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Scottish Superficial Deposits and the Water Framework Directive

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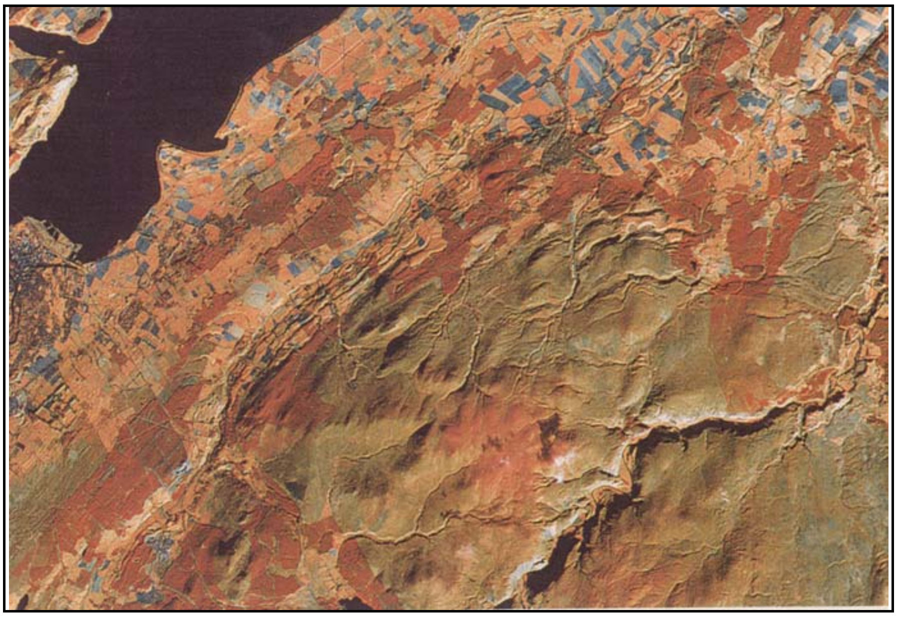

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT CR/02/154N

Scottish Superficial Deposits and the Water Framework Directive

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Superficial deposits near Inverness

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Foreword

This report is the published product of a scoping study by the British Geological Survey (BGS) for the Scottish Environment Protection Agency (SEPA). The work was carried out between February and April 2002.

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Summary

The Water Framework Directive, which entered into force in December 2000, stipulates that Member States must, for groundwater:

Within 4 years – identify river basins and assign groundwater bodies to them. Characterise these groundwater bodies. Identify 'Protected Areas' including bodies of water which supply more than 10 m^3 d^{-1} drinking water supply (>50 people), and identify those bodies which are at risk of not complying with the Environmental Objectives laid down in Article 4.

Within 6 years – establish appropriate monitoring programmes

Within 9 years – establish management plans and surveillance.

Within 15 years – ensure 'good status' is achieved wherever possible. This includes good status of quality and of quantity ensuring a balance between recharge and discharge.

The initial assessment requires an analysis of the main characteristics of each river basin, a review of the impact of human activity and an economic analysis of water use. These objectives implicitly require a review of groundwater abstraction to be carried out, both in terms of volume and use. The initial assessment also requires an evaluation of quantitative and qualitative status of each groundwater body, part of which is the evaluation of a water budget to establish if the resource is sustainable. Detailed understanding of the role of drift deposits in each catchment is, therefore, essential because of their role in influencing recharge to and protection of underlying groundwater. In addition, where sufficiently permeable and extensive, drift deposits will themselves constitute groundwater bodies.

Quaternary deposits occur throughout much of Scotland. They may be of glacial, lacustrine, fluvial, aeolian or marine origin, but are usually only a few metres thick, rarely more than 30 m and exceptionally more than 180 m (e.g. at Bo'ness in the Forth valley).

Most of the glacial deposition occurred during and after the last glaciation some 18 000 years BP. Detritus, or till was deposited beneath and marginal to the ice sheet, and is poorly sorted silt and clay with some sand grade material, cobbles and boulders. The sand grade material may be dominant, as is the case along parts of the Morayshire coast. As the ice sheets withdrew, water again flowed and fluvial deposits such as eskers were laid down within the ice, and broad outwash fans were deposited beyond the ice margin. The outwash fans tend to be coarse-grained with grain size reducing with distance from the ice sheet. Lacustrine silts and clays occur where valleys and drainage channels were blocked. The retreating ice sheets left large tracts of morainic drift in the upland valleys, and subsequent resorting and redeposition has occurred resulting in flights of terraces.

Permeable (more sandy) glacial deposits are widespread with major outwash fans present in the main valleys of the Borders, in the Midland Valley notably in Strathmore, Fife and between Dunbar and Lanark. There are numerous fans along the Highland border of Strathmore, along the southern shores of the Moray Firth and the eastern valleys of the Grampian Highlands.

Late-glacial marine sediments of poorly permeable silt and clay with some sand and gravel occur in the Tay, Forth and Clyde valleys above present day sea level. Raised beach deposits are also common along parts of the east coast of Scotland. Recent deposits include freshwater alluvium, peat and blown sand. Alluvial terraces are common in valleys, with silt and sand the dominant grade material.

Data with which to evaluate the role of superficial deposits and soils on recharge processes and aquifer vulnerability available for Scotland are sufficient to develop GIS format compilations for which algorithms could be written to assess catchment vulnerability and areas of recharge. A

first pass requires ovelaying the soil map to the drift geology map to identfy areas where gley soils and podzolic soils occur which reflect weakly permeable or free draining material below. This greatly assists in characterising the till and morainic drift which is so widely distributed in Scotland. Other data include catchment Base Flow Indices, aquifer vulnerability maps, depth to rockhead, ground slope, depth to water table, borehole data, and abstraction data.

A phased approach is recommended whereby an initial regional scale evaluation of recharge and vulnerability through drift is carried out to an effort of between 6 and 8 man months. This would be followed by refinement, particularly of the algorithms, and identification of data needs for problem areas and at risk areas, again of only a few man months duration. Phase three requires detailed instrumentation and catchment level investigation by way of verifying the regional evaluation and to develop understanding of critical, at risk, catchments further.

1 Introduction

Drift cover in Scotland poses a number of questions for river basin management as outlined in the Water Framework Directive (WFD). A key requirement of the WFD is that surface and groundwaters need to be characterised by risk. The status of a groundwater body is defined by qualitative and quantitative assessment and by whether it is or is not adversely influencing the status of associated surface waters and/or terrestrial ecosytems. There is, therefore, the need to define a water balance for an assessment of sustainability on a catchment scale and identify pollution risks (hazard and vulnerability). The nature and extent of drift deposits as a controlling influence on recharge and on vulnerability (the nature, integrity and extent of till and morainic drift deposits and how these deposits affect recharge processes and runoff and soil interflow) is key to both these determinations.

Drift cover is more widespread and diverse in Scotland than it is in England and its hydraulic role in a catchment water budget is critical. Problems are exacerbated by lack of knowledge about drift cover, as only small areas of Scotland have been mapped comprehensively and have accompanying borehole records that can be interrogated to assign zones or types of similar hydrogeological properties. A key issue is the location of both free draining and weakly permeable clayey till and morainic drift deposits and the influence they have on recharge from rainfall.

The Scottish Environment Protection Agency (SEPA) is conscious of the problems that are likely to arise with assessing the influence of superficial deposits when considering catchment water budgets and understanding pressures from anthropogenic pollution. As a consequence, SEPA has commissioned the British Geological Survey (BGS) to scope the likely issues, to describe the availability of relevant data, and to identify work that will need to be put in place in order to satisfy the requirements of the Water Framework Directive (WFD).

The WFD advocates integrated management of groundwater and surface water on a catchment scale, such that an understanding of the water budget is essential in order to provide an environmental characterisation of each catchment. The Directive requires that 'groundwater bodies' (which are as yet to be defined) be identified in the first instance and that the primary characteristics of these bodies (the physical and chemical status of them) be established along with the degree to which each is at risk of failing to achieve good status as defined in the Directive. Those deemed to be at risk will need further detailed characterisation, monitoring and the introduction of measures to improve their status. The target date for achieving good status where feasible is 2015 although derogations and extensions to this date can be requested.

Timetable for implementation of the WFD

The process and timetable for Member States to achieve the environmental objectives and significant deadlines for the Community to undertake actions within the Directive:

Within 2 years

- Commission to propose specific measures to establish criteria for assessing good groundwater chemical status and identifying trends in pollutants

Within 3 years

- Adopt legislation

Within 4 years

- Identification of River Basin Districts and assignment of groundwater bodies to these Districts
- Characterisation of the Districts
- Identification and listing of protected areas
- review of the impact of human activity on the status of surface water and groundwater
- classification of water bodies, including those that are at risk of failing to meet environmental objectives. The latter must generally be characterised in more detail.
- Economic analysis of water use
- Identify groundwater bodies for which lower objectives are specified

Within 5 years

- if not already set by Commission, Member States to establish criteria for assessing good groundwater chemical status and identifying trends in pollutants

Within 6 years

- groundwater monitoring programme established
- Commission to put in place emission controls for point sources and environmental quality standards for substances on first list of priority substances

Within 9 years

- Establishment of River Basin Management Plans (RBMP) including a Programme of Measures designed to enable objectives to be met.

Within 10 years

- Appropriate water pricing policies put in place

Within 12 years

- measures specified within the River Basin Management Plan become operational

Within 15 years

- ensure ‘good status’ is achieved for all water bodies except where derogations

The objectives of this scoping study are:

- To consider the importance of drift deposits and the data needed to meet the WFD requirements;
- To review the pressures and threats to groundwater in Scotland and where they occur;
- To identify those areas where drift cover is relevant to these issues;
- To carry out a review of current knowledge of the drift in Scotland, data availability, location and format;
- To undertake a literature search of groundwater/drift processes;
- To identify likely information requirements for drift hydrogeology in order to satisfy the WFD;
- To assess methods of data presentation.

2 Superficial deposits of Scotland

The superficial deposits of Scotland were mainly laid down during, or since the last major glaciation. This event, known as the Main Late Devensian (MLD) glaciation, occurred between about 29 000 and 15 000 calendar years ago. An ice sheet expanded quickly to cover the whole of the Scottish mainland in that period, followed by a slow glacial retreat under 'Siberian' conditions, especially in the east of the country. The region had been previously glaciated on several occasions during the Pleistocene, but only isolated pockets of these older glacial sediments have survived the erosive powers of the last ice sheet. These older deposits are relatively common in the Buchan area, which has experienced relatively little glacial erosion (Figure 1 and Enclosure 2)). The climate warmed abruptly 14 700 years ago when tundra vegetation was replaced by one of birch and juniper scrubland. However, the climatic amelioration was short-lived and Arctic conditions returned about 12 500 years ago. A substantial ice cap developed over the western Highlands and small glaciers formed in the high corries of the Cairngorms and the Galloway Hills during the ensuing 'Loch Lomond' glaciation. Most of Scotland remained unglaciated, but repeated freezing and thawing destabilised cohesive glacial deposits, causing them to creep and slip downslope into the valleys, where they commonly accumulated on top of river terraces. The present warm, interglacial climate of the Holocene began abruptly 11 500 years ago. Birch woodland had returned by 10 000 BP, followed later by pine. Though relatively stable, the climate has varied sporadically and has become colder and wetter since 4 300 before present (BP).

Sea level has fluctuated considerably over the past 18 000 years in Scotland. The amount of change that has occurred varies considerably across the country due to uneven post-glacial uplift. During the slow retreat of the MLD ice sheet, relative sea level generally stood approximately 30 m above present day OD (Ordnance Datum) as a result of the considerable depression of the Earth's crust beneath the ice sheet. A series of 'Late-glacial' raised beaches and glaciomarine deposits accumulated along the coasts and within the firths. In many parts of Scotland sea level then fell to about its present level by 12,500 BP and subsequently many metres below OD as the crust rebounded quickly. Many rivers became deeply incised into their floodplains towards the coast at this time. The accelerated melting of the major ice sheets of the world during the Holocene, coupled with the diminishing rebound of the crust, caused sea level to rise to about 10 m above OD by about 6 000 BP, when a 'post-glacial' series of raised beaches and estuarine deposits accumulated. Rivers 'backed-up' during this sea level highstand, causing fine-grained floodplain deposits to accumulate inland. All raised marine deposits and shoreline features in Scotland tilt gently away from a centre of uplift positioned over Rannoch Moor.

The most widespread deposit laid down directly by the MLD ice sheet was glacial **till** or 'boulder clay'. It generally rests on bedrock, covers much of the low ground and extends into the upland valleys. The till generally consists of cobbles, boulders and pebbles mixed with clayey sand and silt (formed of 'rock flour' ground-up by the ice). Tills represent some of the least permeable superficial deposits in Scotland. Although most tills overlying crystalline rocks in the Highlands and parts of the Southern Uplands are more sandy and gravelly compared with tills in the Central Valley, which are commonly more clayey, they are nonetheless relatively impermeable because they have been extremely compacted beneath ice.

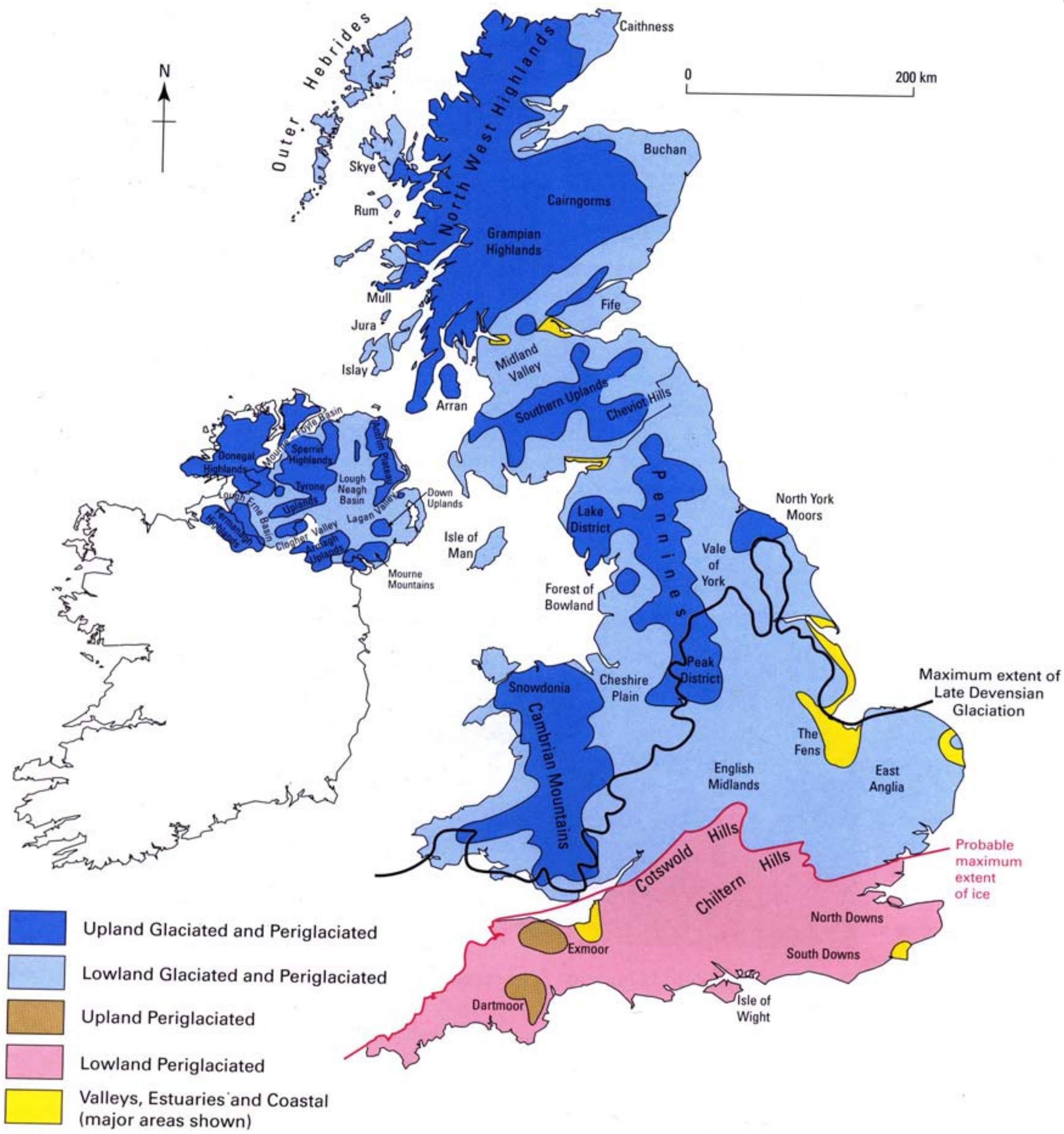

Figure 1 Quaternary provinces of the United Kingdom (from Foster *et al*, 1999) (see also Enclosure 2)

The lithology of the tills strongly reflects the nature of the underlying bedrock. For example, tills in the Southern Uplands tend to contain large proportions of gravel formed of fragments of greywacke sandstone and siltstone. Tills in Strathmore, Berwickshire and Dumfries-shire are generally vivid reddish brown in colour and contain much fine-grained sand and clay derived from underlying 'red-beds'. Tills in the Central Valley are typically clayey and contain much Carboniferous sandstone, mudstone and coal in addition to more far-travelled rock types.

The thickness of tills varies significantly across Scotland, both at the local and regional scale. This is related to a large extent both to the strength of the rocks and pre-existing superficial deposits over which the ice flowed, and to former strengths of flow within the ice sheet. Relatively fast-flowing ice flowed out of the firths and through the Central Valley. Where the ice flowed over deformable materials it commonly created swathes of elongated, hemispherical mounds known as drumlins. Clayey tills are locally tens of metres in thickness within drumlins and where they infill hollows in the bedrock surface or pre-existing valleys (Enclosure 2). In contrast, ice centred over the eastern Grampian mountains and the Borders was relatively sluggish, caused minimal glacial erosion and laid down thin sheets (< 5 m) of till. Tills in Buchan are commonly particularly thin (< 2 m) within the area of minor glacial erosion shown on Figure 2. They are also sandy because they contain a large proportion of decomposed bedrock (Figure 1 and Enclosure 2).

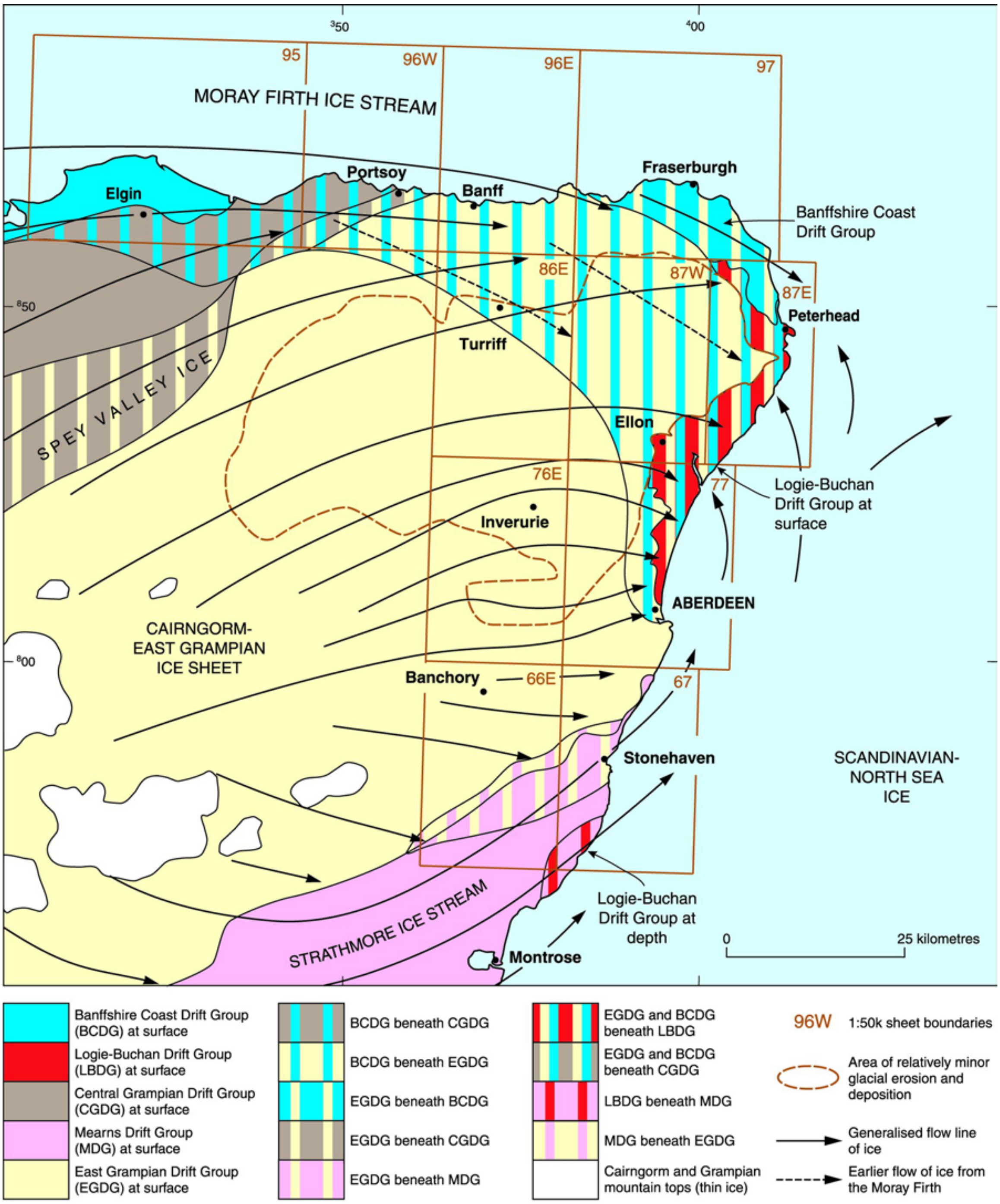

Figure 2 Generalised flow-lines of ice during the Main Late Devensian Glaciation and profile map of the five groups of glacigenic deposits mapped in NE Scotland (from Merritt *et al.*, *in press*)

Some coastal areas of Scotland were invaded by ice flowing from offshore during an early stage in the MLD glaciation. The ice plucked up masses of glaciomarine silt and clay and Mesozoic strata from the sea-bed and deposited them as 'glacial rafts' at the base of the tills locally. These 'rafts' may be several metres thick and hundreds of metres in extent. They are particularly common in Ayrshire, Caithness and along the southern shore of the Moray Firth where they locally dominate the till deposits.

During deglaciation mounds and ridges of heterogeneous bouldery gravel and till were laid down as 'recessional' moraines at the margin of the ice sheet as it retreated. These moraines are most widespread in the valleys of the western Highlands and Cairngorms, but also occur in the Southern Uplands and elsewhere. The deposits forming the moraines are generally poorly consolidated, sandy and permeable. They are identified on older maps as **morainic drift**. They are classified as **hummocky glacial deposits** on more modern maps, although the same colour coding has been used..

The recessional moraines are commonly associated with *glacial drainage channels* that were cut into the underlying till and bedrock at the ice margin during summer thaws. Most of the channels contain some modern drainage, but these watercourses are clearly 'misfits'. Some of the channels are many tens of metres in depth and are major topographical features. Particularly prominent channels occur along the southern flanks of the Ochil Hills, along the northern flanks of the Pentland Hills, across most of Aberdeenshire, along the southern shores of the Moray Firth and in Ayrshire.

Seasonal glacial meltwaters laid down deposits of **glaciofluvial sand and gravel** during deglaciation that now occur as terraces, plateaux, mounds (*kames*) and ridges (*eskers*). Traditionally, terraced and moundy deposits have been identified separately on BGS maps, although names and symbols have changed over the years (see Table 1 below). At present the terraced deposits are identified as 'glaciofluvial sheet deposits' whereas the moundy deposits are 'glaciofluvial ice-contact deposits'. Most glaciofluvial deposits rest on till.

Glacial meltwater deposits are particularly widespread and thick at the former margins of ice that flowed from different centres of accumulation. For example, the famous Carstairs esker system in south Lanarkshire formed at the junction of ice sourced in the Highlands and Southern Uplands. Glaciofluvial deposits are also common within valleys where ice blocked the lower reaches during the deglaciation, causing lakes to form upstream. Meltwaters flowed into the lakes laying down fans and deltas composed of sand and gravel. These deposits are typically moundy and commonly coarsen upwards from silt into sand and then gravel. Large-scale cross-stratification is commonly evident. Examples of deltaic deposits such as these are common in coastal Morayshire, Banffshire and Buchan where ponding occurred along the southern margin of the Moray Firth ice stream after ice inland had retreated. Deltaic deposits are also common in the upper reaches of the Irvine valley in Ayrshire. Most glaciofluvial deposits in Scotland were deposited during the retreat of the MLD ice sheet, but sizeable deposits were also laid down during the subsequent Loch Lomond Glaciation. For example, deltas formed at the heads of several sea lochs along the western seaboard of the Highlands where glaciers entered the sea, which then stood at about 30 m above OD.

The glacial, morainic and glaciofluvial deposits were commonly reworked by outwash streams to form widespread terraces in many valleys. These 'sheet' deposits are typically more gravelly and densely-packed, and more uniform in composition and thickness than moundy deposits. Although moundy deposits are locally several tens of metres in thickness, the sheet deposits are commonly between 5 and 10 m thick. However, moundy and terraced spreads commonly merge together in which case boundaries drawn between them are somewhat arbitrary. The glaciofluvial terraces are generally distinguished from alluvial terraces occurring at lower levels in the valleys by the presence of enclosed hollows (*kettleholes*) that were formed by the melting of blocks of ice trapped within the sediment. Many alluvial terraces were probably created only a short time after the glaciofluvial ones.

Extensive spreads of fine-grained **glaciolacustrine** deposits were also laid down in ice-marginal lakes during deglaciation. They are commonly thinly laminated and impermeable. However, deposits such as these are commonly not distinguished on older geological maps from glaciofluvial deposits. Furthermore, they commonly underlie river terrace gravels and the gravelly alluvial deposits beneath floodpains of major rivers such as the Spey, Deveron, Don, Dee, Clyde, Tweed, Irvine and Esk. On valleysides, these laminated deposits form perched water tables and are particularly prone to landslipping.

The major rivers of Scotland are flanked by flights of **alluvial terraces**, those of the Spey being particularly extensive. The features were formed by braided rivers during the retreat of the MLD ice sheet and during the subsequent Loch Lomond glaciation. They are typically underlain by several metres of densely-packed cobble gravel resting on till; terrace deposits of major rivers such as the Spey are commonly 10 to 15 m thick. The gravels are locally capped by up to about 2 m of sand or loam, especially in the lower reaches of valleys.

Once dense vegetation had become established about 10 000 years ago, most rivers adopted their present single-thread, meandering styles. River floodplains are typically underlain by 1-2 m of loam overlying dense, water-saturated shingle. These deposits are identified as **alluvium** on BGS maps. Unusually, the lowest reach of the Spey is braided and has a gravelly floodplain. Most alluvial deposits rest on till rather than directly on bedrock

Raised beaches are widespread around the coasts of Scotland, particularly along the western seaboard, around the Moray Firth, along the eastern coast between Aberdeen and Dunbar, and beneath the Ayrshire Plain. Late-glacial features are fragmentary, occur up to 40 m above OD and are generally underlain by sand and gravel that passes inland locally into spreads of raised silty clay. Many deposits also pass laterally into glaciofluvial deposits. Post-glacial beach deposits are much more widespread, generally occur no higher than about 10 m OD and are commonly formed of storm beach ridges. Deposits such as these fringe the coast of Spey Bay, where they are formed of several metres of well-sorted, well rounded shingle. The raised marine features are commonly concealed beneath **blown sand**, as for example, at the mouth of the Firth of Tay, beneath Tentsmuir Forest, and on Tiree. The Culbin Sands near Forres form the most extensive area of active sand dunes in Scotland.

The post-glacial raised beaches are commonly associated with large expanses of raised estuarine clays (**carse**), particularly at the heads of the major firths. The Carse of Stirling at the head of the Firth of Forth is the most extensive deposit, but other important expanses occur between Dundee and Perth, around Paisley and Stranraer. The carses are generally underlain by 10 m or more of silty clay resting on a variety of deposits including sand, gravel and peat.

2.1 CLASSIFICATION OF DEPOSITS ON CONVENTIONAL BGS MAPS

The Drift editions of most BGS 1:50 000-scale maps covering Scotland show deposits that have been classified using a *morpho-lithogenetic* scheme and identified by standard colours and symbols, for example, 'Glaciofluvial sand and gravel' in pink or crimson, and 'till' in blue. Many of the symbols have been used on maps produced by the Survey for 150 years and are very familiar. This method of classification has proved to be a practical means of mapping deposits cropping out at the surface and it is particularly appropriate for rapid mapping techniques relying heavily on air photo interpretation.

The drift symbols have been embellished on the more recently-published maps such that lithostratigraphical map codes appear as superscripts, lithological codes as prefixes, chronostratigraphical qualifiers as subscripts and inferred depositional environments as suffixes (Figure 3). More subcategories of deposit are generally found on the detailed 1:10 000 or 1:10 560 maps that are available for large parts of the country. Inevitably, the symbol scheme has been modified over the years with the result that there are variations in presentation between sheets, although the differences are largely semantic (Table 1).

The morpho-lithogenetic scheme does have some failings, however. For example, it does not easily accommodate complicated sequences of deposits or bodies of sediment that contain a mix of lithologies. It also does not allow families of deposits with common attributes to be shown easily. In order to overcome these difficulties, some of the more recently produced maps depict deposits that have been classified *lithostratigraphically* in accordance with internationally agreed codes.

Lithostratigraphy involves the description, definition and naming of rock units. Individual units are normally described and defined using their gross lithological characteristics, by their interrelationships with adjacent units, and on the basis of their unconformable bounding surfaces. The units are ranked in a formal hierarchy of *Bed, Member, Formation* and *Group*. The Formation is generally the basic mappable unit in the hierarchy. All units have been entered into this framework, the *BGS Lexicon of Named Rock Units* and the *Index of Computer Codes* ***{http=//www.bgs.ac.uk}***.

Table 1 Some common synonyms used on BGS drift maps of Scotland (obsolete terms in italics)

Alluvium	*River alluvium* *Floodplain alluvium* Alluvium of the first terrace
River terrace deposits	*Alluvium of the 2nd, 3rd … terrace*
Alluvial fan deposits	*Alluvial cone*
Till	*Boulder clay*
Glaciofluvial sheet deposits	*Fluvioglacial sand and gravel* *Fluvioglacial terrace deposits* *Glacial meltwater deposits … terraced*
Glaciofluvial ice-contact deposits	*Glacial sand and gravel* *Glacial meltwater deposits … moundy*
Glaciolacustrine deposits	*Brick clay* *Loam*
Hummocky glacial deposits	*Morainic drift*

In north-east Scotland, for example, deposits laid down in association with ice that flowed out of the Moray Firth are presently placed within the *Banffshire Coast Drift Group*, whereas deposits laid down by ice that flowed from the Grampian mountains are allotted to the *East Grampian Drift Group*. The distribution of these and other glacigenic groups in North East Scotland are shown in Figure 2, which is a profile map depicting the local interdigitation of formations belonging to five groups. The deposits within this region of Scotland are particular diverse because they were deposited by at least three distinct bodies of ice, the relative positions of the ice streams changed with time during the last (Main Late Devensian) glaciation, and deposits of more than one glaciation occur quite widely. It is now proposed to set up groups covering the whole of northern Britain (Figure 11).

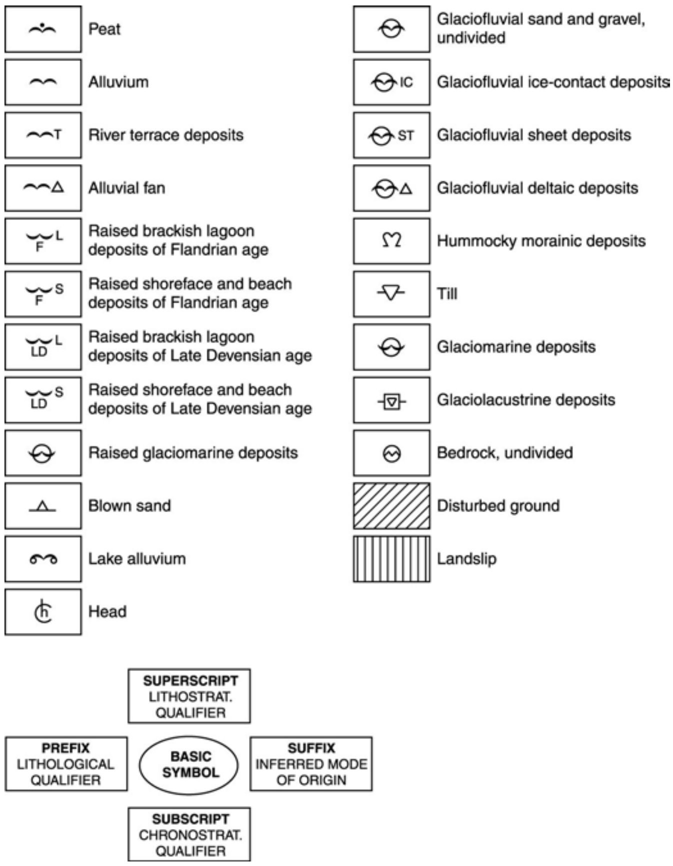

Figure 3 Key to the most common morpho-lithogenic symbols used on recently-published Quaternary maps of Scotland (after Merritt *et al*., *in press*)

2.2 PROPOSED NEW DRIFT GROUPS

A new mapping-related lithostratigraphical framework for the Quaternary of Britain has been proposed recently by McMillan and Hamblin (2000). Although the framework is currently under review and elements of it may change and boundaries refined, the scheme is presented here as it is largely for studies such as discussed in this report that it has been devised. Feedback would be appreciated. The thirteen Glacigenic Groups (or sub-groups) covering Scotland are shown in Figure 11. They are described briefly below, especially the tills, which are of particular hydrogeological interest. It is also proposed that fluvial, lacustrine, estuarine, coastal and aeolian deposits are defined geographically within a series of **Catchment Groups** defined by major river drainage systems (McMillan and Hamblin, 2000).

2.2.1 The Shetland Glacigenic Group

Ice that flowed radially outward from the Shetland Islands laid down compact, matrix-dominated tills characterized by clasts of a rich variety of metamorphic and igneous rock-types together with Devonian sandstone and siltstone. The tills generally occur only in pockets and glaciofluvial deposits are very sparse.

2.2.2 The Banffshire Coast and Caithness Glacigenic Group

This group of deposits contain material derived from the Moray Firth basin in addition to more locally occurring rock types. They occur from Inverness eastwards towards Peterhead and within the eastern portions of Caithness and Sutherland (Figure 11). The tills are typically dark grey, clayey, calcareous and contain ice-worn Quaternary shell fragments in addition to abundant reworked Early Jurassic to Early Cretaceous microfossils and sporadic macrofossils. The uppermost metre or so of the tills are generally decalcified and mottled in colour. Permo-Triassic and Lower Jurassic to Upper Cretaceous strata crop out within the Moray Firth basin and both clasts and large glacial rafts of these rock types are common in the tills of this group. The glaciofluvial sands and gravels of the group generally contain similar suites of clasts to the tills, and shell fragments are common.

It should be noted that locally, both the colour and composition of the tills of this group strongly reflect the lithology of the underlying bedrock. Both in Buchan and Caithness, the bluish grey tills pass beneath younger tills of other groups (Figure 2, 11).

2.2.3 The North-West Highland Glacigenic Group

Ice that flowed outward from the mountains of the north-western Highlands laid down tills and outwash characterised by clasts of tough, crystalline basement rocks. The deposits are typically gravelly and pale grey to light brown in colour. Apart from where they occur in western Caithness, much of their outcrop awaits modern re-survey.

2.2.4 The Inverness Glacigenic Group

This group of deposits was laid down by ice that flowed eastwards from the Great Glen and the NW Highlands to cross Old Red Sandstone strata. The stones in the tills and gravels are largely composed of durable crystalline rock types from the west together with clasts from ORS conglomerates, which are locally bouldery. The till matrices are typically brown in colour, clayey, but contain much fine to medium-grained sand derived from comminuted ORS sandstone. Over Culloden Moor and the Black Isle the tills contain much sandstone rubble. In the Inverness area, psammite-rich glacigenic deposits of the Central Grampian Glacigenic Group commonly overlie those dominated by Old Red Sandstone (Figure 11).

2.2.5 Western Isles Glacigenic Group

Glacigenic deposits are sparse in the Western Isles. They are typically bouldery and contain much medium to coarse-grained sand derived from the comminution of crystalline Lewisian basement rocks. Most of the ground awaits modern re-survey.

2.2.6 The Cairngorm-East Grampian Glacigenic Group

The tills of this group are generally yellowish brown, sandy and patchy, especially across central Buchan (Figure 2). Thicker and more widespread tills occur towards the higher ground in the west and in the valleys of the Dee and Don, where colours range from browns to grey. Although erratics from farther afield do occur sporadically, the colour and clast composition of the tills closely reflect the nature of underlying bedrock of the eastern Grampian Highlands. The sandiness and pale colour of the deposits of this group occurring in central Buchan commonly give them a weathered appearance, suggesting to some that they result from either a pre-Late Devensian glaciation or a pre-Devensian one. However, these characteristics are more likely to result from the incorporation of significant proportions of decomposed bedrock, which is very common in the area. The sand is predominantly medium to coarse-grained and quartzo-feldspathic, having been derived largely from granitic and gabbroic rocks. There is now robust evidence that most of the deposits of the group are of Late Devensian age.

2.2.7 The Logie-Buchan Glacigenic Group

The Logie-Buchan group commonly comprises thick interbedded sequences of clayey diamicton, clay, silt, mud, sand and gravel. Most deposits are typically vivid reddish brown in colour and calcareous. The sands are typically fine to medium-grained, silty, micaceous and contain shell fragments. In addition to locally occurring rock types such as amphibolite, feldspathic psammite, quartzite and meta-greywacke, the deposits contain appreciable proportions of rocks derived from the sea bed to the east, including limestone, calcareous siltstone, white and red sandstone of Devonian, Permo-Triassic, Jurassic, Cretaceous and Palaeocene age. The group is restricted to the coastal lowlands north of Aberdeen, east of Ellon and south of Peterhead (Figure 2), where it forms distinctive, fresh-looking, hummocky topography comprising kettleholes, mounds, plateaux, esker ridges and narrow, winding, steep-sided valleys.

2.2.8 The Central Grampian Glacigenic Group

Deposits of this group were laid down by ice that radiated outwards from a centre over Rannoch Moor in the western Highlands, carrying rock fragments from the Central Highland Migmatite Complex and Caledonian igneous rocks as well as other local bedrock types. The ice flowed via the Great Glen and the lower reaches of the Nairn, Findhorn and Spey valleys. to merge with the Cairngorm-East Grampians ice sheet and the more powerful Moray Firth ice stream. The relative power of the merging ice streams varied through time, resulting in the local interdigitation of deposits (Figure 2). The deposits of this group are typically bouldery and relatively little weathered. Tills are commonly extremely compact and stoney.

2.2.9 The Mearns Glacigenic Group

This group comprises interbedded diamictons, glaciolacustrine silts and clays, and glaciofluvial sands and gravels that are all typically vivid reddish brown in colour. The clasts are mostly derived from the Devonian conglomerates and andesitic volcanic rocks of Strathmore, whereas till matrices and fine grained deposits are mainly derived from Devonian sandstones and mudstones. Many tills are sandy, but unlike those of the Cairngorm-East Grampian group, the sand is fine to medium-grained and bound together in a silty clay matrix. The deposits were laid down by, or at the margins of, ice that flowed north-eastwards into the North Sea basin from Strathmore (Figure 2, 11).

2.2.10 Midland Valley Glacigenic Group

This group of deposits is dominated by clasts derived from rocks cropping out in the Midland Valley, but includes erratics brought by ice from the central Grampian Highlands. Tills are commonly thick (>10m), clayey, very dense, brownish grey in colour and contain much sandstone, mudstone and coal derived from Carboniferous strata. The till deposits are commonly glacially streamlined into drumlins (Enclosure 2) within which over 30m of diamicton can occur locally (Figure 1)

2.2.11 Borders Glacigenic Group

The deposits of this group are typically reddish brown because the fines and sand grade material within them is derived substantially from comminuted Devonian 'red-beds'. In the west, the larger clasts are derived predominantly from the greywacke sandstones and siltstones of the Moffat Hills, from which the ice flowed. Towards the coast the deposits are increasingly dominated by Carboniferous sandstones, limestones, conglomerate and mudstones. The till deposits are commonly glacially streamlined into drumlins.

2.2.12 Southern Uplands Glacigenic Group

The common attribute of deposits assigned to this group is that they include clasts that are dominated by greywacke sandstone and siltstone together with other rocks forming the Southern Uplands. The principal centres of ice dispersion were the Galloway, Moffat and Cheviot Hills (Figure 11). Granitic or dioritic rocks are predominant in the deposits locally, as for example, around Criffel. The greywacke-rich tills are commonly rubbly and partially clast-supported. Till is generally confined to the valleys.

2.2.13 Irish Sea Glacigenic Group

In Scotland, the deposits of this group are typically reddish brown because the fines and sand grade material within them is derived substantially from comminuted Permo-Triassic 'red-beds' of the Solway Lowlands. In contrast, larger clasts are largely derived from the greywacke sandstones and siltstones of the Galloway and Moffat Hills. The deposits were laid down from ice that flowed around the north-western side of the Lake District to merge with ice that flowed southwards across the Irish Sea basin from southern Scotland. The till deposits are glacially streamlined into drumlins (Enclosure 2) within which a 'tri-partite' sequence is commonly preserved consisting of units of sand, gravel, silt and clay sandwiched between tills. The uppermost till of the sequence is commonly sandy whereas the lowermost is more clayey and the thicker, stonier and denser of the two.

2.3 AVAILABILITY OF DRIFT MAPS

The only printed drift geology map covering the whole of Scotland is the **Ten Mile** map (1:625 000) covering the UK north, published in 1977, with a more recent version released in April 2002. A revised drift edition may be available during 2003-2004. The Ten Mile map is a useful scale on which to base regional assessments of the superficial deposits, but it is grossly generalised and many areas have been remapped since 1977 with significant changes made to linework and the classification of deposits. Furthermore, the drift geology of large areas of the country where no data exist were patched in from Soil Survey maps and other sources of information. For example, this was done for most of the Western Isles where little drift mapping has been undertaken. There are no 1:250 000 drift maps of Scotland.

Most, but not all, of the country has drift linework published at the **One Inch** (1: 63,360) scale. These maps have been largely superceded by the **1:50,000** series, which are produced to the same grid (Figure 4), but with each former sheet divided into eastern and western halves. There are still some sheets for which printed maps at the One Inch scale are all that is currently available, a few of them being hand-coloured and cloth-backed and only available for view in the BGS library. Furthermore, many 1:50,000 maps were derived from the older editions with no revision at all, as for example, those covering much of southern Scotland. Many of the One Inch maps of the Highlands and Islands have been published recently as 'Provisional' 1:50,000 maps with only minor desk-top revision (Figures 4 and 5).

Current availability of paper maps changes rapidly. Pending printing, many maps that have been completed are available as print-on-demand. Up to date information can be obtained from the BGS web site (www.bgs.ac.uk) under 'products' and 'catalogue of geological maps and books', although the most up to date corrected copies of the 1:10,000 geological maps are not available by this means. The current availability of digital products can be found on the online catalogue, which can be found at *www.bgs.ac.uk/catalogue*.

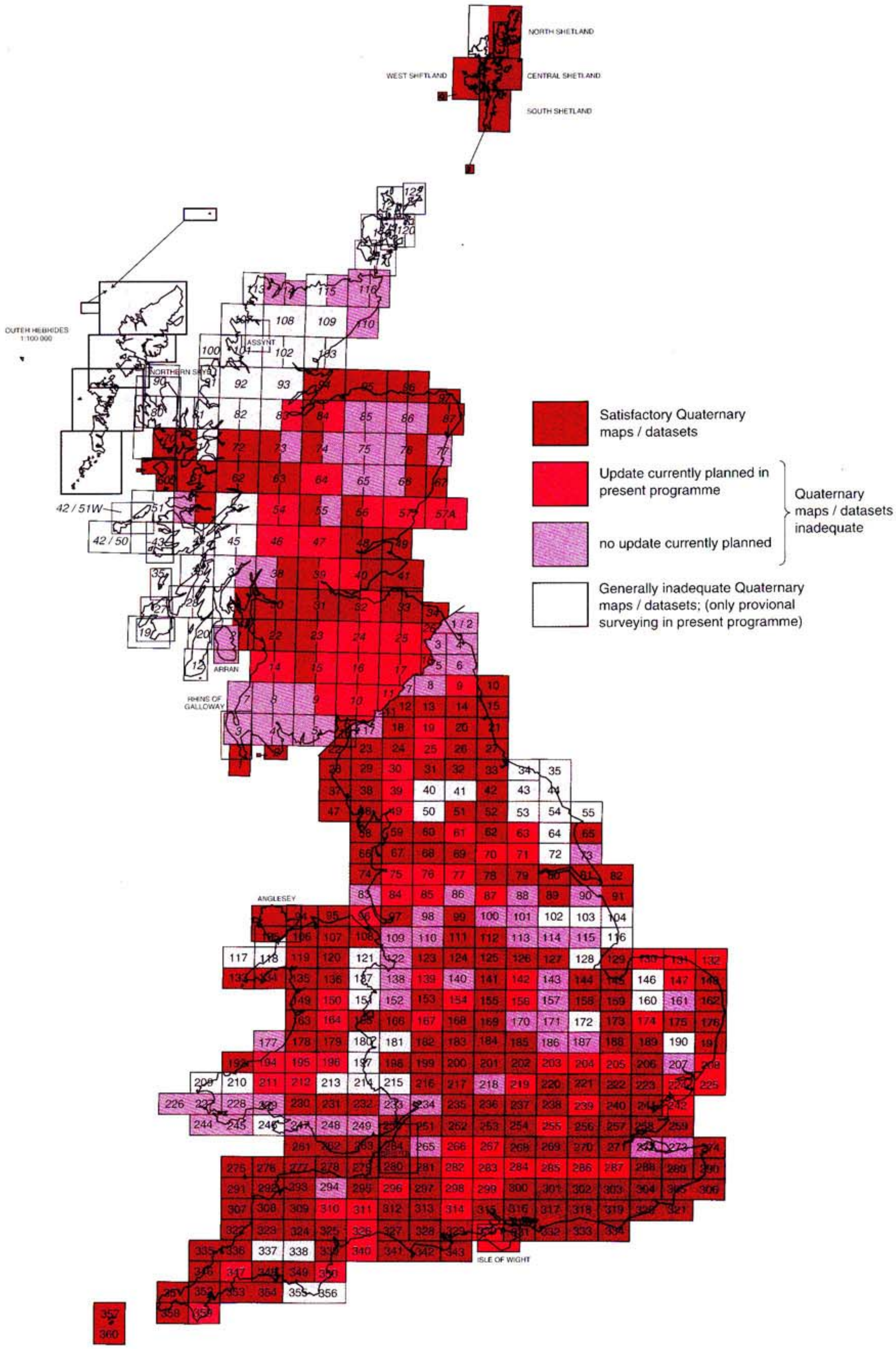

Figure 4 Status of BGS Quaternary mapping at end 1997 (from Foster *et al*., 1999)

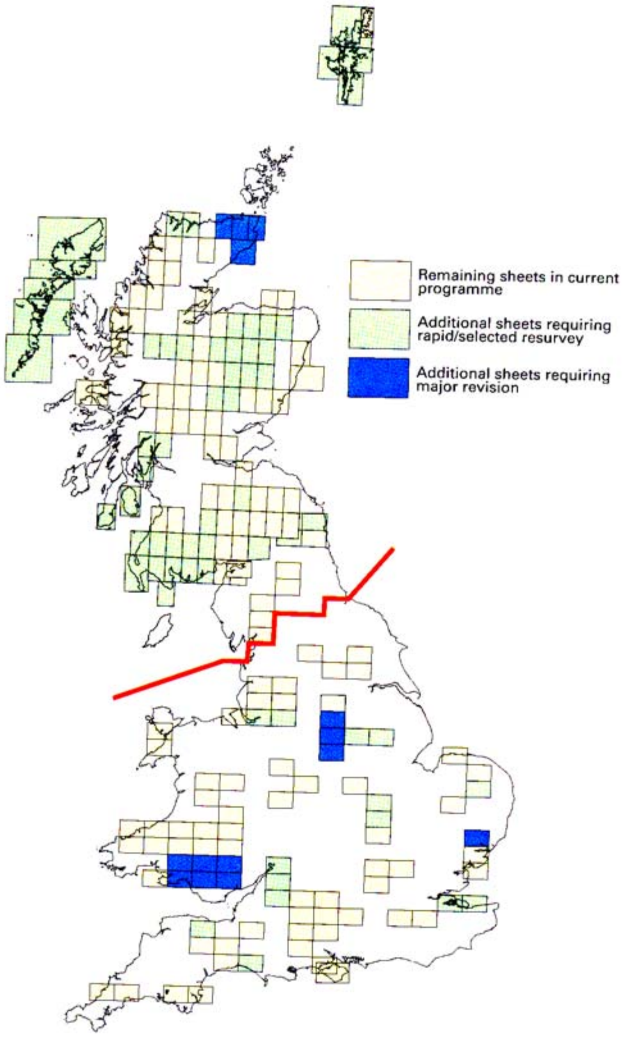

Figure 5 Results of sheet-by-sheet re-evaluation with reference to recently defined user needs and national strategic requirements (from Walton and Lee, 2001)

2.4 DIGITAL MAPS

The **DiGMapGB** (Digital Geological Map of Great Britain) project started in 1998 and the first edition of the 1:50 000 scale dataset was released in November 2001 as *DiGMapGB-50 Version 1*. Each available geological map in Scotland is now obtainable as a digital file of polygon data. These digital maps or tiles are prepared with the geological data arranged in up to four separate geological themes: *solid* (or bedrock geology), *drift deposits* (or superficial geology), *mass movement* deposits (such as landslips), and *artificial* ground (such as man made ground), in so far as this information is available. The data are routinely released in ArcView®, MapInfo® and Geographics® formats, and other formats may be available on request. It is planned to upgrade DiGMapGB-50 Version 1 during 2002 and 2003, but customers holding a current licence will be entitled to these upgrades, once available. Three-dimensional aspects of geology will be held in the Digital Geoscience Spatial Modelling (DGSM) programme, which is currently being developed.

A two-part label, called a 'Lex-Rock' seed, such as 'ALV-SSCL', identifies every polygon on each theme. The first part is the Lex code is an abbreviation of the name of the unit as defined in the BGS Stratigraphic Lexicon (eg. alluvium). For the drift theme this is usually the morpho-lithogenetic unit unless the deposit has been identified lithostatigraphically. The second part is the rock code, which is an abbreviation of the lithology as defined in the BGS database or dictionary (describe SSCL as an example). The lithology represented by this coding is usually the single predominant lithology present, or the two or three main lithologies (eg sand, silt, clay). Other minor or trace lithologies may also be present.

Each tile is typically based on the latest 1: 50 000 or 1:63 360 (one inch to one mile) scale drift geological map that is available with only minor revision. In areas for which there are no suitable geological maps published, the best available old linework has been fitted to the modern topographical base (Figure 6). Many of the tiles in DiGMapGB-50 Version 1 have misfits with their neighbours. Some of these misfits are cartographic errors that have arisen due to the varying techniques used in the compilation of the original published maps. These will be rectified in Version 2. Other misfits, commonly occurring between maps of different ages, will be considered by geologists and re-fitted, where practicable. This refitting will not be possible with older maps and such misfits will not be resolved until those maps are resurveyed (Figure 7).

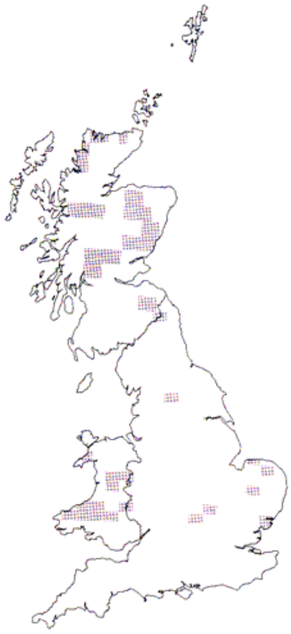

Figure 6 Areas where current geological maps are unsatisfactory for input into DiGMap (from Walton and Lee, 2001)

As with all geological maps, the digital tiles data are interpretations of the geology, invariably based on limited information. DiGMapGB data are available at 1: 625 000, 1: 250 000, 1: 50 000 and 1: 10 000 scales. Whilst the published BGS maps form the basis for the digital geological tiles, DiGMapGB data are not identical to the original paper maps. Where necessary, the nomenclature has been revised to that current at the time of digital compilation. For information on licensing please contact the DiGMapGB co-ordinator (in Edinburgh) for Scotland and Northern England. Conditions for supply of digital data are given in Annex 1.

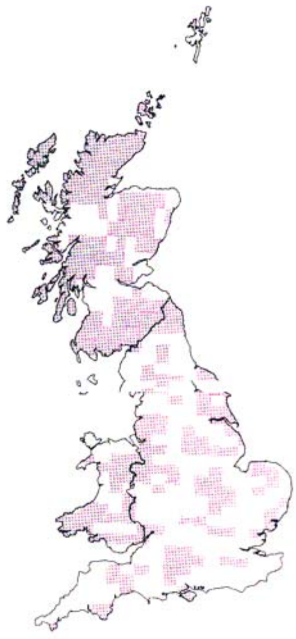

Figure 7 Areas where Quaternary information is unsatisfactory (from Walton and Lee, 2001)

2.5 BGS BOREHOLE AND SITE INVESTIGATION RECORD COLLECTION

BGS holds collections of borehole and site investigation records for Scotland at the Edinburgh office. The collections currently include the records of some 211 500 sites, but they are concentrated around the urban areas on along major roads (Figure 8). There is a digital index of site investigation records for Scotland, and the reports themselves are held on microfiche.

Searches of indexes to many collections relevant to the Quaternary of Scotland can be made on the **Geoscience Data Index** system in the BGS library. This is a developing computer-based system that carries out searches of indexes to digital and non-digital databases for specified geographical areas. It is based on a geographic information system (GIS) linked to a relational database management system. Results of the searches are displayed on maps on the screen. At the present time the databases are limited and are not all complete.

Index information for boreholes has been digitised and incorporated within the Single Onshore Borehole Index **(SOBI)** database. The main functions of SOBI are to provide an up-to-date digital *index* to the detailed records of all onshore (or near shore) boreholes, trial pits, shafts and wells held in the BGS archives in either paper, microfilm or digital format. It allows rapid retrieval of information for use in answering enquiries about the availability of data by both BGS staff and external enquirers. As the database originated from a number of existing tables and from data input from a variety of coding forms, not all fields in the database are populated presently and data that should be in some fields may currently form part of the entries in another. There is a continuous programme of improvement and updating.

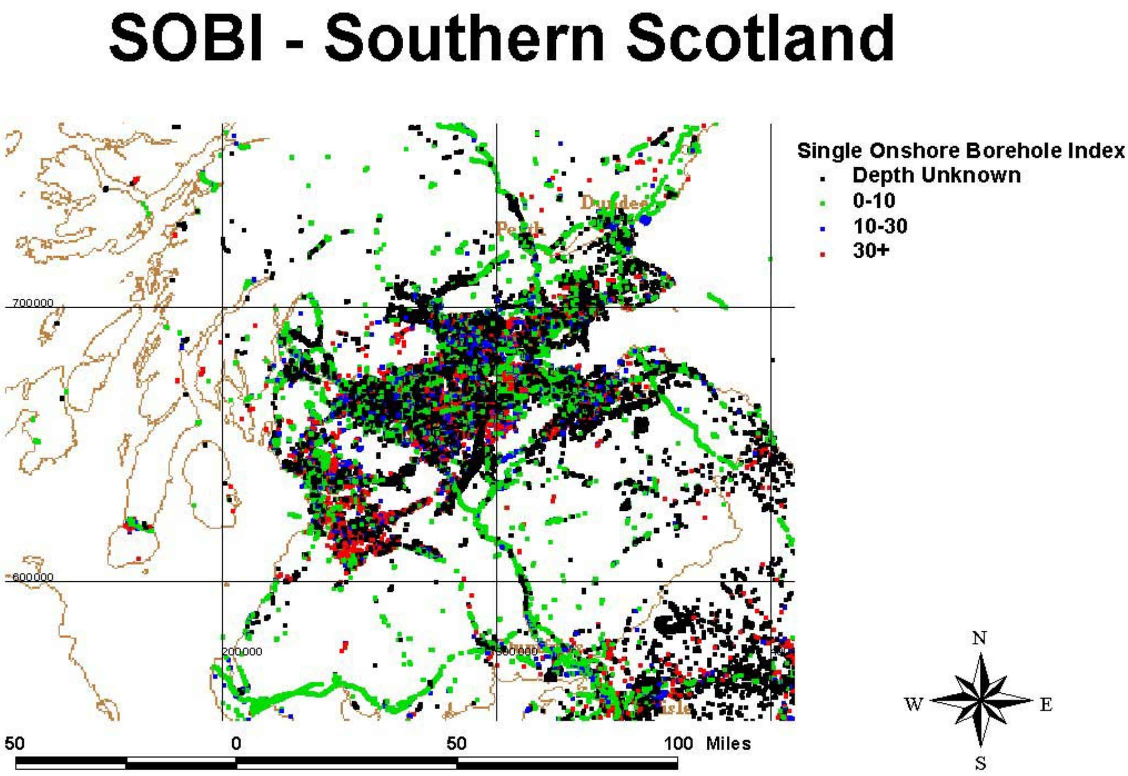

Figure 8 Plot of borehole information from SOBI for the Central Valley of Scotland

The SOBI database presently provides information on the location and surface levels of boreholes, and depths to base. Other information, including depths to rockhead, lithologies, hydrogeology and geological classifications are generally only provided in response to formal enquiries for which standard charges apply.

2.6 DOMAINS AND PROFILE MAPS

Most published drift maps only show deposits cropping out between 1 and 2 m of the surface and no attempt has been made to identify where thick sequences of sediment are likely to occur, especially where they are capped by till. To improve presentation of 3-D subsurface information on the nature and distribution of Quaternary deposits, two types of map have been developed. Where adequate subsurface data exist, lithological *profile maps* have been produced to summarise the lithological succession of sediments and to show the areal extent of families of deposits that have similar vertical profiles. Each profile is defined by the alternation of fine-grained (clay and silt) and coarse-grained sediment (sand, gravel and boulders). Maps of this kind have been produced for Glasgow (Browne and McMillan, 1989,1991).

The Quaternary *domain map* is a form of profile map that aims to show distinct packages of sediment, providing a 2-D model representing 3-D geology. The map is designed to highlight key characteristics of the drift deposits in an attempt to assist a better understanding of their origin, lithology and sequence. The domains can be distinguished on the basis of a number of recognisable field criteria and remotely sensed characteristics in addition to borehole and site investigation information.

The main advantage of the domains approach is that it can be applied in areas where there is little subsurface data, using relatively cost-effective ‘rapid mapping’ techniques. However, it relies heavily on assumptions linking diagnostic landforms to sediments and styles of deformation. It does not easily recognise deposits antedating the last glaciation that no longer have any surface expression and it is unlikely to identify the unexpected. Profile maps are more accurate, but they are based mainly on third-party logs of boreholes from which only disturbed samples were taken. Boreholes often prove ‘the unexpected’ because of the lateral inhomogeneity of the strata.

Quaternary domains maps have been used successfully as a basis for determining hydrogeological domains at Sellafield, in Cumbria (McMillan et al., 2000) (Figures 9 and 10). The method allows a qualitative interpretation of the probable groundwater flow pattern as determined by the lithology, structure and lithological variation of each domain. The influence of intercalated sediments on flow direction can be assessed, as can the influence of patterns of juxtaposed sediments on the overall flow regime. Determination of flow patterns can be quantified subsequently through the measurement of hydrogeological properties of the domain lithologies.

Domains mapping is presently being undertaken at Dounreay, but there are presently no plans for BGS to undertake such work systematically across the country as part of strategic surveying. However, work of this type would be undertaken on commission or possibly through a co-funded, collaborative arrangement. Should systematic domains mapping be required, the first stage would be to decide which of the domains set up at Sellafield and Dounreay are appropriate for a national survey and what other categories might be added.

The degree of certainty using the domains technique may be poor. Nevertheless, domains mapping remains a useful tool which could be deployed in areas of Scotland such as the Midland Valley where many drift deposits are likely to be categorised as being at risk from surface pressures such as industry.

2.7 MAPPING METHODOLOGIES AND REMOTE SENSING

A review of BGS onshore Quaternary products, survey levels and survey techniques was published in 1999, *Quaternary Geology: Towards meeting user requirements* (Foster, Morigi and Browne, 1999). This report assessed the current status of products, the evolving needs of the user community for Quaternary data and the contribution of BGS to national and international Quaternary research objectives. It introduces Quaternary provinces within Britain (Figure 1) for which particular levels and types of survey are applicable and justifiable. It also reviews various ancillary survey techniques that are employed to improve the precision, resolution and detail of Quaternary surveying, for example, drilling and sampling techniques and surface geophysical surveys.

The satellite imagery can be used most satisfactorily to identify former directions and intensities of ice flow and certain Quaternary domains (e.g. drumlin fields). After acquiring the raw digital data from NASA, those bands of visible light and infrared radiation that produce a false-colour image that is most useful for geomorphological and Quaternary geological interpretation are combined. Staff in the Remote Sensing group at BGS recommend that other combinations of bands and thermal wavelengths be investigated to assess the utility of satellite imagery for hydrogeological purposes.

BGS recognises the importance of high-resolution airborne geophysical and radiometric data (HiRES) as key inputs to its multi-disciplinary programme and supports efforts to achieve national coverage. BGS has a well established geochemical survey programme (G-Base) with funding to cover the entire UK by 2012, but the HiRES only commenced in 1998 and has been limited to two surveys. The first of these was a magnetic/radiometric survey over the English Midlands and the second was a trial survey in collaboration the Geological Survey of Finland to test their electro-magnetic system for environmental applications (in 1999).

Both of these airborne surveys were extremely successful in demonstrating the utility of high-resolution magnetic, radiometric and EM data for both mapping and environmental applications, particularly for identifying contaminated groundwater plumes emanating from 'brown-earth' sites and mines. There is a compelling case for completing airborne coverage of at least the Central Valley of Scotland, but the HiRES-1 survey of the English Midlands cost £250,000 for an area of 200x70 km. National coverage cannot be achieved within current BGS Science Budget allocations and some form of co-funding consortium would need to be established to undertake the work.

2.8 CURRENT AND FUTURE PROGRAMME OF STRATEGIC SURVEYING

The current programme of work for onshore geological surveys within the BGS Lands and Resources Directorate over the next ten years is fully explained in 'Geology for our diverse economy' (Walton and Lee, 2001). This report is based on a review of user needs and national strategic requirements for onshore geological information in Britain. The review particularly highlighted the need for more detailed information on the thickness and character of Quaternary deposits. The provision of three-dimensional geological information is seen as being increasingly necessary to address complex environmental and resource-related issues.

The re-prioritised multi-disciplinary onshore geological survey programme (Integrated Geoscience Surveys) will see an accelerated transition from systematic geological mapping to responsive revision of strategically-important information. The programme is delivered via a series of projects, each addressing a geologically-coherent area or survey topic. The revised programme includes completion of basic-level mapping at 1:50k for incorporation into the Digital Geological Map of Great Britain (DigMapGB). The programme is underpinned by a new Quaternary Methodologies and Training Programme (to develop more effective mapping and interpretation of complex Quaternary sequences), by a revised StratBase Project (to populate and maintain a formal stratigraphical database for use throughout BGS) and by a Superficial Deposits Advisory Group (to promote standards of mapping and recording of superficial deposits across all BGS programmes).

A major change in survey methodology is being introduced, based on the digital capture of information and the preparation of geological maps and models in a GIS environment. This will underpin a radical new approach to the delivery of information based on the use of GIS and text databases, supplemented by print-on-demand maps and high-quality printed regional reference works.

These techniques are likely to be of value in data scarce areas where little if any useful drift mapping has been undertaken. However, they are unlikely to add to the characterisation process if reliable mapping data already exist.

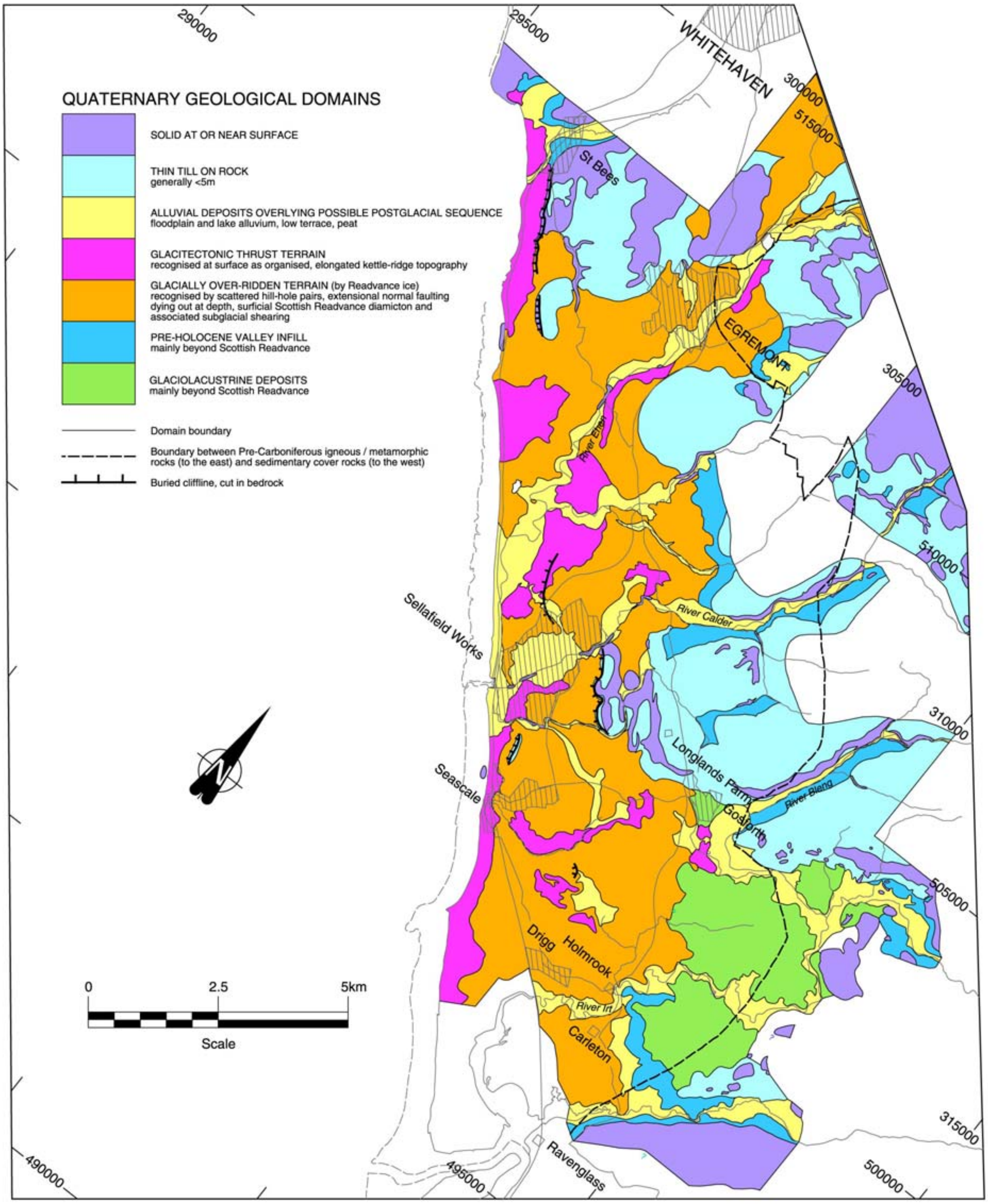

Figure 9 Quaternary geological domains of the Sellafield area (from McMillan *et al*., 2000)

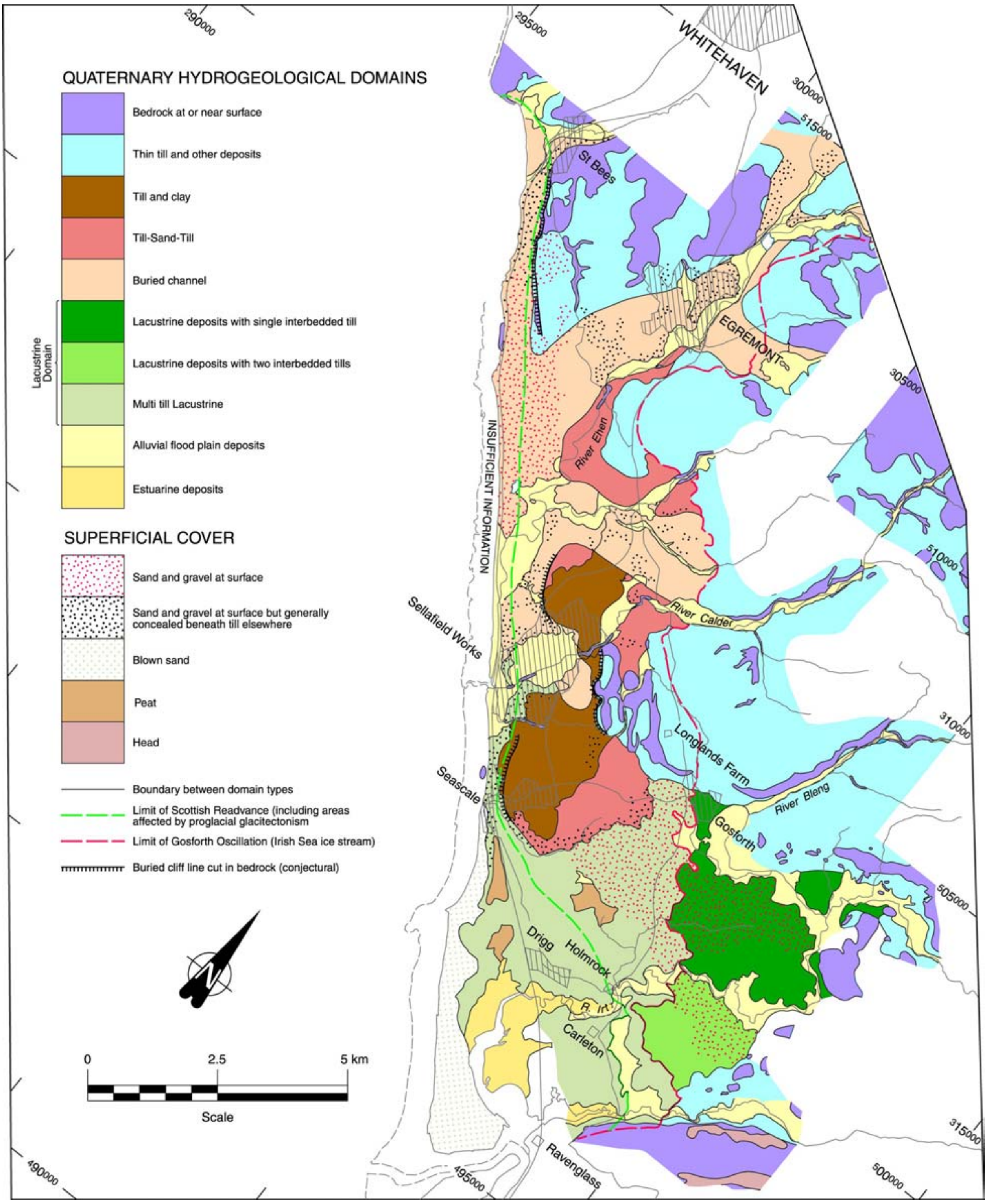

Figure 10 Quaternary hydrogeological domains of the Sellafield area (from McMillan *et al*., 2000)

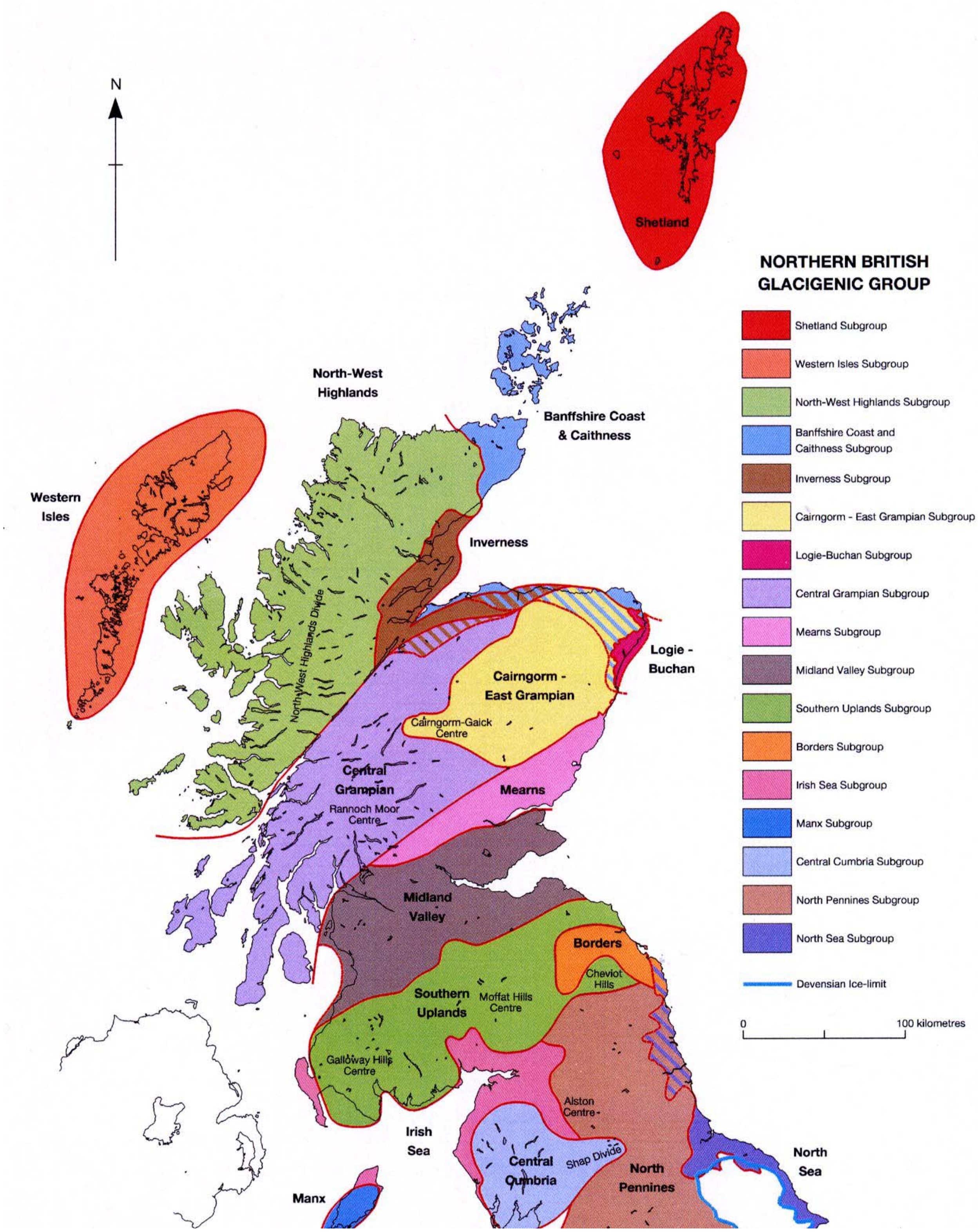

Figure 11 Proposed glacigenic groups covering northern Britain

3 The WFD and superficial cover

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

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

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

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

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

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

Characterisation of bedrock groundwater bodies (a distinct volume of groundwater within an aquifer or aquifers) depends not only on bedrock conditions but also on the superficial cover. A single aquifer unit such as the Permo-Triassic sandstone basin at Dumfries, for example, may be confined by clayey till in one area, covered by permeable gravel elsewhere to form a major area of recharge, covered by marine clay to inhibit sea water intrusion at its lower end and exposed at surface with no superficial cover (Gaus and Ó Dochartaigh, 2000). Each area has its own properties with regard to resource potential, hydraulic interaction with surface waters, vulnerability to pollution, and inherent chemical properties. The superficial material, however, is a controlling factor in the quality and quantity of groundwater within the sandstone aquifer at any given place. From a management point of view the sandstone basin is an obvious candidate to be designated a single groundwater body. From a hydrogeological processes point of view and from the stance of understanding the catchment hydraulics and processes required by the WFD, it is a complex of sub units each with its own discrete hydraulic properties.

3.1 DRIFT HYDROGEOLOGY AND RECHARGE PROCESSES

Whilst more permeable deposits have been studied generally with respect to their potential for resource exploitation, much less work has been carried out regarding less permeable drift deposits. Generic investigation of weakly permeable drift characteristics has largely been undertaken in North America. All work points towards the fact that recharge through drift occurs (van der Kamp, 2001), for example at velocities of greater than 1 m a^{-1} in heterogeneous sandy silty till of hydraulic permeability only 10^{-9} m s^{-1} (Gerber et al, 2001).

The first systematic review of drift hydrogeology in Scotland (Robins and Ball, 1987; 1991) was the result of several years of piecemeal investigation into the resource potential of drift deposits (Table 2). This work did not consider the less permeable drift or its role in the recharge process to deeper bedrock aquifers. It did, however, recognise that variations in lithology occur in the drift over short vertical and horizontal distances, a complexity which may be exacerbated by the presence of buried channels and other sharp features, so that interpolation between boreholes may be difficult and sometimes misleading.

Table 2 Hydraulic properties of Quaternary deposits in Scotland (after Robins and Ball, 1991)

Deposit	Location	Saturated thickness (m)	Hydraulic conductivity (m s^{-1})
Till	Widespread	<30	$<10^{-6}$
Granular glacial and fluvio-glacial	Stewartry District	1-8	8x10-4 to 5x10-3
	Lower Spey	6-15	5x10-5 to 3x10-4
	Kilmichael [NR 861936]	19	1x10-3
	Tomatin [NH 803273]	19	5x10-5
	Kenmore [NN 773455	16	1x10-3
	Loudon Hill [NS 598374]	32	1x10-5
	West Linton [NT 168494	6	1x10-4
	Heriot [NT 402544]	6	2x10-5
Raised beach/blown sand	Tiree [NL 953411]	>5	$2x10^{-4}$
	St Fergus [NK 107509]	<16	10^{-5} to 10^{-3}
	Black Isle	8	$8x10^{-5}$
	Forfar [NO 483514]	<16	$8x10^{-5}$

Resource potential studies in valley alluvium have shown the diverse nature of this material. Jones and Singleton (2000) reported work carried out in the Spey and Fort William water supply schemes and note that borehole yields from these deposits have a fourfold variation in test discharge within each of these controlled and limited project areas. Work carried out by Soulsby et al (2000) demonstrated the important role that alluvial deposits have in regulating discharge to streams as baseflow in both upland and lowland catchments in which storage and transport in the bedrock may otherwise be limited.

Permeable glacial deposits have long been exploited for their supply potential. Again yields are highly variable depending on saturated thickness, connectivity with surface waters, and relative elevation to the regional water table Robins (1990). In terms of the WFD, both drift aquifers and underlying bedrock aquifers need to be characterised.on a consistent basis.

Systematic study of hydraulic properties and groundwater transport processes in weakly permeable drift deposits in Scotland are few. Occasional observations have been reported, including:

- the occurrence of dilated fractures in a thick freshly cut section of clay till near Grangemouth,
- the predominance of permeable sandy clay in areas north of the Highland Boundary Fault,
- and increased runoff in areas of clay till.

The work by Hossain and McKinlay (1991) and Hossain (1992) is, however, particularly pertinent. They compared modelled flow rates and observed flow rates through fractured lodgement tills at three sites in west central Scotland, and were able to identify the contribution of modelled fissures to the overall hydraulic conductivity of the respective tills, thereby demonstrating the significance of fissure flow in tills.

Generic studies of the hydraulic behaviour of till include the review by Foster (1998), and the debate over how drift affects groundwater vulnerability (Palmer et al., 1995). Authors are consistent in reporting that recharge to bedrock aquifers does occur through till, e.g. Soley and Heathcote (1998) reported 36 mm a^{-1} through boulder clay covered interfluves in East Anglia, decreasing to 10 mm a^{-1} in areas of thicker cover where the bedrock aquifer was locally confined. Identifying the processes by which transport takes place is not easy, but is essential to determining the recharge component of the water balance for a given catchment. The recharge project shortly to be let by SNIFFER may provide some steer. However, extrapolation of data may not be feasible as recharge processes and recharge quantities are likely to be more site specific than generic. The ameliorating potential of thick till to pollutants such as nitrate and some pesticides passing through the strata has been described by Rodvang and Simpkins (2001).

The complexity of drift cover in Scotland coupled with a wide variety of depositional environments means that a large number of recharge scenarios are possible. These need to be identified from the outset and their influence on recharge assessed. Where drift deposits overly aquifers they can have a significant influence on the recharge to the aquifer particularly where they are dominated by low permeability lithologies, such as clays, Table 3. The thickness of the deposit is also critical; as a tried and tested 'rule of thumb', where there is less than 3 m of till it is likely to be sufficiently weathered as to be permeable. Between 3 and 8 m of till may allow by-pass flow mechanisms to dominate vertical flow paths, whereas greater than 8 m of till may form an effective cover material depending on the sand content. Where Drift deposits are of limited lateral extent their influence may be of less significance. The till cover of Scotland is extensive, characterised by deposits with a high proportion of clay and overlies important aquifers such as the Devonian and Permo-Triassic of the Midland Valley and south-west Scotland. Bedrock recharge is significantly affected by the overlying till. One important and as yet unresolved issue is the degree of importance of fissure-related by-pass flow, but comparison of drift maps and soil maps will at least reveal where tills are self-draining and where they are not (see below).

Table 3 Generic features common to drift

Feature	Consequence
<3 m clayey till	Likely to be weathered such that it becomes permeable
3 – 8 m clayey till	Fracture paths through the till may allow by-pass flow to predominate over intergranular percolation
>8 m clayey till	Effective cover to deeper aquifers
>10 m of clayey till	Rainfall recharge is reduced to 30% of total
Clayey till on interfluves	Till under tension and may split to create vertical fractures
Clayey till in valleys	Till likely to be compacted and weakly permeable
Free draining soils over clayey till	Indicate vertical transfer of water through till likely
Surface ponding in depressions over till	Will promote recharge locally

The predominant route taken by recharge in drift-covered areas could be more or less direct (Scenarios 1 & 2, Figures 12a and b), via intergranular movement or fracture flow (Klinck et al 1993). It could be via permeable lenses (Scenario 3, Figure 12c) or via past or present topographic features such as valleys (Scenario 4, Figure 12d). There is also the possibility of no significant recharge at all (Scenario 5).

One way of differentiating between the scenarios is to determine the age of water in the various units involved, using isotopes or other environmental tracers as appropriate[1]. Table 4 shows the likely ages. Modern water in both environments in scenario one demonstrates relatively rapid recharge through the till matrix. Scenario 2 with old till pore water implies fissure flow is an important recharge route. Scenarios 3 & 4 relate to high permeability routes for recharge within the till, but are difficult to resolve from each other, though geological or geophysical evidence may enable a distinction to be made. If the water is old in both environments then little if any recharge is likely.

[1] CFC species and SF_6 are valuable modern tracers; analytical costs are typically about £50 per sample for each tracer.

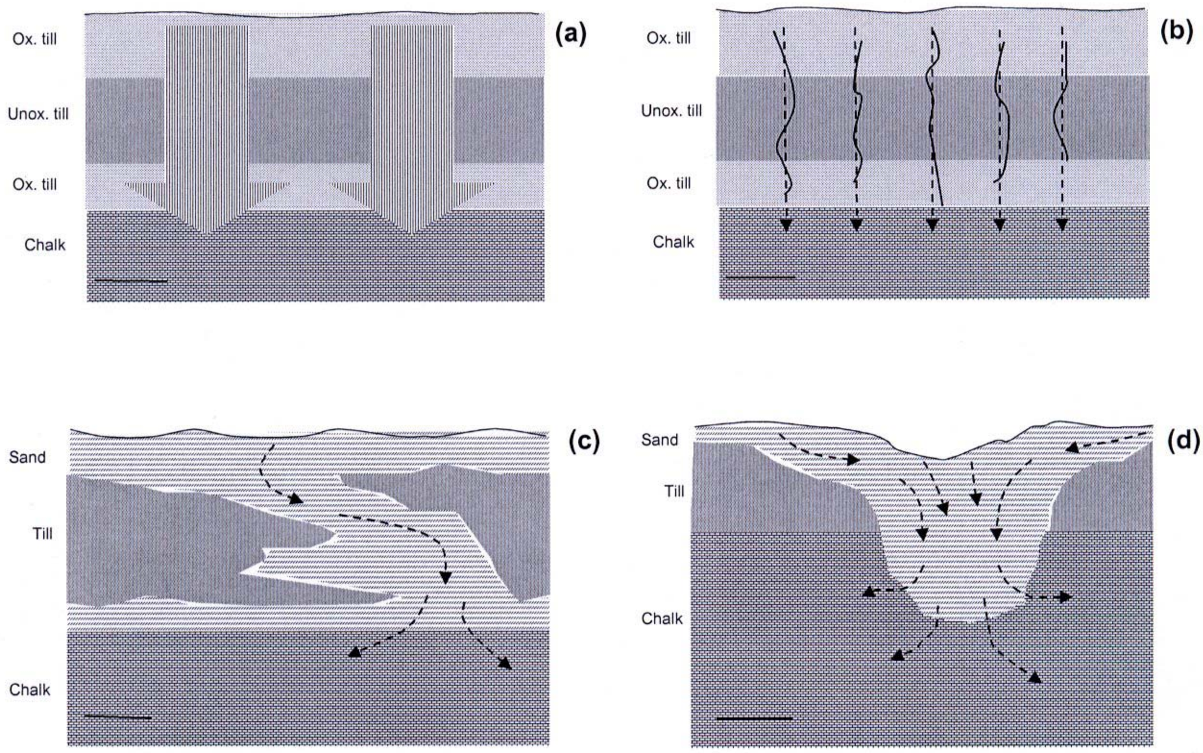

Figure 12 Drift recharge scenarios

(a) Scenario 1: dispersed recharge occurs through till pores, (b) Scenario 2: recharge occurs via till fractures, (c) Scenario 3: recharge occurs through permeable lenses in drift, (d) Scenario 4: recharge occurs via existing or buried valleys. Scenario 5 (impermeable till, no recharge) is not depicted.

3.2 RELIABILITY OF THE DATA

BGS is increasingly moving towards providing maps and interpretive data in digital form. Most 1:50 000 drift geological maps in Scotland are now obtainable as digital files of polygon data under licence (DiGMapGB-50 Version1), however, there are some gaps in the coverage and there are many mismatches between sheets and problems of classification to be resolved. Errors in interpretation and attribution will be attended to rapidly, but some major mismatches and absences of data will take many years to resolve. BGS has developed a programme of strategic mapping to address many of these problems (Walton and Lee, 2001), but welcomes the opportunity of co-funding arrangements with partners both to target, and to bring forward work in areas in which there is a mutual interest (see 'future programme' below).

A re-evaluation of each 1:50 000 geological sheet has been carried out in terms which included the quality of Quaternary information (Walton and Lee, 2001). The assessment took into account the following; economic and environmental considerations (e.g. water supply, sustainable resources, development planning, transport corridors and linear routes); national strategic ground-related issues (flooding, ground instability, mineral resources); the need to complete basic 1:50 000 map coverage.

Table 4 Likely water residence time ('age') and recharge through a till cover (after Klinck et al, 1996)

	Scenario 1 permeable till	Scenario 2 fissured till	Scenario 3 sand lenses	Scenario 4 buried valley	Scenario 5 impermeable till
Till porewater	Modern	Old	Old	Old	Old
Bedrock porewater	Modern	Modern	Modern to old	Modern to old	Old

Taking these factors into consideration, the staff effort required on each sheet to meet the newly-defined user requirements and national strategic needs was then estimated. In the case of Scotland, where Quaternary information is absent in many areas, estimates were given for two levels of revision. These were respectively: (i) absolute minimal coverage based mainly on aerial photographs and remotely-sensed imagery; and (ii) the effort required to provide basic information to meet currently-identified needs, based on rapid revision using a combination of remote sensing and targeted re-survey (but still well below traditional full 1:10 000 walk-over survey). The results of the re-evaluation are summarised graphically in Figures 6-8.

It should be born in mind that the assessment made above was based on a rapid inspection of published maps 1:50 000 or One Inch maps. Detailed maps were not consulted and no ground truthing undertaken. There was also some pressure not to identify too many maps for revision, especially many of the sheets covering remote ground in the western Highlands and Islands. For the purposes of the WFD a rigorous sheet by sheet assessment needs to be undertaken, but it can be assumed that the standard of drift mapping on most sheets could be improved significantly following a targeted resurvey.

Some of the problems with the level of detail shown on the drift maps in general, and, therefore, also with DiGMap output, are listed below. Not all of these relate directly to the WFD. The aim is to achieve a reasonable understanding rather than a well modelled catchment.

- Bedrock ‘at or near surface’ is generally under-represented on maps. This problem is inherent in mapping because if rock does not actually crop out, the geologist cannot be confident about what it is and hence maps drift, usually till, except where augering methods have been used. Conservative estimates of recharge are likely if an over-estimate of till coverage is made. The vulnerability classification of the drift cover in such areas will also be affected and could be mis-represented by a lower categorisation for permeability than is correct.

- Till is generally over-represented as a result of the above. Till is often mapped by default and there are large areas mapped as till where bedrock is within 1 to 1.5m of the surface. For example, till is often mapped high up on the shoulders of mountains in the Highlands. Much of Buchan is covered by less than 1m of till, also parts of Strathmore, where very extensive sheets of till have been mapped. Therefore, the role played by tills in groundwater processes may be overestimated in many areas of Scotland.

- Most published drift maps only show deposits cropping out at the surface and no attempt has been made to identify where thick sequences of sediment are likely to occur, especially where they are capped by till. Exceptions to this are the urban environmental geology maps of, for example, the Glasgow area. Thick drift is a problem in other parts of the lower Clyde valley, around Carlisle and in eastern Aberdeenshire north of Aberdeen.

- Large areas of the western Highlands have been mapped as morainic drift (pale green) on older maps. Parts of these spreads may be better described as till, and they commonly include mounds and ridges of glaciofluvial sand and gravel. However, most glacial, glaciofluvial and morainic deposits are bouldery in these parts, are not assessed in detail and the shortcomings may not be critical from a hydrogeological point of view.
- Glaciofluvial deposits tend to be over-represented on older drift maps. Commonly a boundary is drawn around a collection of mounds giving the impression that the deposits are more extensive than they are. The deposits have been mapped to a greater resolution on most modern maps. Many mounds of weathered bedrock have been mapped as sand and gravel in north-east Scotland and the Borders.
- A mantle of deeply weathered and commonly thoroughly decomposed bedrock that formed during the Tertiary has survived glacial erosion in several parts of Scotland, particularly in central Buchan and beneath the Gaick Plateau in the central Highlands (Figure 1). Bedrock has decomposed to silty sand to depths of 20 m and more, but is not shown as such on any maps.
- Areas mapped as 'alluvium' are commonly underlain by a variety of deposits, including sand, gravel, boulders, loam and peat. Floodplain alluvium (commonly loam on gravel) is generally not distinguished from alluvium occupying enclosed hollows (generally fine grained and peaty). Low-lying alluvial terraces (often built on and unlikely to flood) are commonly not distinguished from floodplain alluvium. Not all areas mapped as floodplain alluvium are now prone to flooding.
- Many areas mapped as peat have since been dug to within 0.5 m or so of the underlying ground, if not cleared away altogether. Many pockets of peat have not been mapped.
- It should not be assumed that all deposits identified as 'raised beaches' on older maps are formed of sand and shingle; many are underlain by silt and clay (former intertidal mud flats or estuarine deposits). Some late-glacial raised beaches are underlain by fine-grained glaciomarine deposits (e.g. east of Inverness).
- Glaciolacustrine silts and clays are commonly under-represented on drift maps of all vintages. Unless these deposits are augered or identified from site investigation records, they cannot easily be distinguished from till; both deposits give rise to clayey, poorly-drained soils, but glaciolacustrine deposits are more prone to landslipping as they are generally thinly laminated.
- 'Head' deposits are generally under-represented on drift maps, though not as much as in southern Britain. These deposits result from the downslope periglacial solifluction and churning of other drift deposits and weathered rocks. They tend to be clayey and locally thicken to several metres on lower hillslopes.
- Glacial meltwater channels are vastly under-represented on most older drift maps. These features are either 'dry' or contain 'misfit' streams, but can concentrate run-off during freak storms. They are commonly partially filled with gravel capped by clayey head deposits and till.
- There are undoubtedly numerous concealed channels, valleys and gorges that are partially filled with gravel and capped by till, but not shown on any maps. They are often impossible to identify until found during detailed site investigations.

Many of the present misfits on DiGMap result from uncertainties in coding up the lithologies of deposits based on limited information, bearing in mind the problems listed above.

3.3 THE PRESSURES AND THREATS TO GROUNDWATER

The principal threats to groundwater are pollution and over abstraction. In Article 2 (33) of the WFD "pollution" is defined as:

The direct or indirect introduction, as a result of human activity, of substances or heat into the air, water or land which may be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems, which result in damage to material property, or which impair or interfere with amenities and other legitimate uses of the environment.

The WFD does not directly define what is meant by the term "pollution pressure" for groundwater. However in Annex II Section 1.4 - Identification of Pressures - the following statement is made with respect to surface waters:

Member States shall collect and maintain information on the type and magnitude of the significant anthropogenic pressures to which the surface water bodies in each River Basin District are liable to be subject.

Once the likely sources of the primary pollutants have been identified the problem remains of translating this information into a measure of "pressure", and judging whether the pollution pressure is enough to place the groundwater body at risk of failing to achieve the Article 4 objectives. (Note CIS group are looking at pressures and impacts and this will inform.)

The pressures on a groundwater body may have an impact, or measurable effect upon it, the nature of which will depend on factors such as the type and severity of the pressure and the degree to which the groundwater body is susceptible to the pressure. The result of a pressure (such as pesticide application to the surface of an aquifer) causing an impact (raised concentrations of the pesticide in groundwater) may often be manifested in monitoring data. Thus, monitoring information can be used to validate predictions of impact obtained from pressure.

The Scottish context with regard to pressures is not significantly different from that in other Member States. However, there are a number of features that are peculiarly pertinent to Scotland which need special mention (Table 5 and Figure 14). These include:

- Disposal of pesticides such as spent sheep dip,
- Deep cultivation for forestry, subsequent felling, etc.,
- Pasture cultivation and dairy farming,
- Industrial activity and waste disposal,
- Mine waters and mine discharges
- Acid rain.

These pressures may be exacerbated by inherent features such as:

- Orographic rainfall, snow melt,
- Steep topographic slopes,
- Upland soils and peat,
- Acid upland catchments,
- Moderate permeability fractured bedrock aquifers,
- Saline intrusion,
- Widespread, partly weakly permeable drift cover.

The role of Drift deposits in influencing these pressures is complex due to the diverse nature and distribution of the drift deposits in Scotland. For example, the disposal of spent pesticide or zealous use of pesticide and nitrogen fertiliser in an upland, sloping, clayey till covered catchment places adjacent surface waters at risk of pollution. Conversely, clay till may protect groundwater from contamination by agricultural activities in some lowland areas, although in so doing the till will reduce the recharge potential to the underlying aquifer. However, in all cases where drift deposits occur within a catchment, they will influence the hydraulic nature of that catchment to an extent that their role in controlling risk to both quantity and sustainability and water quality must be evaluated. Table 5 lists the main threats to groundwater quality in Scotland and the types of drift aquifer potentially affected.

3.3.1 Saline intrusion

Table 6 is a summary of where drift plays a role in either providing a pathway for saline intrusion or where it acts as a barrier. In other parts of coastal Scotland not included in the Table, drift deposits are largely absent and are replaced by exposures of bedrock. In the latter areas, therefore, drift is not considered to be a significant factor in groundwater movement. It can be seen from the Table that, with the exception of the Tweed catchment, all the major rivers in Scotland have a significant thickness of drift deposits at their mouths.

3.3.2 Landfill and industrial areas

Leachate from waste disposal sites may enter the groundwater system via drift deposits. Amongst older sites in Scotland, which do not have engineered containment, many are in old sand and gravel pits within complex glaciofluvial deposits or are where waste has been disposed of directly on to peat moss. Table 7 lists some of the areas where gravelly drift acts as a pathway to leachate and where there may be barriers present. The list is not exhaustive, but indicates that there are many areas in Scotland where waste disposal has the potential to cause contamination of local groundwater systems depending on the nature of the drift. In very general terms, superficial deposits will be important where waste disposal sites are located in lowland parts of the country, with those in upland areas tending to be within hard rock quarries or on peat.

Table 8 is a general summary of the nature of the drift in Scotland’s main industrial areas. River alluvial deposits form the main pathways for industrial pollution reaching the water table. Across much of the Central Belt, however, till cover is widespread. This till is relatively impermeable, as it has been largely derived from Carboniferous strata that contain a high proportion of mudstone. In other parts of Central Scotland, marine, or carse, clays play an important role in protecting deeper aquifers. A good example of this is at Grangemouth where clays over 30 m in thickness overlie the permeable Passage Formation sandstone aquifer.

It will be possible to identify from borehole records, with reasonable accuracy, the extent and thickness of the main clayey deposits, such as in the Forth and Tay catchments. Problems lie with delineating smaller, isolated clay areas where borehole data are sporadic.

Table 5 The threats to groundwater in Scotland

Threat	Area	Monitoring status	Drift units potentially affected	Examples
Saline intrusion	Coastal	Poor	Raised beaches, coastal glaciofluvial deposits	See Table 6 and Figure 14
Pesticides	Arable land	Variable	Shallow tills, glacial sand + gravel	Perthshire
Forestry	Mainly upland	Very little	Tills, Head	None
Industrial activity, waste disposal	Lowlands	Variable	Mainly glaciofluvial sand and gravel	See Tables 7 and 8, plus Figure 14
Over-abstraction	Lowlands, alluvial plains	Variable	Most granular drift	None, but see Table 9
Nitrate	Farmland	SEPA network	All types	See Section 3.3.3
Mine waters	Central belt	Poor	Mainly tills	None See Figure 14
Extraction of aggregates	National	Poor	Glaciofluvial sand and gravel, plus river gravels	Dyke Farm, Moffat. Kinross, Forfar. (Figure 14)
Road and rail runoff	National	Poor	All types	None
Septic tanks	National	None	Glaciofluvial, till, alluvium	Fruit farms in the Arbroath area

Table 6 Summary of coastal drift deposits in relation to saline intrusion

Area	Drift type at coast	Role of drift	BGS Data available
South Moray – Inverness	Raised Beach gravel	Pathway + aquifer	Bhs
Aberdeen	Raised Beach gravel	Pathway + aquifer	Some bhs
Montrose	Raised Beach gravel	Pathway + aquifer	Some bhs
Carnoustie	Raised Beach gravel	Pathway + aquifer	Little
Firth of Tay	Marine clay/Raised Beach	Barrier + pathway	Some bhs
Carse of Gowrie	Marine clay	Barrier	Little
Fife - Tentsmuir	Raised Beach sand/clay	Pathway + barrier	Little
Forth – Grangemouth	Marine clay	Barrier	Env. Geology maps
Forth - Stirling	Marine clay	Barrier	Env. Geology maps
East Lothian	Raised Beach gravel	Pathway + aquifer	Little
Solway – Annan	Raised Beach gravel	Pathway + aquifer	Some bhs
Solway - Dumfries	Raised Beach gravel/clay	Pathway + barrier	Bhs
Kirkcudbright	Marine clay	Barrier	Little
Newton Stewart	Raised Beach/glacial gravel	Pathway + aquifer	Little
Luce Bay/Stranraer	Raised Beach sand	Pathway + aquifer	Little
Irvine	Raised Beach sand	Pathway + aquifer	Bhs
Arran – Brodick	Raised Beach/glacial gravel	Pathway + aquifer	Little
Clyde – Glasgow	Alluvial gravel + clay	Pathway + barrier	Env Geology maps
Tiree	Raised Beach sand + gravel	Pathway + aquifer	Bhs

Table 7 Drift as a factor in waste disposal

Area	Sites where drift as pathway	Sites where drift as barrier
Lothians	Various sand pits	Few
W. Central	Greenoakhill + other sand pits	Few eg.
Dumfries and Galloway	Dumfries (Lochar Moss – shallow sands)	Dumfries (Lochar Moss – lacustrine clays)
Borders	Few	Few
Fife	Ladybank – RB sands	Ladybank – basal till
Strathmore	Forfar – glacial sand and gravel	Few
N, Scotland	Inverness + many small sites on raised beaches	Cruden (partial barrier)

Table 8 Drift in industrial areas

Area	Drift as pathway	Drift as barrier	Overall significance of drift
Lothians	Along coasts (over thin raised beaches) Minor alluvial floodplains	Tills of Edinburgh area and West Lothian	Drift is generally less than 15 m in thickness. Restricted alluvial deposits.
W. Central Belt	Clyde alluvium Glacial infill channels eg. R. Kelvin, R. Leven	Tills mostly across coal mining areas	Important mainly in the lower Clyde valley and Kelvin floodplains. Tends to be generally thin till elsewhere.
Falkirk/Grangemouth	R. Forth and Carron alluvium	Carse clays at Grangemouth	Drift is very important. Delineation between barrier/pathway areas needs further work.
Dundee	Narrow raised beach	Till as a partial barrier inland from coast	Drift is very important along coastal strip.
Aberdeen	Along Dee and Don valley floodplains. Permeable sandy tills are widespread	Few areas.	Drift is more important as a pathway. Few locations where effective barriers occur.

3.3.3 Nitrate

Recent work carried out by BGS on behalf of the Scottish Executive on the establishment of nitrate vulnerable zones involved the collection of data on both shallow and deep groundwater sources (Ball and MacDonald, 2001) (Figures 13 and 15). In summary, the work showed that granular superficial deposits are extremely vulnerable to nitrate leaching. Many wells and springs that abstract water from shallow aquifers in the drift have elevated concentrations of nitrate where arable or dairy farming is practised nearby. In the Dumfries basin, for example, depth profiling of nitrate has shown an advancing front of nitrate-rich water that is dependant on the presence of gravelly deposits and sandy till. Where thick laminated clays occur, deeper groundwater is largely unaffected by nitrate.

In order to produce nitrate vulnerable zones over a large area of eastern Scotland in a relatively short space of time, a methodology was devised that incorporated both superficial and bedrock DiGMap data. The resultant maps show where highly permeable deposits (bedrock or drift) are close to surface. Figure 13 shows an example of this type of map, which has a working scale of 1: 50,000. Figure 15 shows the draft national distribution of NVZs.

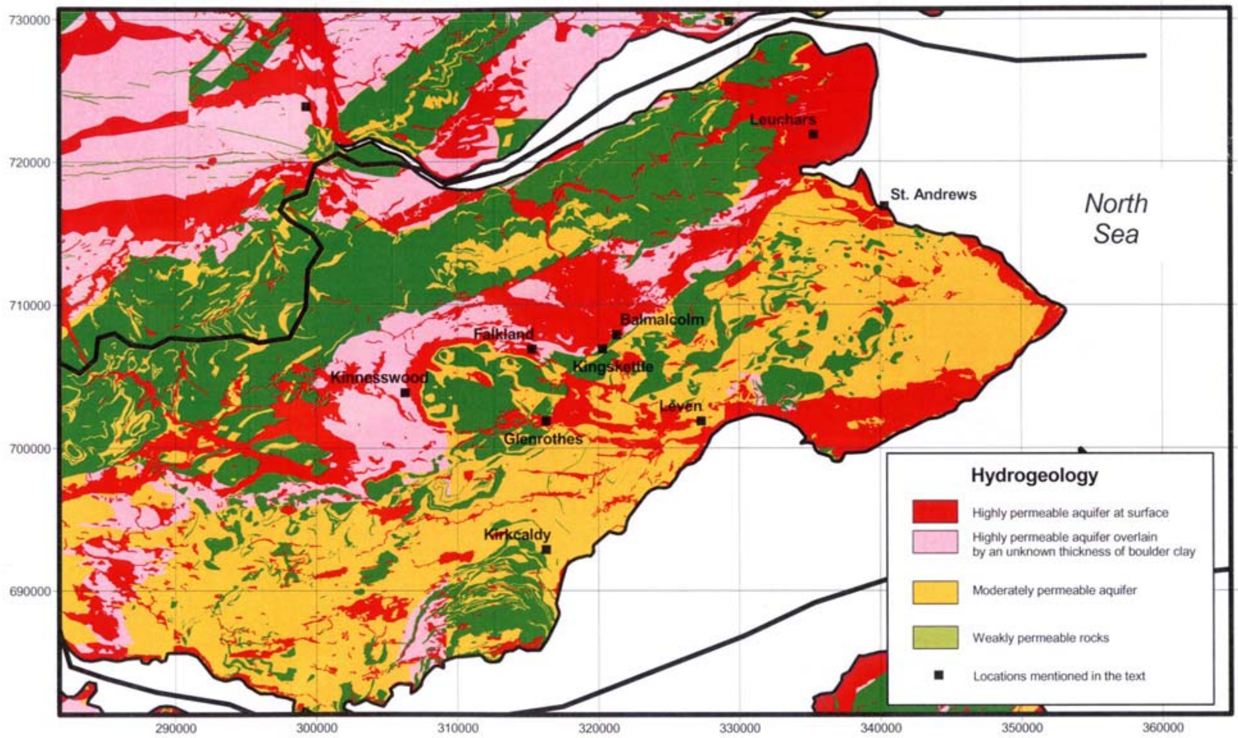

Figure 13 A groundwater vulnerability map of Fife derived from DiGMap data

Using DiGMap coverage, it would be possible to create a vulnerability map of this type for the whole of Scotland. This map could then be used as a layer in a GIS-based reference set for WFD catchment management purposes.

3.3.4 Over-abstraction

There are few examples in Scotland where over-abstraction has occurred within superficial deposits. The principal aquifer type is alluvial gravel for several reasons. This type of deposit forms in water-lain beds that have a relatively consistent permeability over a distance, in some cases, of several hundred metres, allowing groundwater to flow towards an abstraction source from a wide surrounding area. The gravels are normally well-sorted with low clay contents. This results in high permeabilities. Being located under valley floodplains, they are in areas that are natural groundwater discharge zones. Lastly, if abstraction exceeds the sustainable capacity of the floodplain aquifer, water is drawn into the gravels from the river, so minimising the risk of dewatering the floodplain.

Where maps indicate the presence of glaciofluvial sand and gravel, the risk of over-abstraction is higher than in valley gravels. Glacial deposits are more complex, resulting in many discontinuous minor aquifer units. Recharge rates may be lower than for alluvium as the glacial material is often on higher ground and not in discharge areas. The risk of dewatering is higher in this situation. Similar principles apply to other types of superficial deposit. Table 9 lists the types of superficial deposit and the implications for over-abstraction from wells and boreholes

Table 9 Superficial aquifers and over-abstraction.

Deposit type	Permeability classification	Typical source yield	Examples	Consequences of over-abstraction
Alluvial gravels	Very high to moderate-low	10 l/s	Spey scheme Fort William Carradale Ringford	Restricted lowering of water table. Induced leakage of river water into floodplain aquifers. Significant reduction in surface flows in medium-sized valleys in summer. Dewatering of surface marsh areas on floodplain.
Glaciofluvial sand and gravel	High to low	3 l/s	Many wells and springs	Drying up of adjacent springs and marshes. Local subsidence. Lowering of water table in nearby wells.
Raised beach sand and gravel	Very high to low	2 l/s	Tiree Irvine	Saline intrusion. Dewatering of wetlands
Blown sand	High	3 l/s	Tiree Tain	Limited saline intrusion. Affect on wetland habitats.
Till	Low	<0.3 l/s	Many shallow wells	Under present situation in Scotland – low risk of widespread over-abstraction. Dewatering of surface features.

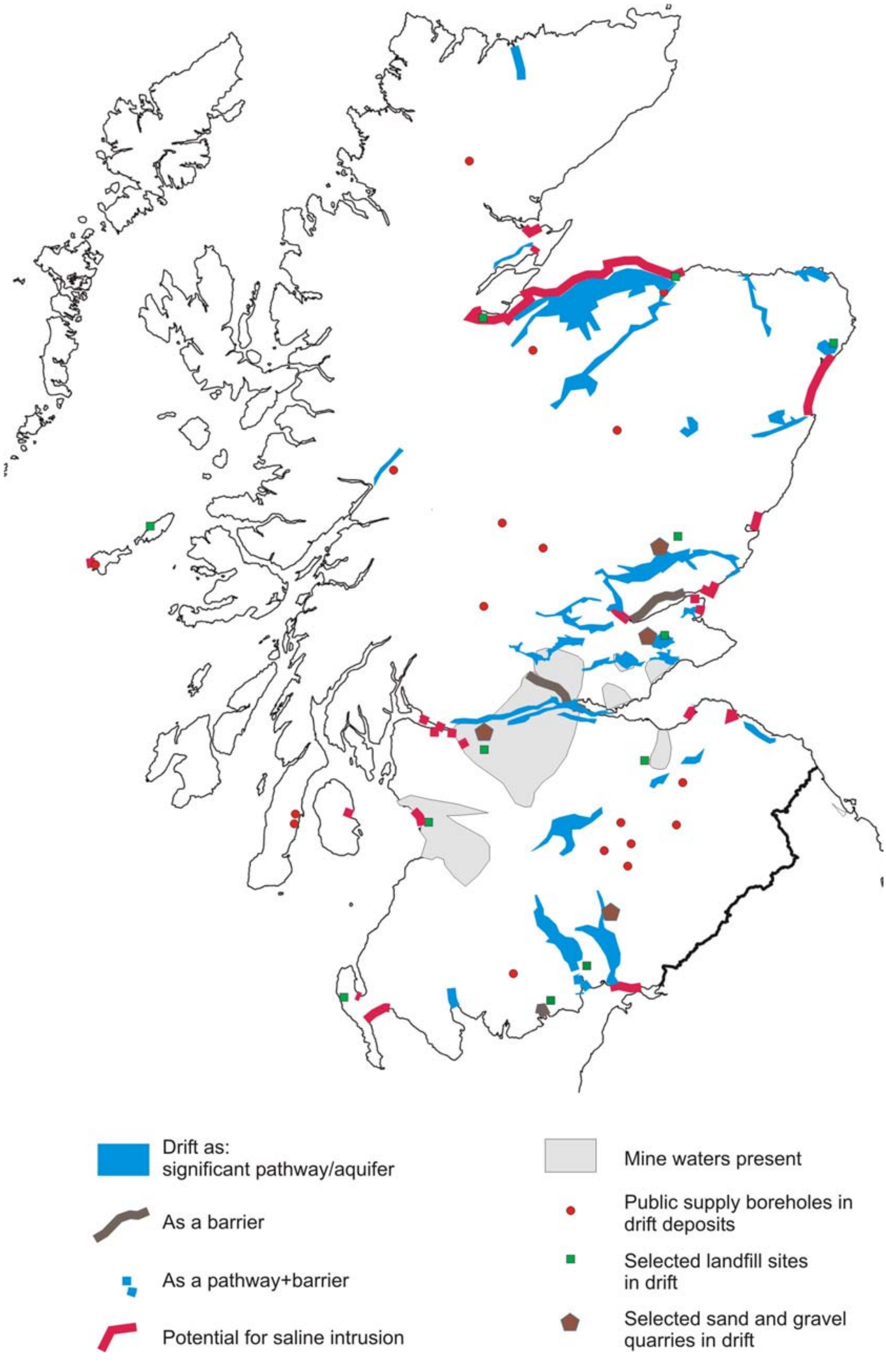

Figure 14 The pressures on drift from saline intrusion, mine water and selected landfill sites

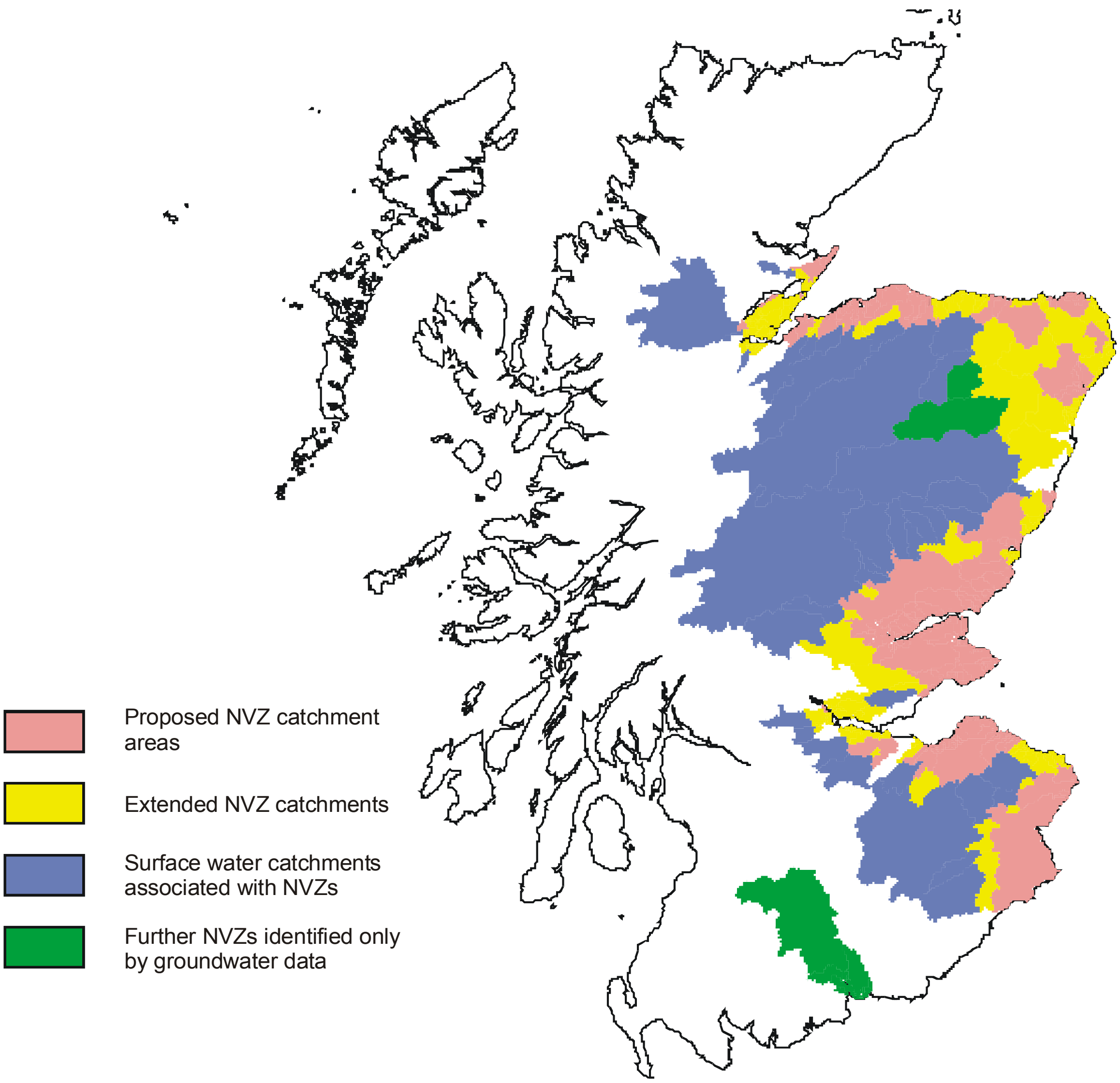

Figure 15 Groundwater Nitrate Vulnerable Zones in Scotland

4 Hydrogeological domains (typology)

Aquifer typology (superficial and bedrock aquifers together) is a means of characterising shallow geological sequences according to their basic hydraulic properties. It can be used to provide a study framework for the evaluation of hydrogeological types, with regard to their resource potential, their groundwater quality status and their vulnerability to pollution, i.e. the role of superficials in reducing or preventing recharge. As such, aquifer typology provides a valuable foundation towards satisfying some of the more significant groundwater data requirements of the WFD. It is a technique particularly suited to Scotland, where the geology is diverse and groundwater flow complex and difficult to evaluate.

The aquifer types can be ranked in terms of likely resource potential, likely water quality, vulnerability to pollution, flow mechanisms (granular/fissure) and size and shape of source capture zones. The classification of the aquifers can be designed as a matrix containing the basic aquifer characteristics, and the typology classes can be described in terms of a range of different fields: resource potential, water quality, vulnerability etc. The fields may also include trends (e.g. likely to be of good status by 2009, etc).

The typology classification can be as large or as small as the user demands. It may include grouped types each containing sub-groups of related type.

The typology classification starts with the solid geology, and drift geology maps to define the geometry of sequences of similar hydraulic properties. It then considers type and role of drift cover, upland/lowland, recharge/discharge, gaining and losing rivers, etc. This broad classification is a desk level assessment using available data and an understanding of the generic hydraulics of the rock types and the risk posed by local activities. The classification is assembled in a GIS format which may also contain a layer showing the threat from human activity. A selection of catchments is required for field control.

This approach provides a basis for more detailed subsequent investigation. Once the typology classification framework is established, and appropriate polygons have been created, the process of investigating groundwater status can begin according to each typology.

Two approaches to classification could be used:

1) Classify all geology types – nothing is excluded, so if, for example till is initially set to allow no recharge, and then recharge is permitted, the classification can be changed and areas of till can easily be incorporated.

The approach would then be to develop a system to classify combined drift/bedrock domains in matrix form. Some examples are shown in Table 10. This system would have to be adapted to the needs of the WFD regarding groundwater body status.

There is a 6 yearly review process in the WFD which will allow new ideas and updates to be made to river basin plans. As many parameters can be defined as thought are necessary (dependant on data). A classification can then be developed by combining the parameters (with weighting if considered appropriate) according to their significance in terms of recharge potential or aquifer potential. Maps can then be produced to show areas classified according to recharge potential and/or aquifer potential.

Table 10 Matrix of superficial and bedrock domains.

	Parameters		**Overall rating**	
Geological characteristics	Resource potential	Natural Water quality	**Overall recharge potential**	**Overall aquifer rating**
Till/sandstone	High	High	Low/moderate	Mod
Till/mudstone	Low	Low	Low	Low
Raised beach/sandstone	High	High	High	High

2) Set criteria to exclude certain geology/superficial/soil types, and classify remainder. This would simplify any subsequent classification that is carried out.

For example, a set of rules could be written to identify and exclude specified rock types such as:

Bedrock = mudstone,

drift = till

etc

However, as almost everywhere will be a groundwater body this approach is limited.

The areas so defined (if any) would be excluded from further consideration, and attention would be focussed on areas where there is a potential resource, and/or the potential for recharge to occur. The maps produced would show only these areas, with the remainder unclassified.

Other criteria can also be utilised. For example, if all areas with elevation greater than 1000 m above sea level can be assumed to have similar hydrogeological characteristics, these could be selected and removed from the general classification.

Data requirements for the typology GIS compilation include:

- 1: 50 000 solid and drift geology maps,
- 1: 50 000 (or larger scale) soil maps (source: MLURI),
- 1: 100 000 aquifer vulnerability maps (where available),
- Depth to rock head contours (where available),
- Borehole data (digitised) including lithological descriptions and breaks,
- Piezometric level,
- Abstraction data,
- Land use (source: MLURI),
- Land slope.

Suitable algorithms will need to be created which allow data to relate to each other in such a way that degrees of vulnerability and degrees of recharge proportional to effective rainfall can be derived. It should be noted that outwith the drift covered areas (i.e. where bedrock crops out) the assigned vulnerability and recharge potential derived from existing vulnerability mapping can be used (1: 625 000 coverage for the whole of Scotland, 1: 100 000 for Fife, Dumfries and Morayshire).

One of the big problems in evaluating recharge/vulnerability in till and morainic drift covered areas is how effective is the cover at excluding recharge and protecting groundwater from pollution. An effective first pass is to create a further three layers to the GIS with the outline of the till and the morainic drift as layer 1, the soil map as layer 2 and the catchment wide Baseflow Index Levels (BFIs) as layer 3. Wherever there are podzolic soils over drift, the drift is likely to be free draining and rainfall recharge is likely to access an underlying groundwater body. Wherever gley type soils occur, the till is likely to be weakly permeable excluding rainfall recharge from accessing deeper aquifers. This simple and readily made assessment begins to classify the drift cover between moderately vulnerable and not vulnerable. Clearly areas of very shallow water table and of steep slope cannot be assessed in this manner and a percentage of the drift cover (possibly about a third) will have to be considered on merit. The BFI polygons provide a check for whole catchments which have a significant groundwater baseflow contribution, i.e. where rainfall recharge is occurring (BFI > 50%), and which do no (BFI <20%).

Groundwater status evaluation may be carried out at two levels. It can be assigned at desk level on the generic basis described above but will require a second level of field validation in those areas deemed at risk or unclassifiable, where some new data gathering will be required to fill known gaps in knowledge. The latter includes the identification of water quality trends due to diffuse pollutants such as nitrate and pesticide, as well as point source contamination, rising mine water levels and other temporal effects. More significantly, specific catchment investigation will require evaluation of a water budget, in theory for those groundwater bodies which supply greater than 10 $m^3 d^{-1}$ drinking water. This will involve field evaluation of recharge and discharge as well as abstraction monitoring through licensing. This may not need a lot of detail or real accuracy if a groundwater body is not at risk with respect to abstraction, as is usually the case in Scotland. It will require quick and easy methods where possible because of the limited timescale.

4.1 DRIFT RECHARGE AND SHALLOW STORAGE

Cognisance of domain approaches to classifying drift aquifers and non-aquifers may help evaluating areas of vulnerability or of poor recharge potential. All superficial deposits allow rainfall recharge to take place to some extent and all offer some degree of storage (Lerner et al., 1990). The typical range of hydraulic properties for generalised lithologies found in Scottish superficial deposits is shown in Table 11. However, it is uncommon to find just one lithology in any given sequence and interbedded sands and gravels or sands silts and clays are more typical for most fluvial and glacial deposits. These can be assembled into geological domains to assist with interpretation of 2-D mapping information coupled with borehole logs (McMillan et al., 2000). Geological domain mapping was pioneered on the west Cumbrian coastal belt where glacial deposits from a number of stadials are present. Quaternary geological domains were defined by distinctive landform-sediment associations and structural characteristics. The geological domains were then translated into hydrogeological domains using hydraulic data available from drilling and testing. In turn the hydrogeological domains could then be assigned a potential rainfall-recharge index, which can later be quantified through a digital time variant groundwater flow model of the area. In the west Cumbrian example, depending on the domain type, between 35% and 100% of the long term effective rainfall (rainfall minus evapotranspiration and runoff) became recharge to the superficial materials or bedrock below.

Table 11 Generalised hydraulic properties for superficial deposits (after Smart and Herbertson, 1992)

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

Prognoses of likely recharge is further complicated by processes such as:

- by-pass flow through sub-vertical fractures in otherwise weakly permeable strata, water having been distributed into the fractures via relatively permeably soil and weathered zone and subsequently again by sand or gravel lenses,
- concentration of saturated zones beneath topographic lows and wet areas of ground,
- rapid recharge into gravel horizons then to seep into less permeable adjacent or underlying strata,
- and by bank side storage (into and out of) adjacent rivers and streams.

Direct application of the Penman (1948, 1963) soil moisture deficit approach is, therefore, unlikely to be useful when dealing with complicated superficial sequences, the like of which prevail in much of lowland Scotland. Rather, the distributed recharge model advocated by McMillan et al (2000) is a preferred approach to solving catchment scale recharge problems, albeit, at a level of effort that is prohibitive for the whole of Scotland with the timescale available.

However, a lot of detail may not be necessary in the first instance, although increasing knowledge and accuracy with time is usefully built into the programme. An alternative approach is to develop a series of instrumented catchments each containing representative drift and bedrock typologies for Scotland. Estimates of recharge to and through these typologies could then be input to models of other areas to assist in developing catchment water budgets and vulnerability risk estimates. However, there are a number of dangers inherent in these calculations particularly in areas of high relief and in coastal areas. Best estimates of evapotranspiration are available only for MORECS 40 x 40 km squares from the Meteorological Office based on the methodology developed by Monteith (1965). Orographic rainfall and steep topography also mean that areal variation in rainfall may be difficult to determine within a single catchment. Finally, the diversity of drift typologies within a given catchment may complicate the estimate of recharge beyond the tolerance of the water budget. In addition, groundwater throughput may not be easy to calculate in areas of fractured bedrock for which few hydraulic measurements are available and recharge estimates could remain unvalidated.

Superficial gravels and sands form useful aquifers in many areas of rural Scotland. All of these aquifers are vulnerable to pollution and all receive direct rainfall recharge. They also provide useful stores of groundwater which tend to spread baseflow discharge and which may also distribute groundwater over lower weakly permeable clays to assist finding pathways through to lower bedrock aquifers. However, any perched drift aquifers need to be characterised in addition to any deeper bedrock aquifer.

5 The way forward

The diverse and complex 3-D distribution of superficial strata in much of Scotland suggests that the time available and the costs of carrying out detailed site specific analysis on every catchment is prohibitive and not strictly necessary to meet the requirements of the WFD. A phased approach to evaluating the role of drift is, therefore, recommended. A summary of data needs, their importance and availability is given in Table 12.

Table 12 Summary of data needs and availability

Data type	Importance	Availability
Drift geology maps	critical	Digital 50 K from large coverage at 50K and partial at 10K
Soil map	critical	Digital cover available for likely at risk areas
Solid geology	critical	Digital at 50K
Borehole records	critical	Over 200 000 sites, coverage variable
Land use	critical	Available digitally
Air photography	useful	Stereo pairs at 10K
Base Flow Indices	useful	Available for larger catchments
Slope	useful	Digital as DTM
3-D drift lithology	useful	Unlikely to be available
Drift hydraulics	useful	Unlikely to be available
Groundwater vulnerability and resource maps	useful	625 K coverage, selected areas at 100 k
Nitrate risk areas	useful	MLURI work
Land use/pollution potential (risk) map	useful	Information is available
Depth to water table	desirable	Partially available
Depth to rock head	desirable	Partially available
Recharge estimates	desirable	SNIFFER project
Abstraction data	desirable	Wellmaster
Satellite imagery	useful	available

Phase 1

Objective

An initial regional scale evaluation of recharge through drift deposits to identify regional differences. These include the difference in clayey till in the Midland Valley to more sandy till in northern Scotland, the prevalence of granular deposits in lowland areas, and the occurrence of thick clayey till in areas such as Grangemouth and Bo'ness, etc.

Methodology

Task1: To carry out a literature survey of vulnerability assessment in drift dominated terrain to identify relevant recharge processes and to catalogue existing evaluation procedures and formulae.

Task 2: make appraisals of algorithms that will link the Scottish data to provide an initial vulnerability indexing.

Task 3: Compilation of topographical, geological, pedological, surface and groundwater data in GIS form using existing digital databases (some new data entry will inevitably also be required).

Task 4: Test and revise vulnerability algorithms using GIS.

Task 5: Maintain dialogue with SEPA, discussion and reporting.

The evaluation is intended to be a rapid GIS based compilation of data, determination of algorithms to associate data levels, and use of the soil map and BFI data to assess the occurrence of free draining clayey till and morainic drift. The work will focus on the likely at risk areas. A detailed literature survey will be carried out during this phase of work.

The initial GIS compilation could be undertaken rapidly. All the required data are available digitally except the BFI polygons. Determination of suitable algorithms can be partly empirically based, partly by trial and error and partly founded on hydraulic logic. This is the hardest part of the work and will require somewhat greater effort to complete to a satisfactory level. Output will be generated digitally and at little expense to create working maps, and written explanations, etc.

Likely effort:

A total of between 6 and 9 man-months effort is envisaged.

Phase 2

Objective

An attempt to further quantify the drift cover according to the vulnerability indices derived in Phase 1. The objective is to refine the algorithms used in Phase 1 and to identify additional data requirements that may help to solve problem areas and those areas which appear to be at risk.

Methodology:

Testing of the algorithms set up in Phase 1 will enable refinement to the vulnerability indexing that was not possible with the initial data sets. This phase of the project will explore which additional data sets could help refine the calculations and whether it is feasible to obtain appropriate coverage. Data sets under scrutiny will include depth to water, groundwater chemistry and provenance, base flow index etc. At risk areas will be assessed to identify if data are adequate and if there is a perceived need for additional primary data gathering to satisfy the requirements of the WFD deadlines.

Dialogue will be maintained with SEPA throughout to ensure correct steer preparatory to reporting.

Likely effort:

Total effort for this phase could be contained within four man-months effort.

Phase 3

Objective:

The delineation of recharge and vulnerability at catchment scale, using data from available instrumented catchments and groundwater throughput calculations. Primary data acquisition will be required.

Methodology:

The output would be:

- an index of groundwater sustainability in terms of recharge, discharge and abstraction, with particular regard to the sustainability of the catchment ecology and habitat (ecology is very tricky to define but is clearly stated in the WFD),
- an assessment of the likely vulnerability of the catchment to pollution by anthropogenic sources identified within that catchment.

The detailed methodology will be derived directly from Phases 1 and 2, and will build from them by adding the catchment scale detail available from a water balance calculation and the risk from Man's activities within the catchment. The methodology assumes that a sufficient number of instrumented catchments will allow extrapolation to 'at risk' non-instrumented areas. Water balance information is already available for certain catchments in Scotland. The catchments for the Fife aquifer and that for the Dumfries basin have already been assessed, and CHASM catchments such as the Ythan may have data available.

Data collection and interpretation:

- The collection of primary data in 'at risk' catchment areas would be expensive, as a certain amount of subsurface investigation would be required. The latter could include shallow boreholes to rockhead, completed with piezometer tubing. Measurement of groundwater levels would indicate response times after rainfall events. CFC sampling of groundwater at rockhead would provide an indication of the age of the water, but this would be extremely expensive to carry out on a catchment-wide basis. A small, but detailed investigation at carefully selected locations within each catchment could provide a good indication of the processes at work
- The use of a power auger to drill shallow boreholes in till deposits is a practical proposition across a wide area. The holes can be completed quickly provided the cobble content of the till is not high. Slug tests can then be conducted in the screened borehole to give an indication of the permeability of the deposit. If the till is reasonably competent, the tests can be carried out in open holes which can then be backfilled afterwards.
- The methodology of such an investigation could involve the drilling of 3 closely-spaced auger holes within a particular drift unit such as till on a 3 km grid basis. The 3 holes would give an average result for permeability at every location. Categories for permeability could be entered as layers on the GIS for each catchment.
- For each catchment, zones could be identified for particular geological environments. Steep hill slopes may contain thin clayey till with head deposits. Lower slopes may be sandier, with silty areas. Marginal valley terraces are predominantly glaciofluvial. Valley floors may be silty with underlying permeable gravel. An augering programme

could be tailored to investigate each of these environments to produce typical values for permeability, recharge response etc.

These outputs contribute directly to the evaluation of groundwater and surface water status required in 2004 and the management plans required to be laid down by 2009, although they could be refined and developed on an ongoing basis.

A number of parallel programmes are available to help with the development of the required methodology. The opportunity already arises within the NERC thematic programme CHASM to instrument drift covered catchments in Scotland (and Northern Ireland). Ongoing work at the Universities of Aberdeen and Dundee, Macaulay, Scottish Agricultural College, British Geological Survey and others could be co-ordinated and focussed towards the issues relating to drift covered catchments, in order to better identify the processes occurring in such catchments. In addition the drift mapping programme, which is part of the core BGS mapping programme, can be focused towards domain mapping to provide basic geological input to the phase 2 and 3 evaluations. Depth to rock-head maps also need to be constructed from available borehole information, and depth to water level piezometric maps need to be generated from borehole data and surface water elevation data.

Likely effort:

This will be an ongoing iterative process that will allow the process of vulnerability evaluation to be refined and improved throughout the implementation phase of the WFD and thereafter. A test case using perhaps five existing catchment studies (not currently) identified could be carried out over a 12 month period.

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Appendix 1

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ANNEX 1 BGS CONDITIONS FOR SUPPLY OF DIGITAL DATA 2000/01

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