An overview of groundwater in Scotland

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Synopsis

Groundwater is an important, but undervalued, national resource in Scotland. Groundwater is present both in the bedrock, where much of the flow is through fractures, and in the superficial deposits, where intergranular flow dominates. The most productive bedrock aquifers are the Permian sandstones and breccia in SW Scotland and the Devonian sandstones in Fife, Strathmore and Morayshire. Alluvium and fluvio-glacial sands and gravels can also form important aquifers and provide some of Scotland's most highly yielding boreholes. Groundwater is generally weakly mineralized with total dissolved solids in the range 100 to 500 mg l^{-1} and is dominated by Ca and HCO_3 type waters.

There are in excess of 4000 boreholes in Scotland, and over 20 000 springs and wells used for private water supply. There are few available reliable data on the total volumes of groundwater abstracted; however, conservative estimates suggest that the total volume is approximately 330 megalitres per day for public water supply, industry, agriculture and private water supply. The volume of groundwater used in public water supply is growing annually; it is currently 7% of the daily 2400 megalitres per day supplied by Scottish Water. Scottish groundwater is under threat from agricultural activity, the mining legacy, septic tanks, localized high abstraction, and general land development. The implementation of the Water Framework Directive, and associated legislation, is an excellent opportunity to sustainably manage and develop groundwater in Scotland.

Introduction

Groundwater is an important resource for Scotland. Water from boreholes and springs contributes to public, industrial and agricultural water supply as well as supporting many rural properties. Groundwater forms the basis of the growing mineral water industry in Scotland and is also used to produce, and market, whisky. However, despite the obvious importance of groundwater it is often undervalued and overlooked as a national asset, probably because of high rainfall and a perception of adequate surface water resources.

Many farmhouses and rural dwellings built before the twentieth century possessed a well beneath the kitchen floor or in the yard outside. The arrival of the steam drilling machine in the late Victorian era provided industry with access to groundwater, but it was interest in dewatering the particularly wet coal mines of central Scotland that first brought groundwater investigation to the fore (Robins *et al.* 2004).

Early interest in groundwater was championed by the Edinburgh Office of the Geological Survey of Great Britain. Some of Scotland's most famous geologists, Ben Peach and John Horne, and later T. R. Robertson and A. G. (Archie) MacGregor wrote many of the groundwater reports in the early years. The first overview of groundwater occurrence in the Midland Valley was that by Cumming (1936), but it took until 1977 before a dedicated hydrogeologist (Ian Harrison) was appointed to the Survey Office in Edinburgh following the earlier appointment of a hydrogeologist (Tricia Henton) to the Clyde River Purification Board.

Springs have formed an important part of public water supply since the nineteenth century, most notably supplying the city of Edinburgh. Borehole drilling for public supply commenced in earnest in the 1970s in Dumfries and Fife when it was realized that cost-effective potable supplies requiring little treatment could be obtained from groundwater in some areas. Development continued throughout the 1980s; this development phase of hydrogeological investigation was capped with two milestones: the publication of the Hydrogeological Map of Scotland (British Geological Survey 1988) and an accompanying description (Robins 1990).

The next phase of groundwater science concentrated on resource protection as well as development. This was heralded by the publication of a national groundwater protection strategy (ADRIS 1995) and development of groundwater vulnerability maps for selected areas, e.g. the national vulnerability map published with ADRIS (1995). A great deal of effort was also put into evaluating contaminated land and other point sources of pollution, both with regard to environmental protection and to land development.

The current phase of hydrogeological investigation in Scotland is one of resource and source management. The drivers are the incoming Directives from the European Union, including the Nitrate Directive and

TABLE 1
A summary of bedrock aquifer productivity in Scotland.

Productivity rating* ($l\ s^{-1}$)	Dominantly intergranular flow	Intergranular / fracture flow	Fracture flow
Very High (>20)	Permian sandstone (*E Dumfries, Lochmaben, Thornhill*) Upper Devonian sandstone (*Fife*)	Permian breccia and sandstone (*W Dumfries, Moffat, Arran, Mauchline*)	
High (10–20)	Carboniferous Passage Formation sandstone	Upper Devonian (*Southern Scotland*) Devonian sandstone (*Moray*) Lower Devonian sandstone (*Strathmore*) Permian and Triassic (*Moray, Solway*)	
Moderate (1–10)		All Carboniferous Formations except mudstones and Passage Formation Devonian conglomerate, siltstone, limestone and argillaceous rocks (*Moray, Turriff, E Ross, Strathmore*) Lower Devonian (*Southern Scotland*) Devonian sandstones (*N of Great Glen*) Jurassic sandstone (*Skye*) Permian (*Stranraer*)	Cambrian limestone and dolomite Carboniferous lavas (*E Lothian*)
Low (0.1–1)		Volcaniclastic sediments Carboniferous mudstones	Dalradian (*except psammites*) Ordovician/Silurian greywacke+siltstone Devonian flagstones (*Caithness+Orkney*) Cambrian rocks (*except dolomite and limestone*) Jurassic+Triassic (*except Burghead, Skye*) Moine pelites Lavas (*except E Lothian*) Torridonian Sandstone
Very Low (<0.1)			Lewisian Dalradian psammites Moine (*except pelites*) Igneous intrusions

*The productivity rating refers to the estimated typical long-term yield from a single, properly sited and constructed borehole.

the Water Framework Directive, each of which requires considerable hydrogeological input (see Clews *et al.* 2005). Central to groundwater management is the role of the national environmental regulator, the Scottish Environment Protection Agency. Recent advances in computing power and in particular the availability of Geographic Information System (GIS) formats are now enabling existing large datasets to be reanalysed on a national scale. A number of major analytical projects have recently provided considerable advances in the understanding of the hydrogeology of Scotland, including the designation of areas at risk from nitrate and pesticide pollution (Ball *et al.* 2005), groundwater that is vulnerable to pollution (Ó Dochartaigh *et al.* 2005), and aquifer productivity (MacDonald *et al.* 2004).

This paper gives an overview of our current understanding of groundwater in Scotland. An extensive reference list is given to help follow up some of the issues in more detail.

Groundwater occurrence

Groundwater occurs throughout Scotland in many different environments and rock types. However, the resource accessible from different rock types varies markedly depending on the permeability and porosity. In bedrock aquifers, much of the flow is through fractures; intergranular flow is important in only a few sandstone formations (see Table 1). In superficial deposits, intergranular flow dominates and fracture flow occurs only in low permeability tills, which have negligible groundwater potential. Recently, GIS-based maps (designed to be used at a scale of 1:100 000) of the accessible groundwater resources across Scotland have

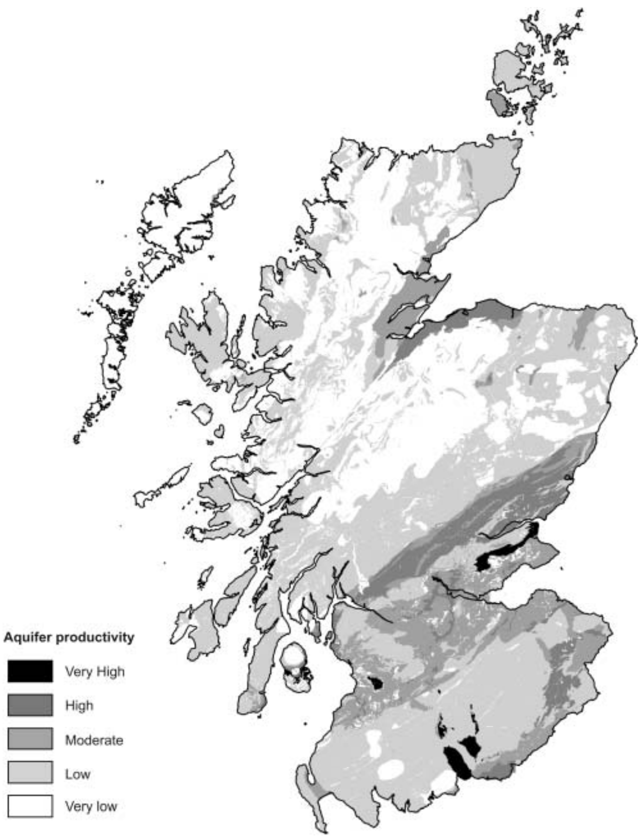

FIG. 1. Bedrock aquifer productivity across Scotland.

been produced for both bedrock and superficial deposits (MacDonald *et al.* 2004).

Bedrock aquifers

Table 1 gives a summary of the flow types and aquifer productivity for bedrock in Scotland; the distribution is shown in Figure 1. The term "aquifer productivity" has been used to describe the potential of an aquifer (bedrock or superficial deposit) to sustain various levels of borehole supply. Properly sited boreholes (or for superficial deposits, a group of boreholes) in high and very high productivity aquifers have the potential to be considered a source for public supply or for industry. Low productivity formations are considered suitable for groundwater supplies to single or small groups of houses.

The flow characteristics and classifications have been made with reference to various sources: laboratory hydraulic data, geophysical logs, and pumping test data where available. However, for much of Scotland these data are not available and the classifications are based solely on lithological descriptions of the rocks, borehole records, drilling experience and the BGS hydrogeological map of Scotland (British Geological Survey 1988). The most productive bedrock aquifers in Scotland are the Permian sandstones and breccias in SW Scotland, and the Devonian sandstones in Fife and eastern Scotland.

Permian aquifers of SW Scotland. The Permian aquifers of SW Scotland comprise thick sequences of sandstones and breccias. Hydrogeological and geophysical investigations have demonstrated that the breccias and sandstones have different hydrogeological properties (Robins & Buckley 1988; Robins 1990; Buckley 2000; MacDonald *et al.* 2003).

Detailed geophysical logging in various boreholes penetrating breccia has shown that much of the inflow is from only three to five fractures; the most productive fractures are between breccia and sandstone layers. Individual fractures have been measured contributing more than 45% of the flow (Buckley 2000). Further evidence of rapid groundwater flow over several kilometres and limited groundwater storage in the breccias has been given by a combined study of groundwater quality and age (MacDonald *et al.* 2003). Pumping tests within the breccia indicate transmissivity from 9–4000 $m^2\ d^{-1}$ with a geometric mean of 400 $m^2\ d^{-1}$ (from 11 tests). Laboratory measurements from core samples from the breccia indicate an average porosity of 8% (mean of samples from two boreholes) and hydraulic conductivity of less than 10^{-4} m d^{-1} (Robins & Buckley 1988; Cheney & MacDonald 1993).

The transmissivity of the sandstones is lower, but the storage higher, than that of the breccia. Average porosity is 20–30% and hydraulic conductivity is generally less than 1 m d^{-1} (Robins & Buckley 1988; Cheney & MacDonald 1993). In Arran, where the sandstones have been baked by igneous intrusions, intergranular porosity and permeability are much less. There are fewer pumping test from the sandstones, but average transmissivity from four tests is 200 $m^2\ d^{-1}$. Geophysical logging (Robins & Buckley 1988; Buckley 2000) again indicates that much of the inflow to boreholes is through fractures, but overall regional flow is slow and likely to be dominated by intergranular flow (MacDonald *et al.* 2003).

Devonian aquifer of Fife. Three formations, the Knox Pulpit Formation, Kinnesswood Formation and Glenvale Formation, form the Fife Devonian aquifer. These, and other Devonian formations, are not as productive where they occur elsewhere. There is considerable variation in porosity and hydraulic conductivity with depth in the aquifer, reflecting variations in grain size. Geophysical logging of boreholes has shown that even where porosity is highest (greater than 20%), fracture flow is still dominant, constituting at least 70% of inflow to boreholes. Highest permeability occurs in the uppermost 10 to 15 m of the saturated zone, where weathering and fracture development have significantly increased secondary permeability (Ó Dochartaigh *et al.* 1999). Mean porosity for the four formations is 19.4% (from ten boreholes) and hydraulic conductivity 0.06 m d^{-1}. Pumping tests from five boreholes indicate transmissivity of 200–800 $m^2\ d^{-1}$ with a geometric mean of 350 $m^2\ d^{-1}$.

Superficial aquifers

Table 2 gives a summary of aquifer productivity for superficial deposits in Scotland; the distribution is

TABLE 2
A summary of superficial aquifer productivity in Scotland.

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

shown in Figure 2. All superficial deposits are assumed to have primarily intergranular groundwater flow (although fracture flow may be important in some tills). The superficial aquifer map is subdivided into three classes according to productivity (high, moderate and low), with the remainder classed as non-aquifer. The classifications were made using BGS data, geological descriptions, and the Hydrology of Soil Types classifications (Boorman *et al.* 1995; Lilly *et al.* 1998; see below). The productivity is only *potential*, because many of the deposits may be too thin to actually contain groundwater. Ó Dochartaigh *et al.* (2005) explain the methodology used to determine areas of partially saturated or dry superficial deposits.

High productivity superficial aquifers comprise deposits that have significant sand and gravel content, such as glaciofluvial sand and gravel, and alluvium. All mapped alluvium and glaciofluvial deposits are included in this category; there are insufficient data to account for variations in permeability and thickness within alluvium and glaciofluvial deposits. Alluvial deposits within valley floodplains, although possibly less than 10 m in thickness, may have the capability to support very large abstraction rates wherever there is good hydraulic contact with adjacent watercourses. Some of the highest yielding boreholes in Scotland are from alluvium deposits: several large public water supply abstractions are located in high productivity superficial aquifers (Jones & Singleton 2000).

Moderate productivity aquifers comprise mainly raised marine deposits. Typically, these contain a high proportion of silt and clay and therefore have lower permeability than the coarser, well-sorted, high productivity deposits. They are also generally thin, which further reduces their potential for yielding large volumes of groundwater. Blown sand is also included in this category since, despite its high permeability, it is rarely more than a few metres thick and is distant from main rivers. Small public water supply abstractions have been located within moderate permeability aquifers in parts of rural Scotland. However, geophysical techniques are often required to help find the best locations for boreholes (MacDonald *et al.* 2000).

Low productivity aquifers comprise sandy and gravelly tills, moraines, mixed lacustrine deposits and landslip material. Much of Scotland is covered by till but only high permeability till and moraine are considered as aquifers. Although variations in till lithology are recognized across Scotland by BGS geologists, there is little relevant information on till lithological variation in the available maps. In order to provide support to geologists' descriptions, till has been subdivided according to permeability using the Hydrology of Soil Types (HOST) dataset of soil hydraulic properties developed jointly by the Soil Survey and Land Research Centre, the Macaulay Institute and the Centre for Ecology and Hydrology (Boorman *et al.* 1995; Lilly *et al.* 1998). The methodology for subdividing the tills is described in detail in Ball *et al.* (2003). In general, the more permeable tills are found across much of the Highlands, Aberdeenshire and southern Scotland.

Non-aquifers have by definition no aquifer productivity and have been omitted from the map. These include the moderate and low permeability tills of Strathmore and central Scotland, and estuarine, marine or lacustrine clays.

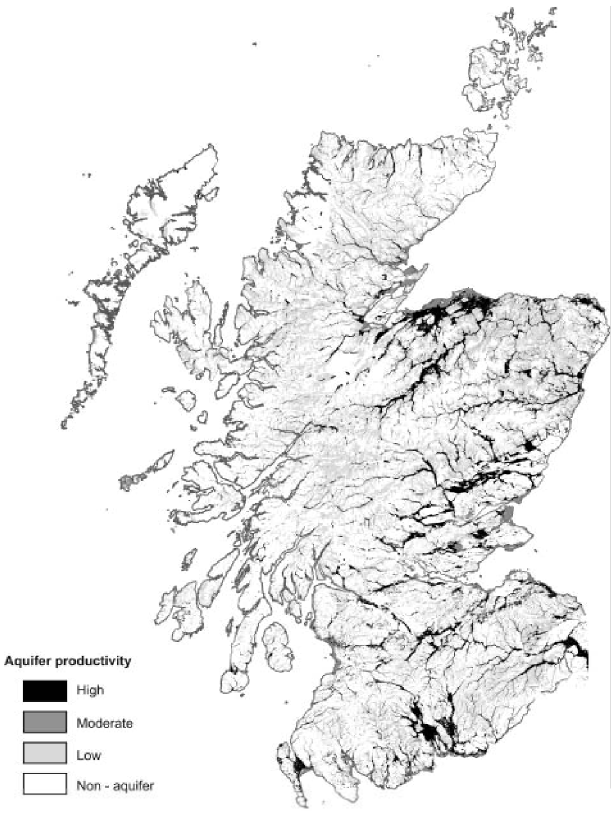

FIG. 2. Superficial aquifer productivity across Scotland.

Hydrochemistry

Much of the abstracted groundwater in Scotland is weakly mineralized with total dissolved solids in the range of 100 to 500 mg l^{-1}. Although a wide variety of water types are present throughout Scotland, many are dominated by Ca and HCO_3; Figure 3 shows the broad correlation between Ca and HCO_3 for the majority of

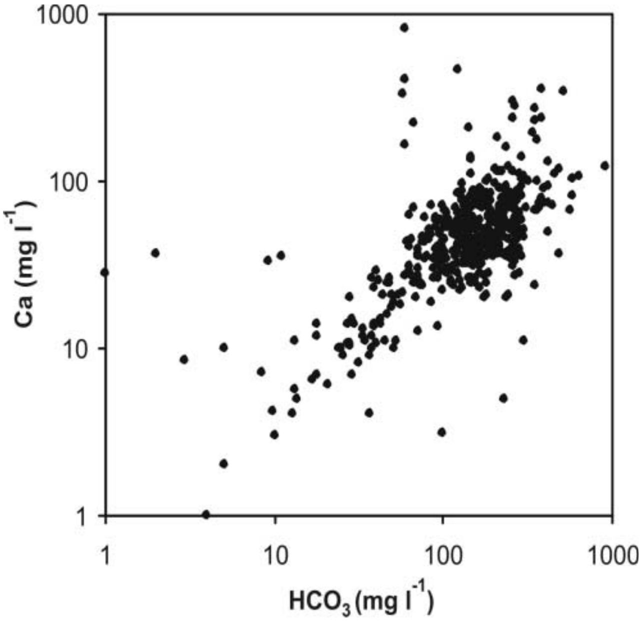

FIG. 3. The relation between calcium and bicarbonate for Scottish groundwaters.

Scottish bedrock groundwaters. Most Scottish groundwaters are aerobic, and there are few occurrences of reducing conditions. This reflects the relatively small size of many of the groundwater units and the short flow paths within them. Below is a summary of the main characteristics of groundwater quality in Scotland from the available data (Robins 2002).

- Groundwater in the meta-sedimentary rocks of the Southern Uplands offers a diverse range of water quality ranging from acidic to alkaline and from weakly to strongly mineralized. Groundwater in the Precambrian crystalline rocks of the Highlands is, for the most part, weakly mineralized with HCO_3 concentrations less than 300 mg l^{-1}.
- Devonian aquifers in the Midland Valley and Strathmore generally contain alkaline water dominated by Ca-HCO_3 and Mg-HCO_3 water types, although Cl and SO_4 are also important in some areas.
- Carboniferous rocks contain similarly alkaline groundwaters except where mining has lowered the pH and enhanced concentrations of Fe and Al in solution. In addition to the usual Ca-HCO_3 groundwater type, some Carboniferous groundwaters veer towards Na-SO_4 and Na-Cl dominance.
- The Permo-Triassic and Jurassic aquifers which have a silicate matrix tend to contain water of near-neutral pH dominated by Ca-HCO_3 and Ca(Mg)-HCO_3 types. Occurrence of dolomitic cement in sandstones in Morayshire creates Mg-HCO_3 type groundwaters, whereas gypsum in the Lochmaben basin creates Ca-SO_4 type groundwaters.
- Groundwater quality in superficial deposits is of variable chemical type depending on the prevailing mineralogy and connectivity with bedrock groundwaters and surface waters. Groundwater is typically of near-neutral pH with HCO_3 concentrations less than 100 mg l^{-1}. High iron and manganese concentrations are often found within the superficial deposits where localized conditions are reducing.
- There are some deeper circulating and more mature groundwaters which mostly discharge at former Spa sites (Robins & Ferry 1992). These include Bridge of Earn, south of Perth, which has a Cl concentration of 1250 mg l^{-1}, and the Na-dominated waters of Moffat, Innerleithen and Melrose in the Southern Uplands. Strathpeffer Spa, north of Inverness, is a young groundwater which has SO_4 concentrations up to 925 mg l^{-1} derived from contact with the shallow fetid and bituminous Spa Beds.

Elevated concentrations of nitrate in groundwater are a concern across much of Scotland (see Ball *et al.* 2005). Concentrations in excess of 25 mg l^{-1} NO_3 are common throughout eastern Scotland where excess nitrogen is produced from farming and the aquifers are vulnerable. In the Eden Valley in Fife, some boreholes in Devonian sandstone show a rising trend of up to 8 mg l^{-1} NO_3 per decade since the late 1970s. In the Dumfries aquifer, one public supply borehole has reacted to local over-pumping with a rise in recorded concentration from only 6 mg l^{-1} NO_3 in 1978 to over 26 mg l^{-1} NO_3 in 2002 (Robins 2002). MacDonald *et al.* (2003) further investigated rising nitrate concentrations in the Dumfries aquifer using CFC and SF_6 as residence time indicators. The work demonstrated that concentrations of NO_3 correlate with the age of the groundwater, with modern groundwater approaching 50 mg l^{-1} NO_3 whereas pre-1950s groundwater contained <10 mg l^{-1} NO_3. Overall concentrations will continue to increase in the future as the pre-1950s water is progressively depleted due to abstraction from the aquifer.

There have been a number of specific hydrochemical investigations undertaken. The first centred on groundwater provenance and age in the Strath Halladale Granite (Kay 1984). Others concentrated on specific issues: Cook *et al.* (1991) studied granite groundwaters in an area affected by acidic rainfall, Soulsby *et al.* (1998) considered the groundwater chemistry of an upland catchment, and Wood *et al.* (1999) discussed the issues surrounding mine drainage in the Midland Valley.

Groundwater use

Groundwater is widely used in Scotland, despite the abundance of surface water. Table 3 gives the approximate volumes abstracted for different uses. Since no abstraction licensing yet exists in Scotland, these volumes are only approximate, based on information from the BGS groundwater databases, Scottish Water, and the private water supply database. A significant omission from this table is the environmental use of groundwater as baseflow to rivers and in sustaining wetlands. There are in excess of 4000 boreholes across Scotland used for public and private supply, industry and agriculture, and many more (>20 000) small springs and wells used for private water supply.

TABLE 3

Average daily groundwater use in Scotland 2004. There is considerable uncertainty surrounding the amount used for agriculture and private water supplies

Use	Volume (Ml d^{-1})
Public water supply boreholes	100
Public water supply springs[a]	70
Industry	80
Agriculture	40
Private water supplies[b]	40
Total	330

[a]The volume of water from springs may be much higher as springs that feed into a reservoir are often classified as surface water

[b]There is considerable confusion surrounding the amount of groundwater used in private water supplies, this estimate is conservative.

Public water supply

Groundwater, either abstracted from boreholes or captured from springs, constitutes approximately 7% of public water supply in Scotland. This relatively small proportion, however, hides the true strategic and economic importance of groundwater (see the location of the main borehole supplies in Fig. 4). In small rural communities where less than 0.1 Ml d^{-1} is required, a borehole is an attractive alternative to piping water tens of kilometres or installing expensive treatment plants to treat peaty surface water (Grose *et al*. 1998). In 2004, there were 40 sites abstracting groundwater for public water supply. Scottish Water is increasingly exploring groundwater options for rural communities.

The main bedrock aquifers exploited for public water supply are the Permian Basin of Dumfries (Robins & Ball 2005), the Devonian aquifer in Fife (Ó Dochartaigh *et al*. 1999) and the Permian sediments in western Arran (Ball & Buckley 1998). High yielding supplies from superficial deposits are found in Fort William (Johnstone & Rennie 1991), the Spey Valley (Watt *et al*. 1987) and Howden, in the Borders (see Fig. 4).

The true volume of groundwater used for public water supply is likely to be much higher than the 7% quoted above. Many springs are captured and fed into reservoirs (e.g. the Pentland springs south of Edinburgh) before being used for public water supply: these sources are classed as surface water. In addition, baseflow from groundwater contributes up to 30% of river water (see Soulsby *et al*. 2005): in dry summers groundwater is the main component of water in rivers and therefore helps to sustain the public water supply network.

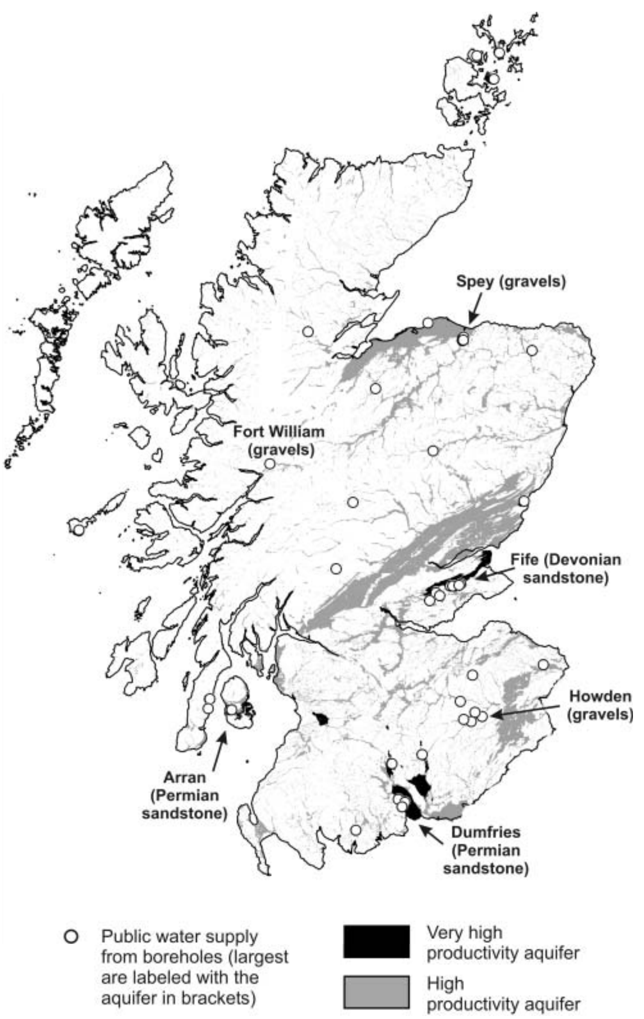

FIG. 4. Public water supply boreholes in Scotland.

Industrial use of groundwater

Groundwater has many important industrial uses, most notably for bottled water where the perception of green glens and pristine low salinity groundwaters has been used to good effect despite the vulnerability of some of these sources to anthropogenic pollution (Robins & Ferry 1992). Scottish mineral water companies supply 40% of the UK bottled water requirements, a market that has a total value of £1 billion. Both the total market, and Scotland's share, have been growing significantly over the past 10 years. The whisky industry, currently worth over £2 billion to the Scottish economy, also uses groundwater, and plays heavily on the mystery of the groundwater sources (Cribb 1998). However, the largest industrial users are for more mundane purposes: vegetable washing and processing, fish farming, golf courses and cooling in manufacturing.

Agriculture

Agriculture is an important user of groundwater in Scotland. There are approximately 200 irrigation boreholes, mainly located in eastern Scotland around Strathmore, the Borders and Aberdeenshire. These boreholes abstract only in the summer months, from June to August/September, and generally do not operate in wet years. Recent dry summers have seen a marked increase in the number of irrigation boreholes being drilled. More widely dispersed are farm supplies for cattle watering and washing in dairy, poultry or pig farms. There are probably in excess of 500 boreholes drilled for farm use, and many more make use of springs and wells.

Private water supplies

There are thought to be between 20 000 and 30 000 private water supplies in Scotland, mostly abstracting groundwater from springs, wells and boreholes. Accurate statistics for both the number of private water supplies and the volume of groundwater used are difficult to find. According to official statistics from the drinking water regulator in Scotland (DWQR 2003) there are approximately 18 000 private supplies for domestic use, and 2000 for commercial use (e.g. hotels and campsites). They estimate that 80 000 people are dependent on private water supplies for domestic use and 60 000 through commercial use. In total this amounts to approximately 40 Ml d^{-1}. Other estimates from work carried out by the Macaulay Institute for SEPA have both the number of sources and the amount abstracted considerably higher (Reid *et al.* 1999): 30 000 sources and abstraction >100 Ml d^{-1}.

The quality of water from private water supplies is a serious issue. Reid *et al.* (2003) found a high proportion of supplies in Aberdeenshire contaminated with coliforms and elevated nitrate concentrations.

Environmental use

The environmental use of groundwater is rarely documented or accounted for. Groundwater sustains river flows throughout the year and even in small upland streams may account for 30% of the flow, invaluable for sustaining salmon populations (Soulsby *et al.* 2000) and keeping streams and rivers viable over dry summers. In addition, groundwater has an important role in sustaining wetlands and fragile ecologies, such as parts of the machair (seasonally waterlogged sandy coastal plains). A further role of groundwater, rarely accounted for, is its ability to assimilate, dilute and break down contaminants and waste.

Threats to groundwater

Groundwater in Scotland is under threat from anthropogenic activity. The most pressing problems are contamination from agricultural activity and the legacy of mining in Scotland; over-abstraction of groundwater is not yet a serious problem. Figure 5 shows the location of some of the major threats to groundwater quality: mining and agricultural nitrate.

Nitrate concentrations in Scotland are elevated and, across approximately 14% of Scotland, at risk of exceeding the EU standard of 50 mg l^{-1} NO_3. Ball *et al.* (2005) describe in detail the nitrate problem in Scotland and the process for identifying nitrate-vulnerable zones (NVZs). Within these zones, new guidelines for the use of fertilizer and the spreading of slurry have been issued and should help to reverse the trend of rising nitrate. Concentrations of other agricultural contaminants, such as phosphate, pesticides and herbicides, are also elevated in several locations.

Scotland's long history of mining has left a legacy that threatens groundwater quality. Figure 5 shows the location of much of Scotland's shallow mining (<200 m) mainly for coal; the locations of metalliferous occurrences (many of which have been mined) are also shown. Contamination from the flooding of abandoned coal mines has already affected much of the groundwater in central Scotland and threatens surface water quality where the groundwater discharges at the surface (Younger 2001). The small metaliferous mines across Scotland could also lead to localized contamination of groundwater, although there has been no serious study of this issue and little understanding of the scope of the problem.

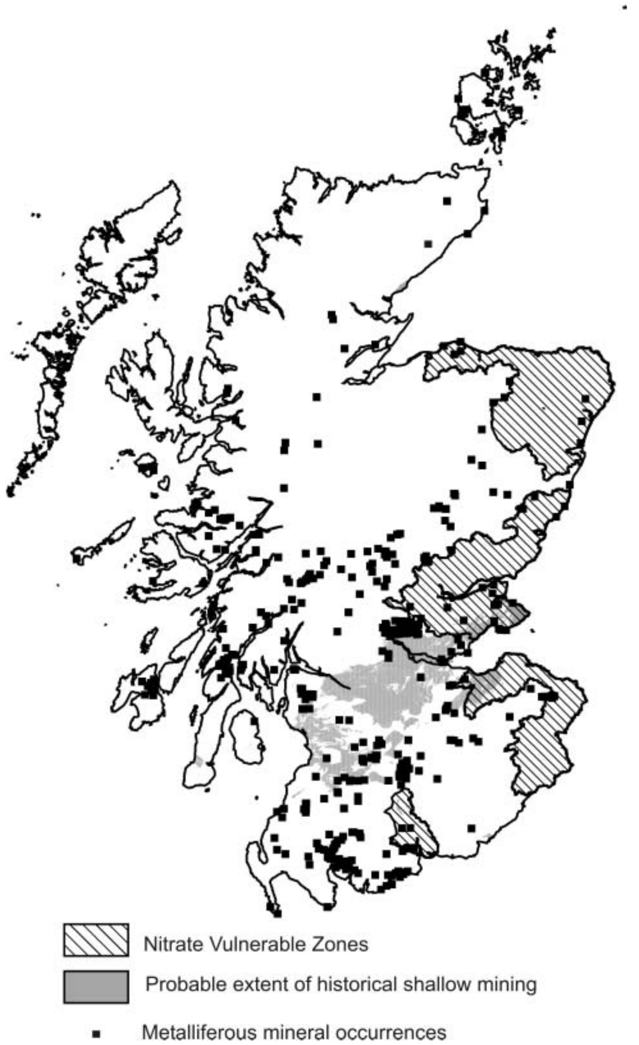

FIG. 5. The location of two of the major threats to groundwater quality in Scotland: nitrate from agriculture and contamination from mining.

Ongoing development of Scotland's land surface also threatens groundwater quality. Contaminated land, building foundations, landfill sites, septic tanks, petrol stations, road drainage and the disposal of sheep dip and other wastes all need to be managed in such a way that groundwater is protected for future generations. One of the main ways of ensuring that groundwater is taken into account in land use planning is through the use of groundwater vulnerability maps. Ó Dochartaigh *et al.* (2005) describe the development of a groundwater vulnerability screening tool for Scotland which will be used as part of the implementation of the EU Water Framework Directive in Scotland (Clews *et al.* 2005).

Conclusions

Scotland has a long history of using groundwater for private domestic supply, and more recently for public, industrial and agricultural uses. However, the development of hydrogeology as a science in Scotland started only in the 1970s and has recently been advanced by the EU Water Framework Directive.

Groundwater is present throughout much of Scotland, both in bedrock and superficial deposits. The most productive bedrock aquifers are the Permian sandstones and breccia in SW Scotland and the Devonian sandstones in Fife, Strathmore and Morayshire. Alluvium and fluvio-glacial sands and gravels also form important aquifers and provide some of Scotland's highest yielding boreholes.

There has been little systematic survey of the natural groundwater quality in Scotland, but what data exist indicate that groundwater is generally weakly mineralized with total dissolved solids in the range 100 to 500 mg l^{-1} and dominated by Ca and HCO_3. There are obvious exceptions, most noticeably in the spa towns. There are elevated concentrations of nitrate where agricultural activity is intense and high iron and manganese in some superficial deposits.

There are in excess of 4000 boreholes in Scotland and over 20 000 springs and wells used for private water supply. There are few available data on the volumes of groundwater abstracted. However, estimates suggest that the total volume may be approximately 330 megalitres per day. The volume of groundwater used in public water supply is growing annually: currently 7% of the daily 2400 megalitres per day supplied by Scottish Water is from groundwater sources.

Scottish groundwater needs to be managed and is under threat from agricultural activity, the mining legacy, septic tanks and general land development. The EU Water Framework Directive provides a useful framework to continue to use, manage and protect groundwater over the coming years.

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