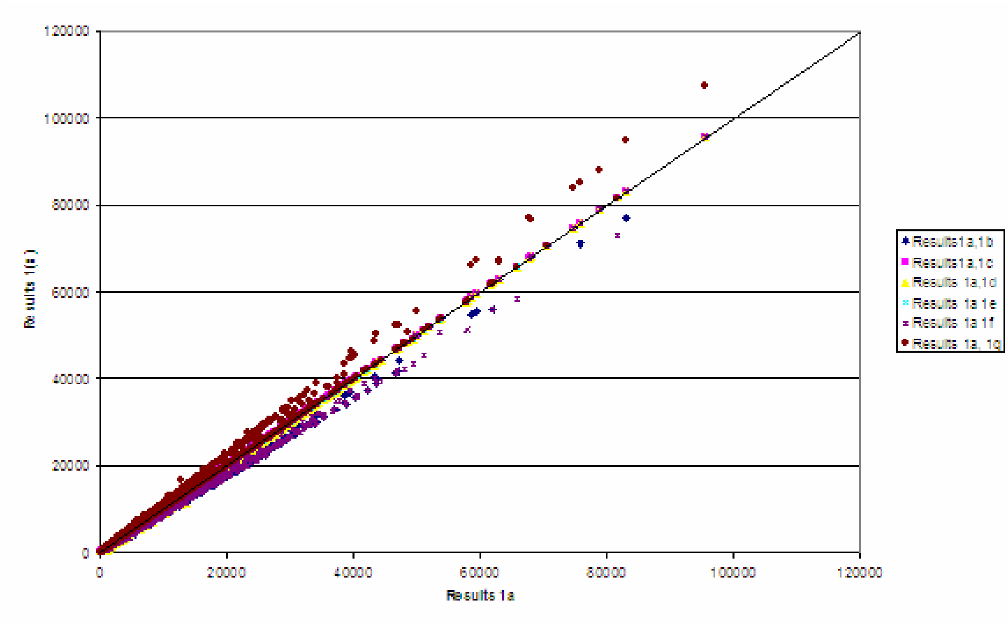


Figure 1 Comparison of predicted SWB fine sediment

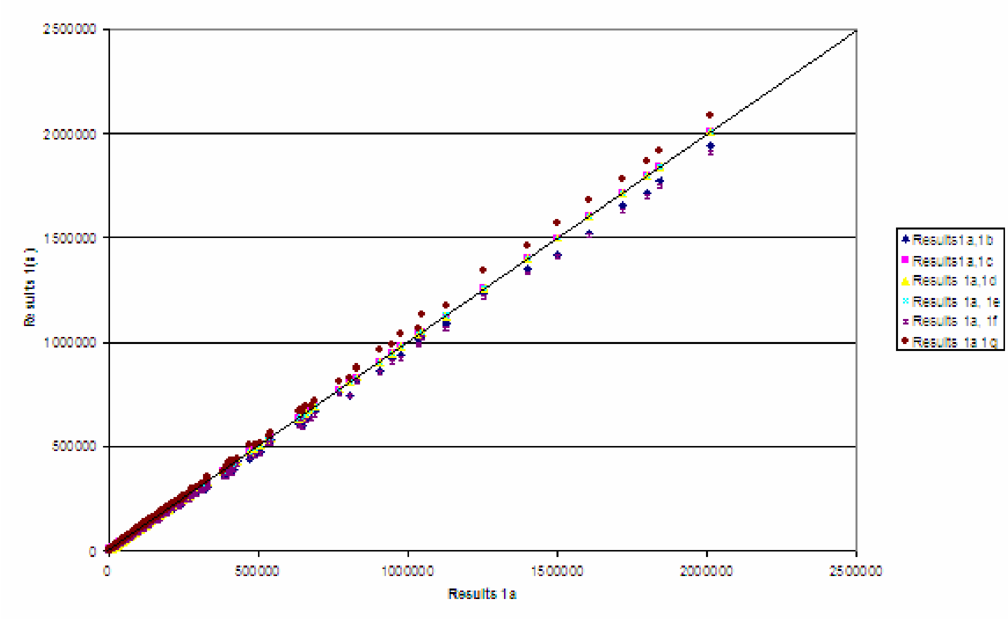


Figure 2 Comparison of predicted total catchment fine sediment (including upstream SWBs)

Appendix E: Summary of method

This guidance outlines, step by step, the process of producing this HZ classification for an individual SWB. It does not seek to explain the development or reasoning behind the typology as this is covered in the main body of the report.

The user will be able to follow the guidance and produce their own HZ classification for an individual catchment provided they have access to the relevant data.

The typology is based on a number of axes. This guide describes the process for calculation of each axis in turn, and then shows how these axes are brought together for the production of the final typology.

There are six main axes in the typology, which are listed in Table 1. The first two axes are required for the development of other axes, and only the final four are explicitly captured within the final typology. It should be noted that the geochemistry axis consists of three separate axes, each representing different attenuation properties of underlying geology.

Table 1 The axes which are used to produce the HZ classification

Axes
Fine sediment supply
Stream power
Sediment permeability
Sediment thickness
Subsurface permeability
Sediment geochemistry

In order to aid explanation of the methodology followed, flow charts and reference tables are used where appropriate. Where the reference tables are not significant in size these are included within the text, where the tables are larger, they are referenced to the main report.

Fine Sediment Supply axis

Figure 1 presents an overview of the methodology for estimating the Fine Sediment Supply axis classifications.

1. Calculate the area of land within the SWB catchment that has a land use (as defined by the LCM2000 map) of high erodibility. Highly erodible land-use types are defined as Coniferous or Arable. This is determined from a revised LCM2000 map in which the original vegetation classes have been aggregated into five classes (see Appendix B Table 1).

2. The area of land use with high erodibility is the **Potential Supply of Fine Sediment** (m^2).

3. Calculate the SAAR for the incremental catchment (mm/year).

4. Using Table 2, determine the **Rainfall Class** of the SWB.

5. Calculate the Mean Slope of the SWB, in degrees using the 50-m CEH DTM.

6. Using Table 3, determine the **Slope Class** of the SWB.

Table 2 Rainfall classes

Rainfall class	SAAR (mma^{-1})
Low (1)	< 800
Moderate (2)	800 - 1500
High (3)	> 1500

Table 3 Slope classes

Slope class	Slope (Deg)
Low (1)	< 3
Moderate (2)	3 - 7
High (3)	> 7

7. Using Table 4, determine the **Erosivity Weighting** as defined by **Slope** and **Rainfall** of the SWB. Find the Slope Class within the left hand column and read along this row until the appropriate Rainfall (SAAR) Class column. This value is the **Erosivity Weighting** as defined by **Slope** and **Rainfall**.

Table 4 Decision matrix for Erosivity Weighting from SAAR and Slope

	SAAR		
Slope	Low (1)	Moderate (2)	High (3)
Low (1)	1	1	2
Moderate (2)	2	2	2
High (3)	2	3	3

8. Calculate the **Drainage Density** within the SWB.
Calculate the length of rivers within the SWB using the 1:50,000 CEH river network map. The **Drainage Density** is the ratio of this to the SWB area.

9. Using Table 5, determine the **Erosivity Weighting** as defined by the **Drainage Density**.

Table 5 Erosivity Weighting as defined by Drainage Density classes

Erosivity Weighting	Drainage Density (km/km^2)
Low (1)	< 1
Moderate (2)	1 - 2
High (3)	> 2

10. Calculate the **Sediment Transportability** whereby:

Sediment Transportability =
Erosivity Weighting as defined by **Slope** and **Rainfall**
+ Erosivity Weighting as defined by the **Drainage Density**.

11. Calculate the **Supply of Fine Sediments** for SWB whereby:

Supply of Fine Sediments to SWB =
Potential Supply of Fine Sediment/Sediment Transportability.

12. Calculate the **Total Supply of Fine Sediments** for the SWB catchment.

Total Supply of Fine Sediments =
Total Supply of Fine Sediments to SWB
+ Σ**(Total Supply of Fine Sediments for upstream SWBs)**.

Power axis

1. Calculate the **Average Percent Slope**, as average percentage slope. Extract the slope value of the 50-m DTM grid squares that intersect with the SWB river. Calculate the average percent slope of these grid cells.

2. Calculate the **Mean Flow** within the SWB river at the point of the outlet. There are two methods of calculating the annual mean flow depending on the data availability.

   Where estimates generated from LF2000 could be obtained, the influenced (incorporation of abstractions and discharged) mean flow is used.

   Where no estimates generated from LF2000 are available, the 1 km resolution runoff-grid was used to generate the 'natural' runoff, hence mean flow, within the catchment.

3. Calculate the Power of SWB such that:

   Power = **Average Percent Slope** * **Mean Flow**

Sediment Thickness axis

1. Calculate the **Sediment Thickness**, where thickness is a relative measure such that:

   Sediment Thickness = Total Supply of Fine Sediment/Power

Sediment Permeability axis

The Sediment Permeability axis consists of two components (existing drift permeability and deposited sediment permeability).

Drift Permeability

1. The 1:50,000 BGS Drift map was used to determine the percentage of each Drift Rock Code which was intersecting the SWB river.

2. Where there is no drift calculate the intersecting area of the SWB river which intersects sandstones or chalks. Sandstones are assumed to contribute to size class 4, chalk is assumed to contribute to size class 6. These are treated as additional Rock Codes within the next stage.

3. Extract the Rock Codes that exist within the catchment from Interim Report 2 Appendix C, Table 25.

4. Within each Rock Code, for each Size Class:
   If Size Class Code = 'y' then X = 1. Else X = 0
   Z = Number of Size Class Codes where code is 'y'.
   Rock Code Percentage Size Class = Rock Code % *X/Z

5. For each Size Class:
   Sum Size Class = Rock Code Percentage Size Class (i) + Rock Code Percentage Size Class (ii) etc.

6. Calculate the **Percentage of Drift** for each **Permeability Class.**
   Sum the size classes together to represent the percentage within each. Do this according to the classifications within Table 6.

Table 6 Permeability Classes for each Size Class

Permeability	Size classes
Low (L)	Peat, clay, silt
Moderate (M)	Sand, gravel
High (H)	Pebbles, cobbles, boulders
Bedrock (B)	Bedrock

7. If there is more than 50% of any aggregated permeability class then the resultant **Drift Permeability of the SWB** is the same as this class.

   If there is no permeability class that accounts for more than 50% of the SWB then all classes that account for more than 15% are said to be present. Use Table 7 to assign the resultant **Drift Permeability** according to which of the permeability classes are flagged.

   Note that an example of this procedure is presented within Figure 2.

Table 7 Assigning the resultant Drift Permeability

Permeability class present (Y)				Resultant Drift Permeability
L	M	H	B	
			Y	B
		Y		H
		Y	Y	H
	Y			M
	Y		Y	M
	Y	Y		M
	Y	Y	Y	M
Y				L
Y			Y	L
Y		Y		M
Y		Y	Y	M
Y	Y			L

Y	Y		Y	M
Y	Y	Y		M
Y	Y	Y	Y	M

Deposited Sediment Permeability and Combined Permeability

1. **Power**, Total **Supply of Fine Sediments** for SWB catchment, **Fine Sediment Thickness** and **Drift Permeability classifications** are needed.

2. Table 8 is then used to determine the **Combined Sediment Permeability**.

Table 8 Rules for defining the Combined Sediment Permeability

Fine Sediment Depth Classification	Drift Permeability Classification	Resultant permeability if Power is less than 2	Resultant permeability if Power is Greater than 2
H	B	L	L
H	H	L	L
H	L	L	L
H	M	M	M
L	B	M	H
L	H	M	H
L	L	M	H
L	M	M	H
M	B	M	M
M	H	M	M
M	L	M	M
M	M	M	M

Figure 3 presents an overview of the process used to determine the **Combined Sediment Permeability**.

Subsurface Permeability Axis

1. Obtain the BFI of the SWB using the CEH HOST map. Calculate BFI from the proportions of HOST classes within the SWB catchment, using the weightings presented within the HOST Report (Boorman *et al*. 1995. *Hydrology of Soil Types: A Hydrologically Based Classification of the Soils of the United Kingdom*, Institute of Hydrology).

2. Use Table 9 to determine the subsurface permeability class for the SWB.

Table 9 Subsurface permeability relative to SWB BFI

Subsurface permeability	BFI
Low	0–0.4
Moderate	0.4–0.6
High	0.6–1

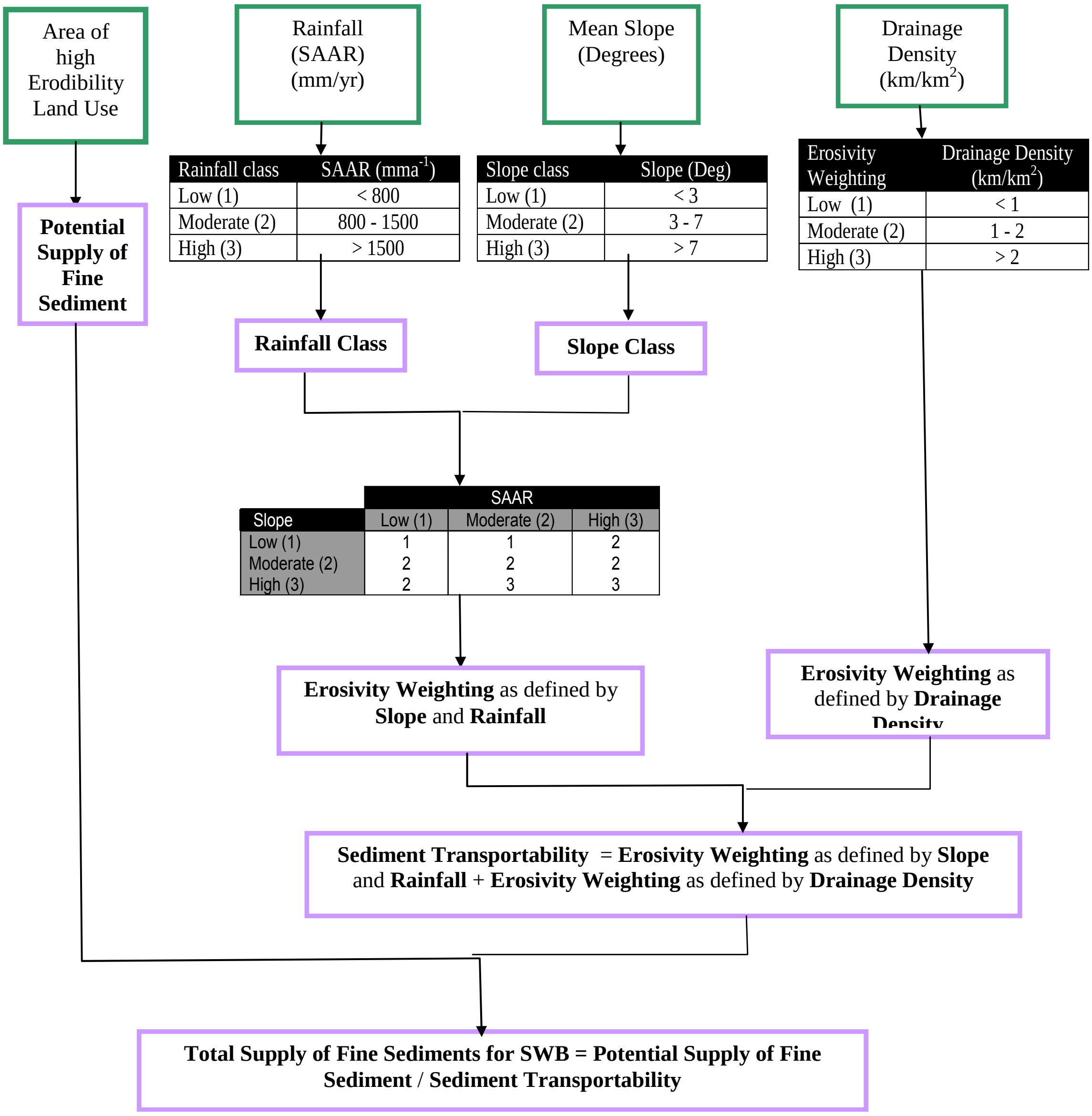
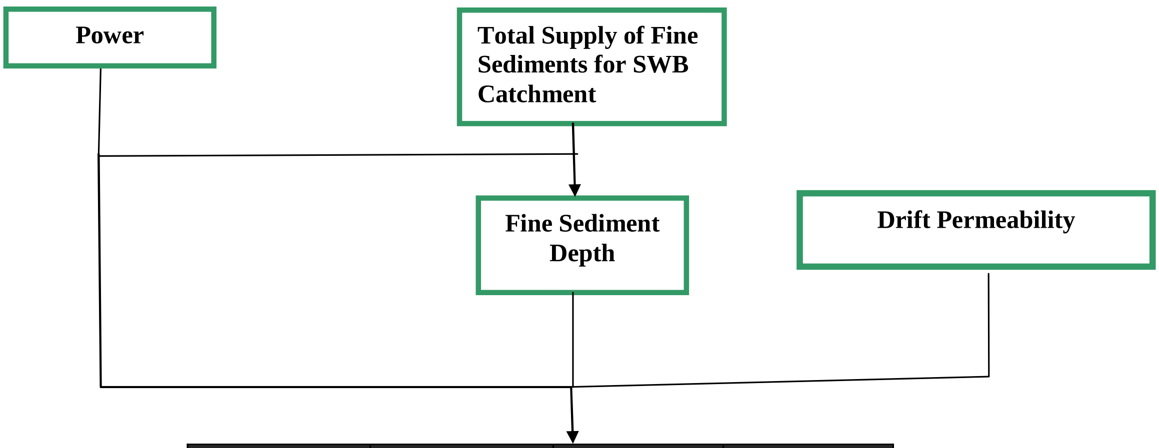


Figure 1 Flow chart showing the process for determining the Fine Sediment Supply Axis

				Size Class							
Rock Code	No. of Size Classes	% Rock Code	Drift Description	Peat	Clay	Silt	Sand	Gravel	Pebbles	Cobbles	Boulder
				1	2	3	4	5	6	7	8
CLSS	3	40	CLAY, SILT AND SAND		y	y	y				
				0	=1*(40/3) =13.33	=1*(40/3) =13.33	=1*(40/3) =13.33	0	0	0	0
PES	2	60	PEBBLY SAND				y		y		
				0	0	0	=1*(60/2) =30	0	=1*(60/ 2) =30		
Sum for each Size Class				0	13.33	13.33	43.33	0	30	0	0
Sum for each Permeability						26.66		43.33			30

Figure 2 Example for the calculation of the Percentage of Drift for each Permeability Class for a catchment which has 40% CLSS and 60% PES



Fine Sediment Depth Classification	Drift Permeability Classification	Resultant permeability if Power is less than 2	Resultant permeability if Power is Greater than 2
H	B	L	L
H	H	L	L
H	L	L	L
H	M	M	M
L	B	M	H
L	H	M	H
L	L	M	H
L	M	M	H
M	B	M	M
M	H	M	M
M	L	M	M
M	M	M	M

Combined Sediment Permeability = Resultant Permeability

Figure 3 Flow chart showing the process for determining the Combined Sediment Permeability

Geochemistry Axis

1. The 1:50,000 BGS Bedrock map should be used to determine the percentage of each Bedrock Lexicon code intersecting the SWB river. Where this is not in digital format the 1:625,000 BGS Bedrock map should be used.

2. Calculate the percentage of geochemistry attenuation class for the SWB. Each lexicon class had been previously mapped to geochemistry attenuation classes for CEC, FOC and TIC. These are available in digital format. Note that only lexicon classes that collectively account for 90% of the bedrock surface area have been mapped.

3. For each of CEC, FOC and TIC: where one attenuation class (low, medium, high) accounts for more than 50% of the river length this class is assigned to

the water body. Where this is not the case, classes which account for greater than 30% are assumed to be present. Where more than one class is present, using a precautionary principle, the SWB is assigned with the class which has the lowest attenuation capacity.

Hyporheic Zone Classification

Take the results from each of the axes and combine these to form the final typology. Figure 4 summarises the process for producing the final typology.

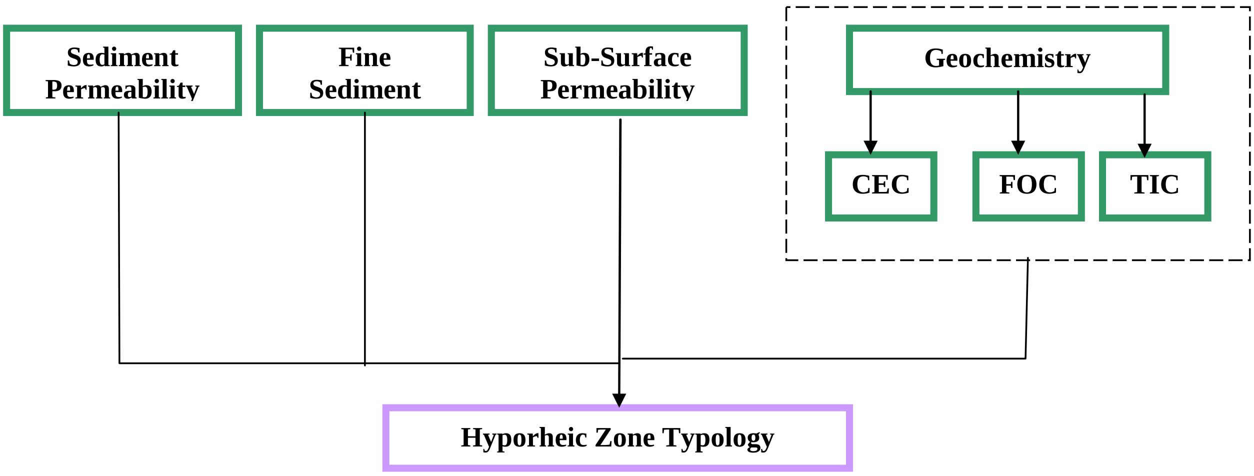


Figure 4 Flow chart showing the process for determining the HZ classification

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List of abbreviations

BFI	base flow index
BGS	British Geological Survey
BOD	biological oxygen demand
BTEX	benzene, toluene, ethylbenzene, and xylenes
CEC	cation exchange capacity
CEH	Centre for Ecology and Hydrology
CSO	combined sewer overflows
DTM	Digital Terrain Model
EA	Environment Agency
EC	European Commission
EQS	Environmental Quality Standards
EU	European Union
FEH	Flood Estimation Handbook
F_{OC}	fraction of organic carbon
GIS	geographical information system
GQA	General Quality Assessment
HOST	Hydrology of Soil Types
HZ	hyporheic zone
LCM2000	Land Cover Map 2000
LDP	longest drainage path
LF2000	Low Flows 2000
PAHs	polycyclic aromatic hydrocarbons
PCE	tetrachloroethene
PE	potential evapotranspiration
RHS	River Habitat Survey
SAAR	Standard Average Annual Rainfall
SPR	standard percentage runoff
SWB	surface water body
TCE	trichloroethene
TIC	total inorganic carbon
WB	water body
WFD	Water Framework Directive

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

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