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Scotland's aquifers and groundwater bodies

Groundwater Science Programme

OPEN REPORT OR/15/028

BRITISH GEOLOGICAL SURVEY

GROUNDWATER SCIENCE PROGRAMME

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Scotland's aquifers and groundwater bodies

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Artesian groundwater flowing from a public supply borehole, Arran, Scotland

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Summary

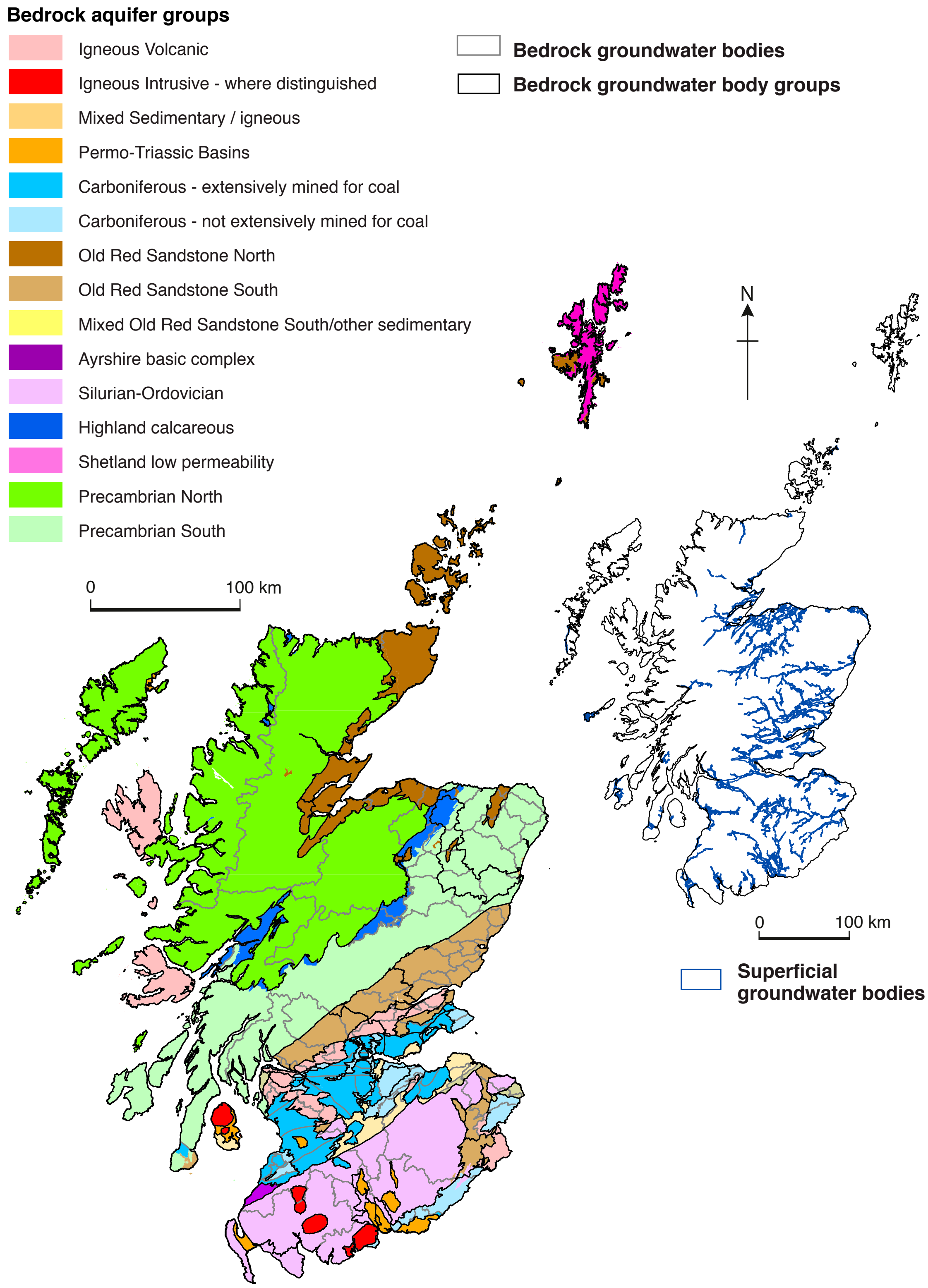
Scotland's groundwater is a highly valuable resource. The volume of groundwater is greater than the water found in our rivers and lochs, but is hidden from sight beneath our feet. Groundwater underpins Scotland's private drinking water supplies and provides reliable strategic public water supply to many rural towns; it also sustains the bottled water and whisky industries and is relied upon for irrigation by many farmers. Groundwater also provides many important environmental functions, providing at least 30% of the flow in most Scottish rivers, and maintaining many precious ecosystems.

Groundwater management in Scotland is delivered primarily through the River Basin Management framework. Groundwater bodies are a key component of this, defining areas of groundwater that behave in a similar way, both naturally and in response to pressures from human activity. Groundwater bodies provide a risk-based framework for prioritising action to remediate problems, and preventing new problems.

Scottish groundwater bodies have undergone a major review for the second River Basin Management cycle, using the latest geological information from the British Geological Survey (BGS), and improved experience of groundwater management from the Scottish Environment Protection Agency (SEPA). A key new development is the separation of groundwater bodies into two layers: a shallow layer of superficial groundwater bodies, and a deep layer of bedrock groundwater bodies. This is important in order to help target action. Shallow groundwater bodies are more at risk from activities such as agriculture, whilst deeper bodies are more at risk from activities such as mining.

This report provides a summary of the results of the review, which has been a collaborative project by BGS and SEPA. It documents the process of how the groundwater bodies and aquifers of Scotland were defined, and describes the hydrogeology of each of the main aquifers. The report can therefore be used as a technical introduction to the hydrogeology of Scotland. The two maps overleaf illustrate Scotland's aquifers and the latest iteration of groundwater bodies as developed during this project.

Groundwater in Scotland is widely used for many purposes.



Scotland's aquifers and groundwater bodies: deep bedrock (main map) and shallow superficial (inset). Contains OS data © Crown Copyright and database rights [2015].

1 Introduction

1.1 OVERVIEW—USING THIS REPORT

This report describes the results of a collaborative project between BGS and SEPA to delineate the groundwater bodies within Scotland and describe the different aquifers in the country. There were three main aims:

1. To explain how Scotland's groundwater bodies were delineated. These bodies are a vital component of Scotland's River Basin Management planning which is the means by which the water environment is managed in Scotland.
2. To provide a summary of the current understanding of Scotland's aquifers at a regional scale, with references to more detailed information where available.
3. To provide information to underpin Scotland's submissions to the European Union to demonstrate compliance with the Water Framework Directive.

This section (Section 1) provides context and a brief introduction to groundwater and groundwater management in Scotland. It is written for policy makers and those with a role in delivering sustainable development. Sections 2 to 4 provide technical details of the development of aquifer groups and groundwater bodies. Section 5 presents an overview of the hydrogeology of each of the aquifer groups in Scotland. It is written in the form of a manual for those with some technical groundwater (hydrogeological) knowledge, but includes summaries which may be useful for non hydrogeologists.

1.2 GROUNDWATER IN SCOTLAND

Scotland's groundwater is described in some detail on Scotland's Environment website (Scottish Government 2014a), with contributions from the British Geological Survey (BGS), the Scottish Environment Protection Agency (SEPA) and the Drinking Water Quality Regulator (DWQR). Here we provide a summary.

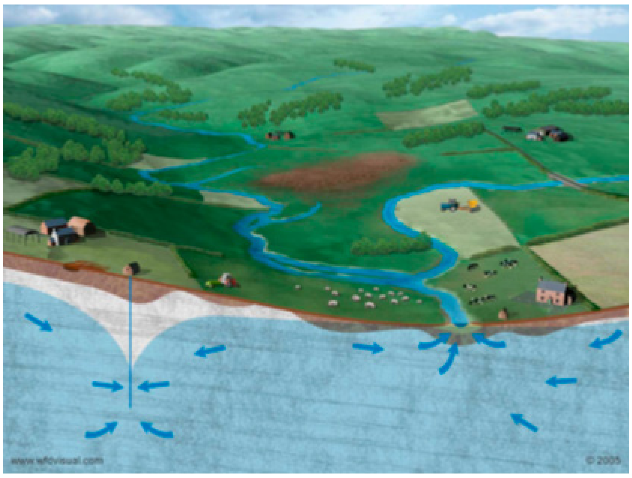


Figure 1 Groundwater flows beneath our feet to wells (boreholes), springs, rivers and wetlands. Source: www.wfdvisual.com/.

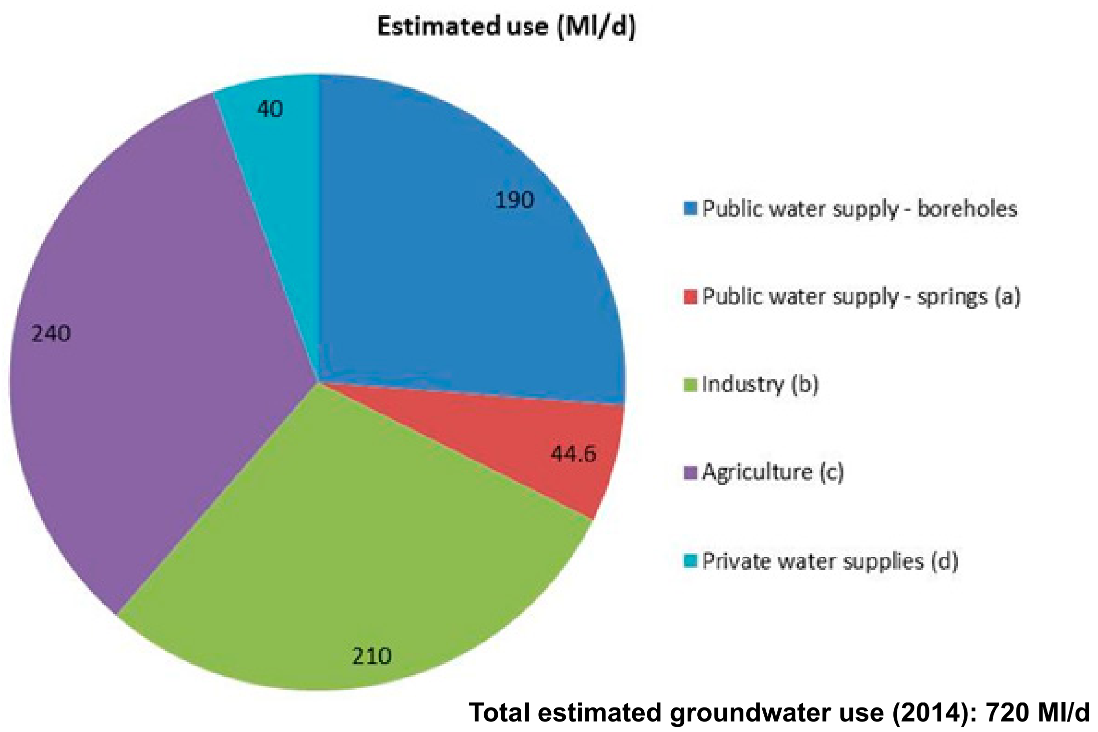
Almost all groundwater starts life as rainfall. Some rain is taken up by plants, some runs over the land surface or through soils to rivers, and some soaks down through the soil into aquifers. Below the water table, all the spaces in the soil or rock are completely filled with water — groundwater (Figure 1). In Scotland, groundwater occurs almost everywhere beneath our feet, and the water table is usually within 10 m of the ground surface. As a store of water that can provide a reliable source of water for drinking and other purposes, groundwater is often accessible close to where it is required, and is cheaper to treat than surface water in lochs and/or reservoirs. In rural areas in particular, groundwater is a vital water source, and it plays an important role in Scotland's economy.

Groundwater's value to society is partly in its provision of drinking water, providing 73 per cent of Scotland's private water and 5 per cent of public water supplies, for at least 330 000 people in total (DWQR, 2013). Groundwater for public water supply is abstracted from approximately 100 boreholes and springs across Scotland, and supplies some of our major rural towns. More than 4000 boreholes, and some large springs, are used for large private, industrial or agricultural supplies; and many more — approximately 20 000 — boreholes, small springs and wells provide private water supplies for at least 80 000 people (MacDonald et al., 2005, DWQR, 2013).

Groundwater is also very important for Scotland's economy. Groundwater provides almost all of the water sold by the bottled water industry (DWQR, 2013); and underpins Scotland's whisky exports, providing 70 per cent of the water bottled by the whisky distilling industry. It is widely used in other industries, such as brewing and fish farming, and for agricultural and recreational (including golf course) irrigation. The approximate volumes of groundwater abstracted for different uses are shown in Figure 2.

Groundwater plays an important environmental role, supporting surface water ecosystems through baseflow to rivers and lochs throughout the year. This is particularly critical in dry summers, and in the east of Scotland where lochs do not provide significant alternative sources of water storage. On average, it is estimated that groundwater sustains more than a third of the annual flow in all river bodies, even in small upland streams, rising to over 60 per cent in some rivers in drier eastern Scotland (Gustard et al., 1987). Groundwater baseflow to rivers is invaluable in maintaining healthy river ecosystems, including for salmon populations (Soulsby et al., 2000) — hence indirectly supporting another part of the Scottish economy — and in sustaining wetlands and fragile ecosystems, such as our coastal machairs.

Another role of groundwater is its ability to assimilate, dilute and break down contaminants and waste. One example is domestic septic tank discharges, which are specifically designed to make use of the ability of soil and groundwater to break down microbes and nutrients. By accepting excess surface water flows, groundwater also helps to mitigate flooding, for example through the increased use of infiltration-based sustainable drainage schemes (SuDS).



(a) The volume of water from springs may be much higher, as springs that feed into reservoirs are often classified as surface water
(b) Industrial use includes distilling and mineral water
(c) Seasonal use
(d) There is considerable uncertainty surrounding the amount of groundwater used in private water supplies: this estimate is conservative

Figure 2 Groundwater use in Scotland, 2014. Much of Scotland's rural population relies on groundwater, and it plays a vital role in Scotland's economy. Left: artesian public water supply borehole, Arran; centre: Wells of Dee spring, headwaters of the River Dee; right: groundwater is fundamental to Scotland's mineral water industry, and important in the whisky industry.

1.3 GROUNDWATER MANAGEMENT AND GROUNDWATER BODIES IN SCOTLAND

Groundwater occurs across the whole of Scotland. In some areas, groundwater is more at risk of contamination or overabstraction than in others, due both to the pressures put on groundwater and also the inherent nature of the soil and geology. More than 80 per cent of Scotland's groundwater resources are considered to be in good condition (Scottish Government, 2014a); of the remainder, three main areas of impact are observed:

- larger-scale pollution impacts in eastern and southern Scotland and the Central Belt, from legacy industrial activity and agricultural nutrients;
- more localised and dispersed impacts from isolated instances of poor practice in waste management; and
- localised instances of overabstraction

To help manage groundwater it is important to define the areas most vulnerable to contamination or overexploitation, and areas that are already showing degradation. The process of definition is based on two concepts: aquifers and groundwater bodies. An aquifer is a subsurface geological layer which is sufficiently permeable to allow a significant flow or abstraction of groundwater. In Scotland, due to its particular geological history and to its rainfall, all rock types and most unconsolidated superficial deposits can be aquifers. Groundwater that can be abstracted for human use therefore occurs underneath most of Scotland.

However, Scotland's aquifers vary markedly depending on their hydraulic characteristics, natural geochemistry, thickness, and extent (MacDonald et al., 2005). Some aquifers are capable only of supplying small amounts of groundwater, enough to support dispersed small domestic demand, whilst others can provide yields sufficient to supply towns such as Dumfries and Aviemore. Many aquifers act as natural filters and are able to provide natural protection from pollutants, whilst others are much more vulnerable. Some aquifers have large natural storage which can buffer low rainfall over periods of several months or years, whilst others cannot. Particular aquifers are under much more pressure from industrial pressures than others. These differences all mean they require different management strategies.

To address this, Scotland's *aquifers* have been first differentiated and characterised on the basis of relevant criteria, and then subdivided into management units, called *groundwater bodies*. These delineations are a helpful tool for managing groundwater, and the identification of groundwater bodies is a requirement of the EU Water Framework Directive (2000/60/EC). The remainder of this report is focussed on explaining the key differences between Scotland's aquifers.

Groundwater protection in Scotland

Scotland's groundwater, rivers, lochs, and coastal waters have all been subdivided into water bodies. These bodies form the basis of River Basin Management Planning in Scotland. Groundwater is different from surface and coastal waters in a number of ways:

- Groundwater is a hidden resource, and poorly understood by the public.
- Groundwater is the key resource for small, widely distributed private drinking water supplies, for which expensive forms of treatment are not practical.
- Groundwater occurs almost everywhere below the land surface of Scotland, at various depths.
- Groundwater is more resilient to degradation than surface water, but, if degraded, the effects can last for decades or centuries.
- Groundwater is difficult and expensive to monitor.

For these reasons, in groundwater management there is a significant emphasis on preventing problems arising, rather than treating the impacts. However, because groundwater occurs almost everywhere and is widely relied on, it is not practical to attempt to eliminate all pressures on and risks to groundwater. The greatest risk is posed by hazardous chemical pollutants, and so a key aim is to prevent these from entering groundwater in the first place. For lower risk pollutants, and for abstraction pressures, a risk based approach to regulation means assessing each new pressure against the capacity of the groundwater body to assimilate the pressure. To address historic problems, the status of Scotland's groundwater bodies are classified (and reclassified) on a regular basis, into one of five categories: high, good, moderate, poor or bad; those bodies at risk of deteriorating status are also identified. Where the status of a groundwater body is identified as poor or at risk of deterioration, these bodies are prioritised for action to improve the situation. More details can be found in the River Basin Management Plans for Scotland (SEPA, 2009a).

Groundwater bodies are therefore the fundamental basis for both identifying existing problems of groundwater management in Scotland, and for preventing new risks to groundwater arising. They help to inform decisions on where groundwater monitoring is required in order to help clarify risks and demonstrate that any actions taken are effective.

The Scottish Environment Protection Agency (SEPA) is responsible for the regulation of most issues related to groundwater in Scotland. The key pieces of primary legislation in this regard are the European Water Framework Directive (WFD) (2000/60/EC) and the Groundwater Directive (2006/118/EC). These establish a series of environmental objectives for groundwater that must be achieved within a framework protecting the wider water environment and ecosystem health. More information on the legislation that SEPA implements, and on other authorities involved in regulation, can be found in the River Basin Management Plans for Scotland and on Scotland's Environment Website (Scottish Government, 2014b).

2 Data sources

The key sources of data and information used to develop the aquifer maps and groundwater bodies in Scotland are described in this section. Digital geological maps were used directly to form the basis of the linework of the aquifer groups and subsequent groundwater bodies. Maps of aquifer productivity, groundwater vulnerability and hydrogeology, and the hydrogeological understanding that they encapsulate, helped to inform the classification of each aquifer.

2.1 GEOLOGICAL MAPS

Digital geological maps for Scotland are produced as part of the BGS DiGMapGB onshore datasets (http://www.bgs.ac.uk/products/digitalmaps/digmapgb.html), which are based on the different series of published BGS geological maps. The DiGMapGB datasets are available as vector data at a variety of scales and in a variety of formats in which they are structured into themes primarily for use in geographical information systems (GIS), where they can be integrated with other types of spatial data for analysis and problem solving in many earth-science-related issues.

The main geological mapping dataset used for Scottish aquifer classification is the British Geological Survey (BGS) DiGMapGB-50, at 1:50 000 scale (bedrock and superficial deposits). The DiGMapGB-50 data typically provide a digital version of the geology as shown on the map face of the published 1:50 000 scale paper map. No topography is shown. Most geological units are represented by polygons in the data and are arranged in up to four themes, as available: Bedrock (formerly 'solid' geology); Superficial (formerly 'drift' deposits or Quaternary); Mass Movement (mostly landslide); and Artificial (or artificially modified or man-made ground). Geological units such as thin coal seams and fossil bands and other features such as faults, mineral veins and some landforms, which are all shown as lines on the published maps, are held in a fifth, Linear, theme.

The DiGMapGB-50 dataset forms the basis of the aquifer productivity (Section 2.2), bedrock aquifer groups (Section 3.2), superficial aquifer groups (Section 3.3), and subsequent groundwater body (Section 4) classifications. The larger scale BGS DiGMapGB-625 1:625 000 (bedrock) geological mapping dataset has also been used for a separate project to subdivide bedrock aquifers using slightly different criteria, in order to highlight specific hydrochemical issues and controls (Section 2.4).

2.2 AQUIFER PRODUCTIVITY

GIS-enabled maps of aquifer productivity for bedrock and superficial aquifers in Scotland were first developed by BGS in 2004 based on the 1:50 000 scale DigMapGB dataset (MacDonald et al., 2004, 2005), and refined (Version 2) in 2011 (Ó Dochartaigh et al., 2015a).The maps categorise two key physical properties of aquifers: the dominant groundwater flow type in an aquifer, and the aquifer's potential for sustaining various levels of borehole water supply. The maps are designed for use at a scale of 1:100 000, making them suitable for regional assessments.

The bedrock aquifer productivity map has three groundwater flow categories: significant intergranular flow; mixed fracture/intergranular flow; and fracture flow. In Scotland, most groundwater flow in bedrock aquifers is through fractures; intergranular flow is important in only a few sandstone formations. The bedrock map has five aquifer productivity classes: very high, high, moderate, low and very low, which are based on a judgement of the typical long term sustainable abstraction rate from a properly sited, constructed and developed borehole (Figure 3).

All superficial deposits aquifers in Scotland are assumed to have primarily intergranular groundwater flow. The superficial deposits productivity map has four productivity classes (high; moderate to high; moderate; and a category to signify that a deposit is 'not a significant aquifer'), based on a judgement of the typical long term sustainable abstraction rate from a properly sited, constructed and developed borehole or a group of boreholes (Figure 3).

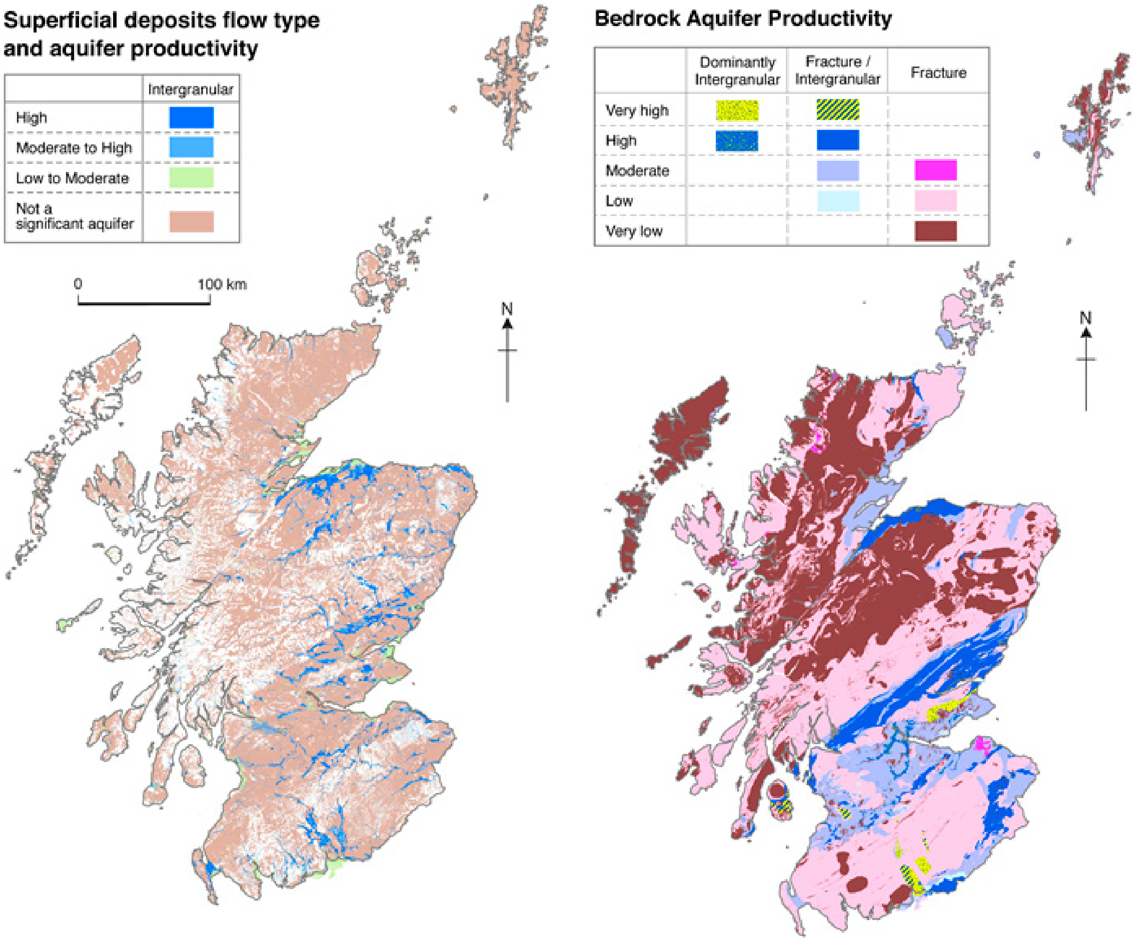


Figure 3 Superficial deposits and bedrock aquifer productivity maps for Scotland (from Ó Dochartaigh et al., 2015a). Contains OS data © Crown Copyright and database rights [2015].

2.3 GROUNDWATER VULNERABILITY

A digital groundwater vulnerability map for Scotland was first produced by BGS in 2004 (Ó Dochartaigh et al., 2005) and refined (Version 2) in 2011 (Ó Dochartaigh et al., 2015b) (Figure 4). The map shows the relative vulnerability of groundwater at the uppermost water table to contamination. It is based on a number of different datasets, primarily 1:50 000 scale digital bedrock and superficial deposits geology (DiGMapGB-50), aquifer productivity (from the maps described in Section 2.2) and permeability, superficial deposits thickness (derived from BGS borehole records), depth to water table (from BGS datasets), and aspects of soil thickness, permeability and saturation (from the Hydrology of Soil Type (HOST) dataset produced by the James Hutton Institute).

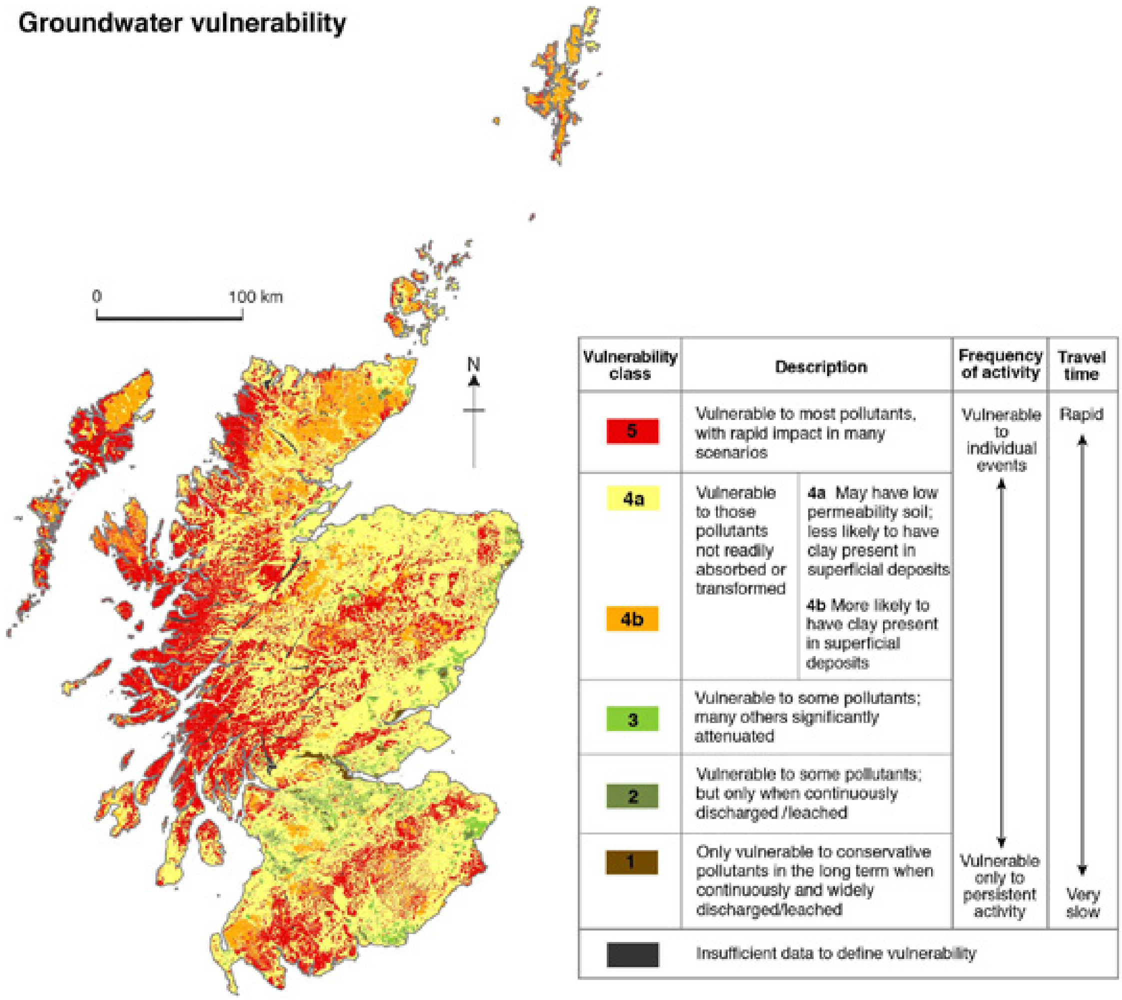


Figure 4 Groundwater vulnerability map of Scotland (Ó Dochartaigh et al., 2005; Ó Dochartaigh et al., 2015b). Contains OS data © Crown Copyright and database rights [2015].

2.4 GROUNDWATER CHEMISTRY

The project *Baseline Scotland*, which was jointly conceived and funded by BGS and SEPA in 2004, is improving data availability and general understanding of the natural chemistry of groundwater in Scotland's bedrock aquifers. Nearly 650 analyses of groundwater chemistry have been interpreted to characterise the ranges in natural background groundwater quality across Scotland. Parameters measured include major and trace inorganic chemistry, dissolved organic carbon, stable isotopes and residence time indicators. The new groundwater chemistry information is being used in a number of ways, including helping to establish threshold values as a basis for assessing the chemical and quantitative status of groundwater bodies as part of Water Framework Directive requirements.

Aquifer geology is a key control on groundwater chemistry. For the purposes of interpreting and characterising Scottish groundwater chemistry, bedrock aquifers were categorised according to their overall influence on groundwater chemistry, using a very similar methodology to that used to subdivide aquifer groups, but based on 1:625 000 scale geological linework (DiGMapGB-625), and using slightly different criteria to highlight specific hydrochemical issues and controls. One main difference was to maintain the distinction of major igneous intrusions (mostly granitic) across the Highlands in dominantly Precambrian metamorphic or, in Skye and Mull, volcanic terrain, because the available data indicate that groundwater chemistry can vary noticeably between these rock types, although they can have similar physical aquifer characteristics.

A full report on the baseline chemistry of Scotland's bedrock groundwater is in preparation. A statistical summary of selected chemical parameters for each of the aquifer groups in this report (Section 5.2 to 5.12).

3 Delineating aquifers in Scotland

3.1 INTRODUCTION

An aquifer is a geological layer that is porous and permeable enough so that it can yield a significant quantity of water to a borehole, well or spring, or provide significant baseflow to rivers, lochs or other surface water bodies. The characteristics of an aquifer – e.g., how productive it is, or the baseline chemistry of groundwater within it – are largely controlled by geology. Therefore, as a precursor to delineating groundwater bodies, Scotland's geology was first classified into broad aquifer groups, according to their physical aquifer properties and controls on natural groundwater chemistry.

Aquifer groups were classified consistently across Scotland based on 1:50 000 scale 2D digital geological maps produced by the British Geological Survey (DiGMap-50 Version 5.18). These show the lateral extent and boundaries of the uppermost geological units: for superficial deposits, this is the ground surface; for bedrock, it is either the ground surface (if bedrock is exposed at the ground surface) or rockhead (if bedrock is overlain by superficial deposits).

These 2D maps don't show how geological units change with depth. By using both superficial and bedrock maps, we can incorporate a 3D element to aquifer and subsequent groundwater body classification. However, this doesn't show where bedrock geology changes with depth. At present, 3D geological models are not available for most of Scotland, and so it is not possible to develop a consistent fully 3D methodology for aquifer classification. However, across most of Scotland, depth changes in bedrock geology do not have significant impacts on groundwater, as they do not cause significant changes in aquifer properties or controls on groundwater chemistry. There are a few cases where bedrock changes with depth are known to have significant groundwater impacts, and therefore to have significant implications for groundwater management, and these have been accounted for in the classification of groundwater body boundaries (Section 4).

The classification of aquifer groups is described in Sections 3.2 (bedrock) and 3.3 (superficial deposits).

3.2 BEDROCK AQUIFERS

Scotland's bedrock geology was classified into broad aquifer groups which have distinctly different physical aquifer properties and/or controls on natural groundwater chemistry. The aquifer groups are shown in Figure 5 and listed in Table 1. The characteristics of the aquifers are described in Section 5.

Bedrock aquifers were grouped first according to their rock type – calcareous rocks; dominantly noncalcareous sedimentary rocks; and fractured igneous or metamorphic ('hard') rocks (Table 1). Within these categories, they were further subdivided based on the aquifer productivity and other hydrogeological maps and data available for Scotland (Section 2). Across Scotland, the age of the rocks is a key control on aquifer productivity, and geological age was therefore the main criterion on which aquifer boundaries were drawn. There were two exceptions:

- In some cases, aquifers of particular ages have been subdivided. This was either because parts of the aquifer have been subject to significant human alteration (in particular, treating separately Carboniferous aquifers which have been extensively mined for coal), or because the rocks of the same age and type are significantly different in different parts of Scotland (for example, Old Red Sandstone rocks, which are divided between northern and southern/central Scotland; and Precambrian rocks, which are also divided into a northern and a southern group) (Table 1).

- In some cases, areas of complex geology have been simplified in order to define aquifers suitable for effective management. Some small areas with very complex geology have been combined and categorised as mixed aquifer types. These are shown on the map in Figure 5. In other areas where many small outcrops of one rock type are surrounded by a dominant rock of another type, a minimum area of 10 km^2 was defined as the lower limit of a hydraulically significant aquifer, following UK-wide guidance (UKTAG, 2011). Any small outcrops of less than 10 km^2 in area have been incorporated into the surrounding aquifer.

The rocks underneath large lochs and other surface water bodies are generally not mapped on British Geological Survey geological maps. For the purposes of defining aquifers and groundwater bodies, geological boundaries were extrapolated across lochs.

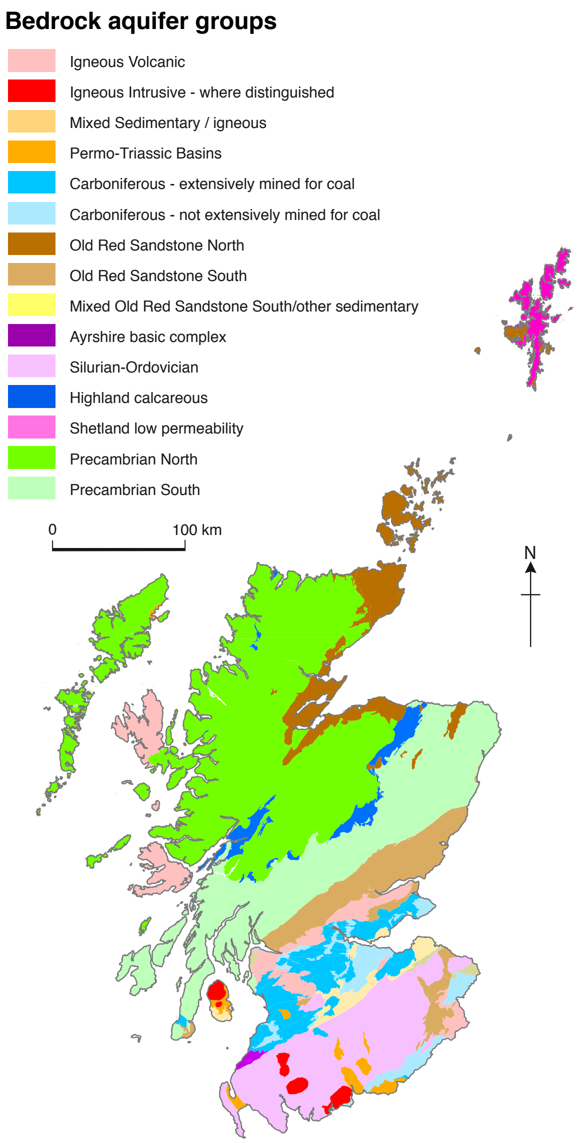


Figure 5 Bedrock aquifer groups in Scotland. Contains OS data © Crown Copyright and database rights [2015].

Table 1 Summary of bedrock aquifer groups in Scotland.

Aquifer type	Aquifer group
Sedimentary aquifers extensively mined for coal (dominantly noncalcareous)	Carboniferous – extensively mined for coal
Sedimentary aquifers (dominantly noncalcareous)	Carboniferous – not extensively mined for coal
	Old Red Sandstone (North and South)
	Permo-Triassic
	Mixed Old Red Sandstone South/other sedimentary (dominantly Carboniferous – not extensively mined for coal, or Silurian–Ordovician)
	Mixed Igneous/Sedimentary
Fractured igneous and/or metamorphic ('hard') rock aquifers	Igneous Intrusive – where distinguished (only large outcrops surrounded by aquifers with significantly different hydrogeological properties – e.g. Permo-Triassic – are distinguished. Smaller outcrops and those surrounded by aquifers with similar hydrogeological properties – e.g. Precambrian – are not distinguished)
	Igneous Volcanic
	Silurian–Ordovician
	Precambrian (North and South)
	Shetland low permeability (Precambrian, Highland calcareous, igneous intrusive and volcanic)
	Ayrshire basic complex (Silurian–Ordovician ophiolite complex with Silurian–Ordovician, igneous intrusive and volcanic)
Calcareous aquifers	Highland calcareous

3.3 SUPERFICIAL AQUIFERS

Virtually all superficial deposit – or unconsolidated – aquifers in Scotland were deposited in the last 20 000 years during the Quaternary geological period, during and after the latter part of the last glacial period. The only exceptions are small areas in Aberdeenshire where significant thicknesses of in-situ weathered bedrock have been preserved. This kind of preservation is rare in northern Britain, where more typically glacial processes during the Quaternary eroded any weathered bedrock. The principal superficial aquifers in Scotland are deposits of gravel and coarse sand, including alluvial sand and gravel, raised beach and blown sand deposits, and glaciofluvial sand and gravel.

The productivity of superficial aquifers is primarily defined by their lithology, which both controls aquifer permeability, and is one of the main controls on aquifer storage potential. The aquifers can also be defined by the different processes of aquifer sediment transport and deposition (e.g. glaciofluvial, alluvial or marine). These processes are a major control both on aquifer lithology and on 3D geometry (the lateral extent and thickness), which is the other main control on aquifer storage potential. Some thick, permeable superficial deposits deposited in deeply weathered bedrock channels are overlain by low permeability nonaquifer deposits, and are therefore not mapped at the ground surface, but may form highly productive aquifers.

Three superficial aquifer groups are therefore defined in Scotland, according to their age and provenance (Quaternary unconsolidated or pre-Quaternary weathered) and whether they crop out at the ground surface or are hidden. The extent of these aquifers is shown in the map in Figure 6, and their characteristics are summarised in Table 2.

The superficial aquifer map is largely based on the superficial deposits productivity map for Scotland (Figure 1) which shows the distribution and productivity of all superficial aquifers cropping out at the ground surface. Only superficial deposits categorised as having high or moderate to high productivity (Figure 3) have been classed as superficial aquifers. Included with these aquifers are significant buried superficial aquifers, which are not shown on 2D geological maps, and the significant areas of in-situ weathered bedrock in north-east Scotland. This map of superficial aquifer groups was used as the starting point for delineating superficial groundwater bodies (Section 4.3).

Table 2 Superficial aquifer groups in Scotland.

Aquifer group	Description
Quaternary aquifers cropping out at ground surface	Significant outcrop/thickness of unconsolidated Quaternary deposits that have been eroded and transported, generally by rivers, ice or the sea.
Buried Quaternary aquifers ('buried channels')	A subset of Quaternary aquifers, typically forming thick sequences, generally of glaciofluvial gravels and sands, which have infilled deep bedrock channels, but are covered by nonaquifer deposits and therefore not shown on 2D maps. Only significant in parts of the Central Belt.
Weathered bedrock	Significant thicknesses of in-situ weathered bedrock. Found in Aberdeenshire where Tertiary weathering of intrusive igneous and Precambrian rocks has not been eroded and removed by Quaternary glacial processes.

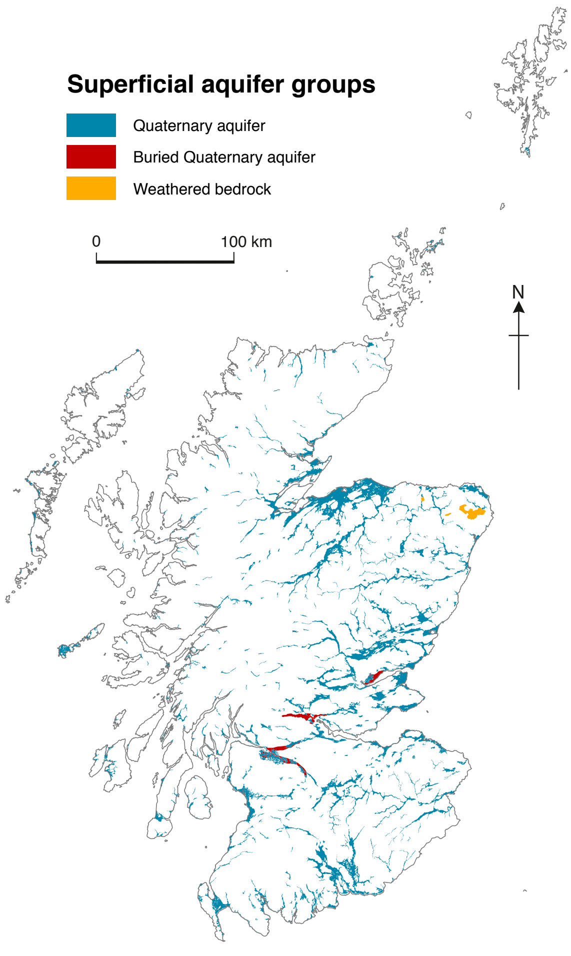


Figure 6 Superficial aquifer groups in Scotland. Contains OS data © Crown Copyright and database rights [2015].

4 Groundwater bodies in Scotland

4.1 INTRODUCTION

A groundwater body is a groundwater management unit required by the EU Water Framework Directive (2000/60/EC), defined according to Article 2.12 of that Directive as 'a distinct volume of groundwater within an aquifer or aquifers'. Delineating and characterising groundwater bodies requires knowledge of the hydrogeology and groundwater resources of the relevant aquifers.

This report describes the second revision of groundwater bodies in Scotland since 2005, as part of the ongoing River Basin Management cycle. The changes shown in this report incorporate lessons learned from the management process to date, and the availability of new and improved data and information. The most significant new development is the separation of groundwater bodies into two vertical layers: a shallow layer of superficial groundwater bodies, and a deep layer of bedrock groundwater bodies. This is important in order to help target action. Shallow groundwater bodies are more at risk from activities such as agriculture, while deeper bodies are more at risk from activities such as mining.

The groundwater bodies have been grouped to form larger areas – termed 'groundwater body groups' – for the specific purpose of assessing the risk to groundwater from nitrate. This has been done by grouping groundwater bodies with similar bedrock and superficial geology, soil, land use pressure, and water quality monitoring data, such that the groundwater bodies in a groundwater body group all show similar concentrations of nitrate in groundwater. Aggregating a large number of water quality monitoring results across a groundwater body group allows for more confidence in subsequent risk assessments.

For the latest revision, described in this report, the primary basis of the groundwater bodies is the definition of aquifer groups and their hydrogeological characteristics, as defined and described in Sections 3 and 5, using the latest 1:50 000 digital geological maps (DigMap-50, Version 5.18), supplemented by other datasets described in Section 2 and by geological expert knowledge from BGS geologists. Where necessary, the aquifer groups have been subdivided or grouped together to allow for more effective groundwater management, as described in Section 4.2 (bedrock groundwater bodies) and Section 4.3 (superficial groundwater bodies).

4.2 BEDROCK GROUNDWATER BODIES

4.2.1 General methodology for delineating groundwater bodies

The bedrock aquifers shown in the map in Figure 5 are the starting point for the delineation and characterisation of bedrock groundwater bodies in Scotland. Groundwater bodies and groups of bodies are shown in Figure 7. The aquifers are described in detail in Section 5.

The way these aquifers are defined reflects key groundwater flow characteristics which are, in turn, the main drivers for differences in groundwater management approaches. The aquifers are therefore the key building blocks of groundwater bodies, and in most cases, groundwater bodies follow aquifer boundaries. Aquifers have only been subdivided into smaller groundwater bodies, or amalgamated into larger bodies, where necessary or appropriate for particular management reasons. The criteria for further subdivision that were adopted in this revision were as follows:

- Areas of higher pressure from human activity, mostly driven by diffuse pressures from mining and agriculture.
  - Mining: BGS and Coal Authority information were used to identify deep coal-fields, extensive areas of historical oil shale mining, and clusters of open cast mining sites. In some parts of the Central Belt, Carboniferous sedimentary rocks that have been extensively mined for coal occur at depth below Carboniferous rocks that don't contain significant coals and have not seen extensive coal mining. The geological and bedrock aquifer maps only show the rocks that crop out at the surface. In such cases, where the 2D maps do not reflect the 3D geology, and that difference has significant impacts for groundwater and groundwater management, groundwater bodies have been delineated so as to also reflect the deeper geology. Additionally, in some areas significant oil shale mining, which can have significant impacts on groundwater, is known to have occurred in Carboniferous rocks which have not been extensively mined for coal, and this has been incorporated into the groundwater body delineation.
  - Agriculture: relative differences in the degree of nitrate loading, soil type, agricultural land capability, and topography were taken as broad measures of farming intensity. Soil type, land capability and nitrate information were obtained from the James Hutton Institute. Decisions were also influenced by SEPA's knowledge of the location of clusters of agricultural groundwater abstraction and significant point sources of pollution.
- Differences in management of pressures, which were driven by River Basin boundaries and by Advisory Group areas of responsibility. Area Advisory Groups are a key administrative component underpinning River Basin Planning. More details can be found in the River Basin Management Plans for Scotland. Scotland's first river basin management plans were published in 2009, and the second are due to be published by the end of 2015 (SEPA, 2015).

In all cases, groundwater bodies were subdivided based on hydraulic criteria, in accordance with UK-wide guidance (UKTAG, 2011). This means that groundwater body boundaries represent groundwater flow boundaries. Two methods of subdivision were used:

Surface water catchment boundaries. This was used for aquifers where groundwater flow is usually controlled by topography (Table 3). The main river catchment boundaries were used as the basic subdivision. In areas with more pressures on groundwater, these were further subdivided on the basis of tributary catchments. Where the intersection of catchment and geological boundaries produced very small, 'mosaic', subdivisions, these were simplified so that the minimum groundwater body size is 10 km^2, to define hydrologically sensible groundwater bodies of manageable size. These situations were dealt with on a case-by-case basis. Geological criteria usually took preference, meaning that some groundwater bodies cross catchment boundaries. There are also a very small number of 'multipart' groundwater bodies, in which separate outcrops of similar geology were assigned to the same body, although they may be separated by a few kilometres.

Geological and structural features, such as faults and folds. This was used for aquifers where groundwater flow is usually controlled by geology (Table 3). Appendix 1 provides more information.

Where surface water catchment boundaries were used to define aquifer subdivisions, SEPA carried out the subdivision; where geological criteria were used, BGS carried out the subdivision.

Where there is no reason for subdividing bedrock aquifers, groundwater bodies can be large. Some bodies in areas of lower risks to groundwater are over 500 km^2. In areas of higher risk, 100 to 200 km^2 is more typical. A minimum area of 10 km^2 was used for all groundwater bodies, except for:

- islands smaller than 10 km^2 which have a population of more than 50 people, or
- geological units smaller than 10 km^2 which support a key feature such as a large drinking water abstraction or a wetland.

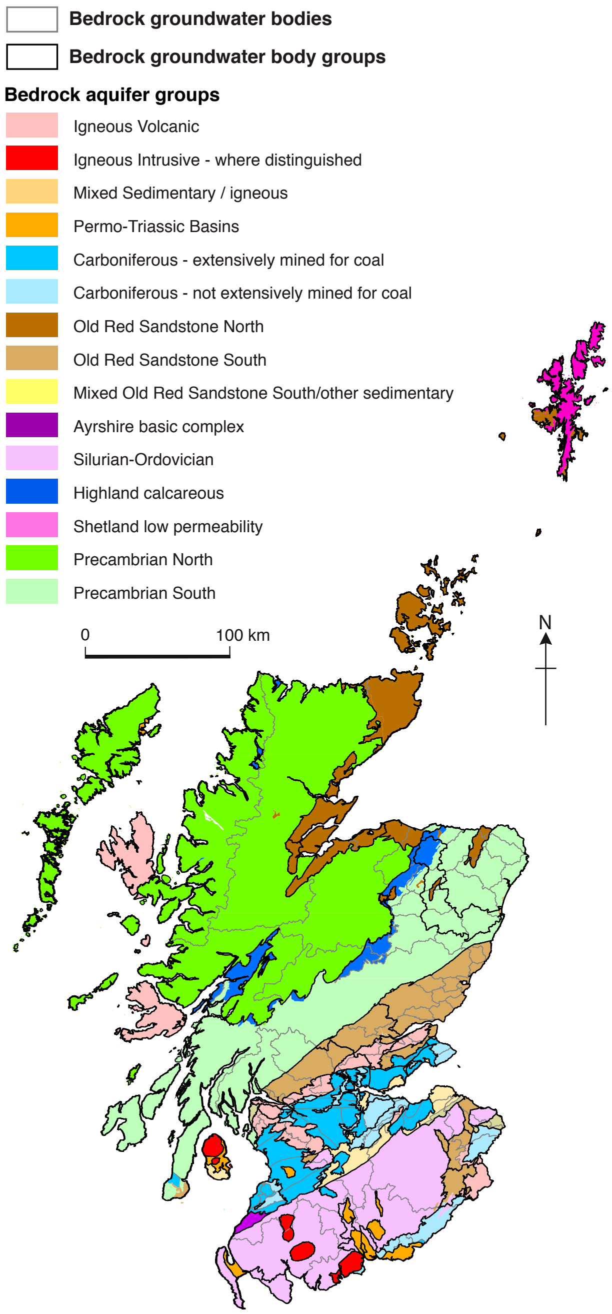


Figure 7 Bedrock groundwater bodies in Scotland.
Contains OS data © Crown Copyright and database rights [2015].

4.3 SUPERFICIAL GROUNDWATER BODIES IN SCOTLAND

The boundaries of superficial aquifers (Section 3.3) were used as the basis for defining superficial groundwater bodies in Scotland. Superficial groundwater bodies are shown in Figure 8.

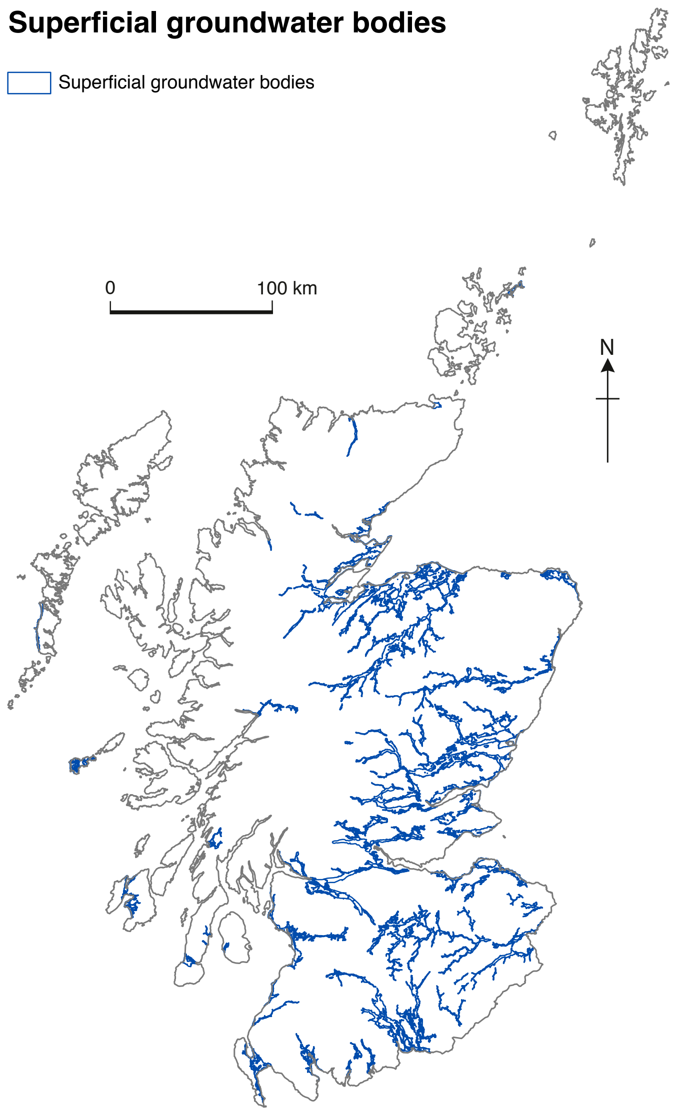


Figure 8 Superficial groundwater bodies in Scotland. Contains OS data © Crown Copyright and database rights [2015].

The superficial aquifers are defined based on their hydraulic properties (permeability and storage) and 3D extent. These characteristics drive differences in the approach to groundwater management and to delineating superficial groundwater bodies. A key feature of superficial aquifers, in contrast to bedrock aquifers, is their scale and distribution: they typically form smaller outcrops which are more widely distributed (Figure 6). The main issue during the process of defining superficial groundwater bodies was to exclude small and/or narrow and/or thin outcrops of superficial deposits, which are unlikely to form significant aquifers which require active management. This includes narrow linear deposits along minor valleys, even where these are connected to more extensive deposits in major valleys. This process is summarised as follows:

- All superficial aquifers with an area of less than 1km^2 were removed. Where the total area of a superficial body in a catchment was less than 10km^2, all areas were deleted unless there was a clear feature dependent on groundwater such as a large drinking water abstraction or a wetland.
- Where superficial deposit outcrops are so small or their aquifer productivity so uncertain that they were not considered to function as a separate aquifer from the bedrock, the bedrock and superficial bodies were merged. This was particularly the case in parts of Aberdeenshire where alluvial and glaciofluvial deposits and weathered bedrock were merged with the underlying bedrock. In effect, this removed the superficial bodies from these areas, leaving only the bedrock body underneath.
- Superficial aquifers were subdivided using surface water catchments. The main river catchments boundaries were used as the basic subdivision. In very large catchments, or areas of higher risk to groundwater, these were further subdivided on the basis of tributary catchments.
- Where the resulting bodies crossed bedrock groundwater body boundaries, the superficial bodies were usually split at or near the bedrock body boundaries, in order to maintain a relationship between each bedrock body and its overlying superficial bodies. However, this last step was not undertaken where this process would have produced unrealistically small groundwater bodies or many small unconnected portions of a larger body.

5 Aquifer characteristics

5.1 INTRODUCTION

This chapter provides a summary of the hydrogeology of the main aquifer groups in Scotland.

The bedrock aquifers are shown in the map in Figure 5 and listed in Table 2, and their physical and chemical characteristics are summarised in Table 3. Also in Table 3 is a general summary of the dominant strata overlying each of the bedrock aquifers, related to their impact on infiltration to, and the vulnerability of groundwater in, the bedrock aquifers.

The superficial aquifers are shown in the map in Figure 6 and summarised in Table 3.

The hydrogeology of each aquifer group is summarised in Sections 5.2 to 5.12, including geology, aquifer properties, groundwater flow characteristics, and groundwater chemistry.

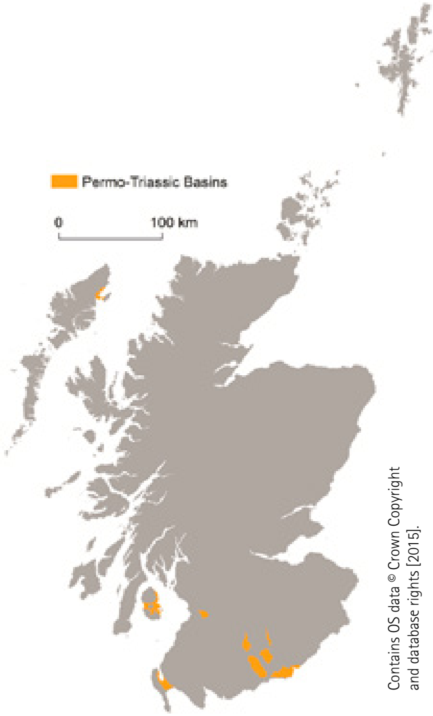
Table 3 Summary of aquifer characteristics. For more detail see individual descriptions in Sections 5.2 to 5.11.

Aquifer	Dominant groundwater flow type	Dominant aquifer productivity	Dominant1 groundwater flow path length	Typical ground-water flow depth	Dominant groundwater age	Dominant baseline groundwater chemical type	Dominant overlying strata
Permo-Triassic	Significantly intergranular (sandstone); Fracture (breccia)	Moderate to very high	1 km + Geological control usually dominates over catchments	100s m	Years to millennia	Moderately mineralised; oxic Ca-Mg-HCO_3 dominated	Variable.
Carboniferous – not extensively mined for coal	Fracture (minor intergranular), except Passage Formation – significantly intergranular	Moderate (except Passage Formation) to high	1–10 km Geological control usually dominates	100s m	Years to millennia	Often anoxic; Moderately mineralised; often anoxic; wide range of water chemistry types	Generally thick and low permeability.
Carboniferous – extensively mined for coal	Fracture (minor intergranular) and through mined voids	Moderate	1–10 km Dominated by impacts of historical mining	100s m +	Months to millennia	Moderately to highly mineralised; often anoxic; wide range of water chemistry types; often elevated iron.	Generally low permeability. Thick in valleys, thinner elsewhere.
Old Red Sandstone North	Fracture (minor intergranular)	Low to high	1 km + Usually follows main river body catchments	10s to 100s m	Decades to centuries	Moderately mineralised; often anoxic; Ca-HCO_3 dominated	Variable: thick and low permeability in Caithness; generally higher permeability elsewhere.
Old Red Sandstone South	Fracture (minor intergranular)	Moderate to very high	1 km + Usually follows main river body catchments	10s to 100s m	Decades to centuries	Moderately mineralised; generally oxic; Ca-Mg-HCO_3 dominated	Generally thick, moderate to high permeability
Silurian–Ordovician	Fracture	Low	0.1–1 km + Usually follows local surface water catchments	10s m	Years to centuries	Weakly to moderately mineralised; oxic; Ca-Mg-HCO_3 dominated. Some notable highly mineralised springs (Na-Cl-SO4 type)	Thin, low permeability on hillslopes; thicker and permeable in valleys.
Highland calcareous	Fracture	Low to moderate	0.1-1 km + Karstic. Flow paths highly unpredictable	10s to 100s m	Months to decades	Oxic, weakly to moderately mineralised a-HCO_3	Generally thin and highly permeable.

Aquifer	Dominant groundwater flow type	Dominant aquifer productivity	Dominant[1] groundwater flow path length	Typical ground-water flow depth	Dominant groundwater age	Dominant baseline groundwater chemical type	Dominant overlying strata
Precambrian North	Fracture	Very low to low	~1 km Usually follows local surface water catchments	10s m	Years to decades	Weakly mineralised; variable redox conditions; Ca-Na-HCO_3-Cl	Thin, low to moderately permeable on hillslopes; thicker and permeable in valleys.
Precambrian South	Fracture	Very low to low	0.1–1 km Usually follows local surface water catchments	10s m	Years to decades	Weakly mineralised; variable redox conditions; Ca-Na-HCO_3-Cl type	Thin, low-moderately permeable on hillslopes; thicker and permeable in valleys.
Igneous Volcanic	Fracture	Low	0.1–1 km Usually follows local surface water catchments	10s to 100s m	Months to decades	Weakly to moderately mineralised; oxic; Ca-HCO_3 dominated	Generally thin or absent.
Igneous Intrusive	Fracture; sometimes weathered intergranular	Low	100s m Usually follows local surface water catchments	10s m	Years to decades	Generally weakly mineralised and oxic; variable chemistry but often with low SO4	Generally thin and permeable, or absent.
Igneous/ sedimentary	Fracture (minor intergranular)	Low to moderate	0.1–1 km + Sometimes geologically controlled	10s to 100s m	Years to centuries	See relevant sections above	Variable, generally low to moderate permeability.
Shetland low permeability	Fracture	Very low to low	0.1–1 km Usually follows local surface water catchments	10s m	Years to decades	No data	Generally thin and low permeability.
Ayrshire basic	Fracture	Very low to low	0.1–1 km Usually follows local surface water catchments	10s m	Years to decades	No data	
Superficial aquifers	Intergranular	Moderate to high	0.01–1 km Usually follows main river body catchments	10s m	Weeks to years	Variable redox conditions, weakly to moderately mineralised with a wide range of water types, but often Ca (Na) HCO_3 (Cl)	Generally absent.

[1] *Dominant* here refers to the typical/modal range of flow path lengths. Shorter and longer outliers also occur.

5.2 PERMO-TRIASSIC



Permo-Triassic

Groundwater flow type	Significantly inter-granular (sandstone); Fracture (breccia)
Aquifer productivity	Moderate to Very High
Groundwater flow path length	1 km +; geological control usually dominates over catchments
Groundwater flow depth	Hundreds of metres
Groundwater age	Years to millennia
Baseline groundwater chemistry	Oxic, moderately mineralised. Ca Mg HCO_3 dominated
Overlying strata	Variable

5.2.1 Geological summary

The main onshore surface outcrops of Permo-Triassic aquifers in Scotland are in the west and south-west, most of which take the form of basin infills surrounded by older rocks. Away from the south-west, there are small Triassic outcrops in the Hebrides and along the western coast of the Highlands, and on the Moray Firth coast near Elgin. Virtually all Permo-Triassic outcrops in Scotland comprise terrestrial sedimentary rocks, and most of the main basins are dominated by aeolian sandstones, interbedded with breccias representing more fluvial deposition. The main basins are generally thought to be many hundreds of metres thick. In the Dumfries Basin, the maximum aquifer thickness is inferred to be between 1.1 and 1.4 km (Robins and Ball, 2006), although the Permo-Triassic aquifer in the Annan basin is only approximately 100 m thick.

5.2.2 Physical aquifer properties and groundwater flow

Permo-Triassic rocks form some of the most productive aquifers in Scotland. They are often characterised by the complex layering of two different geological units – sandstone and breccia, which can lead to a dual aquifer system dominated by fracture flow but intergranular storage (Figure 9). The hydrogeology can be further complicated by the nature and thickness of any overlying Quaternary deposits, which can be a significant control on the interaction between groundwater in the bedrock aquifer and surface water, such as acting as a source of delayed recharge to the underlying bedrock aquifer, or confining it to various degrees. Multiple groundwater abstractions and discharges in some of the aquifer basins also impact on the local hydrogeology.

Permo-Triassic breccias – such as the Doweel Breccia Formation in the west of the Dumfries basin – typically have very low intergranular permeability and porosity (Table 4), and high secondary (fracture) permeability. Sandstones typically have relatively higher intergranular porosity and permeability, but much less fracture development. Fracture flow is generally concentrated along subhorizontal discontinuities: in particular, bedding-plane fractures along the breaks between breccia and sandstone layers. Horizontal permeability is therefore commonly much greater than vertical permeability. In some areas, though, there is significant subvertical fracturing associated with basin-marginal fault trends, which can allow rapid recharge deep into the aquifer. In breccias transmissivity is significantly higher, groundwater flow more rapid and groundwater storage more limited, than in sandstones, in which groundwater flow is slower and storage higher (Table 4). Groundwater age reflects this, with the bulk of water within sandstones typically older – more than 50 years old – than the bulk of water in breccias, which is dominated by water recharged since the 1990s. However, small volumes of much older groundwater – possibly more than 10 000 years old – are stored in pores in the matrix of sandstones interbedded with breccia in the west of the Dumfries basin.

Significant fracture inflows occur at up to 100 m below ground level, and smaller inflows have been measured to at least 13 m depth. Groundwater can flow many kilometres laterally along continuous subhorizontal fracture systems (Robins and Ball, 2006).

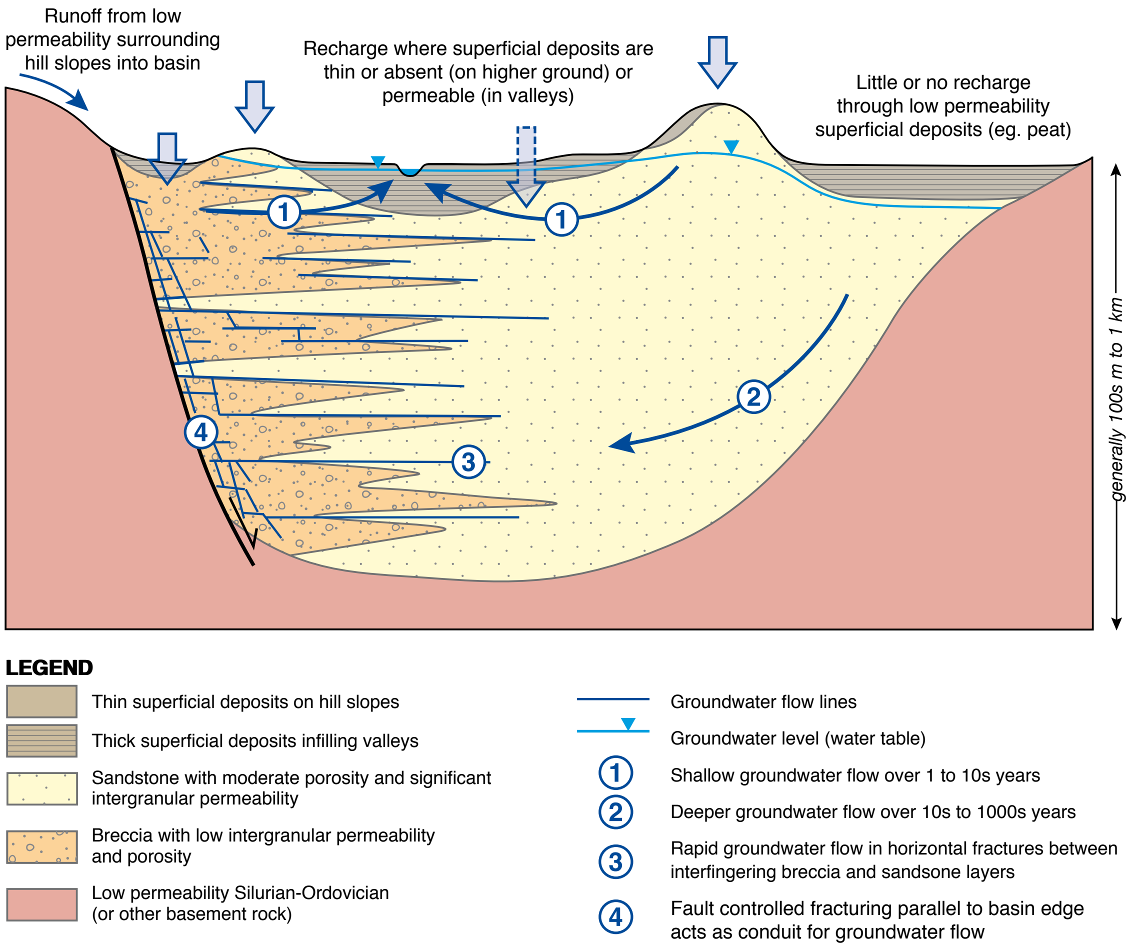


Figure 9 Schematic cross-section of the hydrogeology of a Permo-Triassic basin in Scotland.

Table 4 Summary of available aquifer properties data for Permo-Triassic aquifers.

	Porosity (%)	Horizontal matrix hydraulic conductivity (m/d)	Vertical matrix hydraulic conductivity (m/d)	Transmissivity (m^2/d)	Specific capacity ($m^3/d/m$)	Storativity	Operational yield (m^3/d)
Sandstone (Dumfries)	26 (5)	1.9 (5)	0.95 (5)	55–320 (5)[1]	60–360 (3)[1]	0.00005–0.0003 (4)	<500 (<15)
Breccia (Dumfries)	12 (5)	<0.009 (4)	<0.0002 (3)	10–4000[1] (14)	25–1500[1] (15)	0.0002–0.003 (7)	>2000 (~30)
Other mainland Permian basins	18–25 (11)	0.4–2.5 (10)	0.1–4.5 (8)	500–800	125–210 (18)	0.0005–0.001 (8)	600–900 (<20)
Triassic (Annan-Gretna)	19–20 (5)	0.02–0.03 (5)	0.015–0.012 (5)	50 (2)	30–50 (3)		80–190[1] (4)
Arran	20 (2)			55–65 (9)	50–60 (9)		

[1] Total range in measured values
Number of values indicated in brackets
Single values are averages; ranges generally indicate mean and median values except where indicated
Data from the British Geological Survey

5.2.3 Summary of baseline chemistry

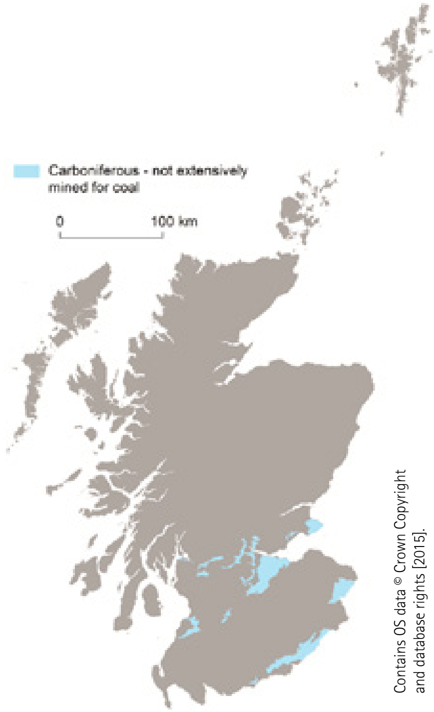
The chemistry of groundwater in the Dumfries Basin aquifer is described in detail in British Geological Survey (2006) and MacDonald et al. (2000). A summary of the baseline chemistry is provided in Table 5.

Table 5 Summary of baseline chemistry of Permo-Triassic aquifers.

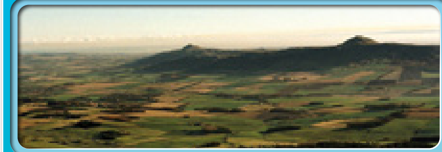
Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	62	0	19.4	26.4	37.5	58.6	82.2
Cl	mg/L	62	0	11	14.2	18	22.9	46.7
DO_2	mg/L	20	2	NA	1.22	4.19	7.43	10
Fe	µg/L	61	16	1.7	3	11	74	226
HCO_3	mg/L	62	0	48.8	83.4	139	200	241
K	mg/L	62	0	1.1	1.2	1.65	2.26	3.59
Mg	mg/L	62	0	6.89	10.7	17.2	21.8	29
Na	mg/L	62	0	7.64	9.45	11.8	17	27.5
NO_3 as NO_3	mg/L	57	2	1.59	7.07	17.24	28.73	43.80
pH		57	0	6.18	6.8	7.18	7.46	7.78
SEC	µS/cm	58	0	196	326	405	510	654
SO_4	mg/L	62	0	6.98	11.1	20.2	31.6	73.1

[a] number of samples
[b] number below detection limit

5.3 CARBONIFEROUS SEDIMENTARY AQUIFERS, NOT EXTENSIVELY MINED FOR COAL



Carboniferous - not extensively mined for coal



Groundwater flow type	Fracture (minor intergranular), except Passage Formation - significantly inter-granular
Aquifer productivity	Moderate (except Passage Formation - High)
Groundwater flow path length	1–10 km; geological control usually dominates
Groundwater flow depth	Hundreds of metres
Groundwater age	Years to millennia
Baseline groundwater chemistry	Often anoxic; generally moderately mineralised
Overlying strata	Generally thick and low permeability

5.3.1 Geological summary

These Carboniferous sedimentary rocks contain little or no coal, although some contain other minerals such as oil shale. They crop out dominantly in Scotland's Central Belt (known as the Midland Valley in geological terms), with smaller outcrops in southern Scotland, particularly along the border with England. The main geological formations are the Strathclyde, Inverclyde (both largely in the Midland Valley), Border and Yoredale (both largely in southern Scotland) groups. They generally comprise repetitive sequences of sandstone and siltstone beds with thinner interbedded mudstones and, more rarely, limestones and coals. The thickness of the sedimentary sequences varies from generally 600 to 1000 m in the various outcrops in southern Scotland, up to 2000 to 3000 m in the Midland Valley (Read et al., 2002). These Carboniferous rocks have not been extensively mined for coal. Some areas have seen localised coal mining and/or mining for oil shale, limestone, fireclay or metals (MacDonald et al., 2003).

5.3.2 Physical aquifer properties and groundwater flow

Carboniferous sedimentary rocks typically form multilayered and vertically segmented aquifers. Sandstone units tend to act as discrete aquifer units, separated by lower permeability siltstones, mudstones and coals; limestone beds have variable permeability, but are generally thin in comparison with the whole aquifer sequence, so their overall impact on groundwater flow is typically only significant on a local scale. Faults divide the sedimentary sequence vertically: some are permeable, acting as preferential flow pathways, and others act as barriers to groundwater flow (Figure 10). The exception is the Passage Formation, which forms an extensive productive aquifer within the Carboniferous rocks (Ball, 1999).

The sandstones tend to be fine grained and well cemented, with relatively low intergranular porosity and permeability (Table 3, Table 6), and therefore fracture flow dominates groundwater movement throughout the aquifer, and aquifer permeability depends on the local nature of natural fracturing. The Passage Formation, by contrast, has higher porosity and a larger proportion of groundwater moves by intergranular flow.

Carboniferous sedimentary rocks tend to form moderately productive aquifers (Table 6). However, the higher transmissivity and specific capacity values recorded may relate to aquifers which have been impacted by mining (Section 5.4).

Groundwater flow paths are likely to be complex, due to the naturally layered nature of the aquifers, which tends to impart preferential horizontal flow, and the predominance of fracture flow. Groundwater may be present under unconfined or confined conditions, at various depths, and different groundwater heads are seen in different aquifer layers. Groundwater residence times are often in excess of 60 years (Ó Dochartaigh et al., 2011).

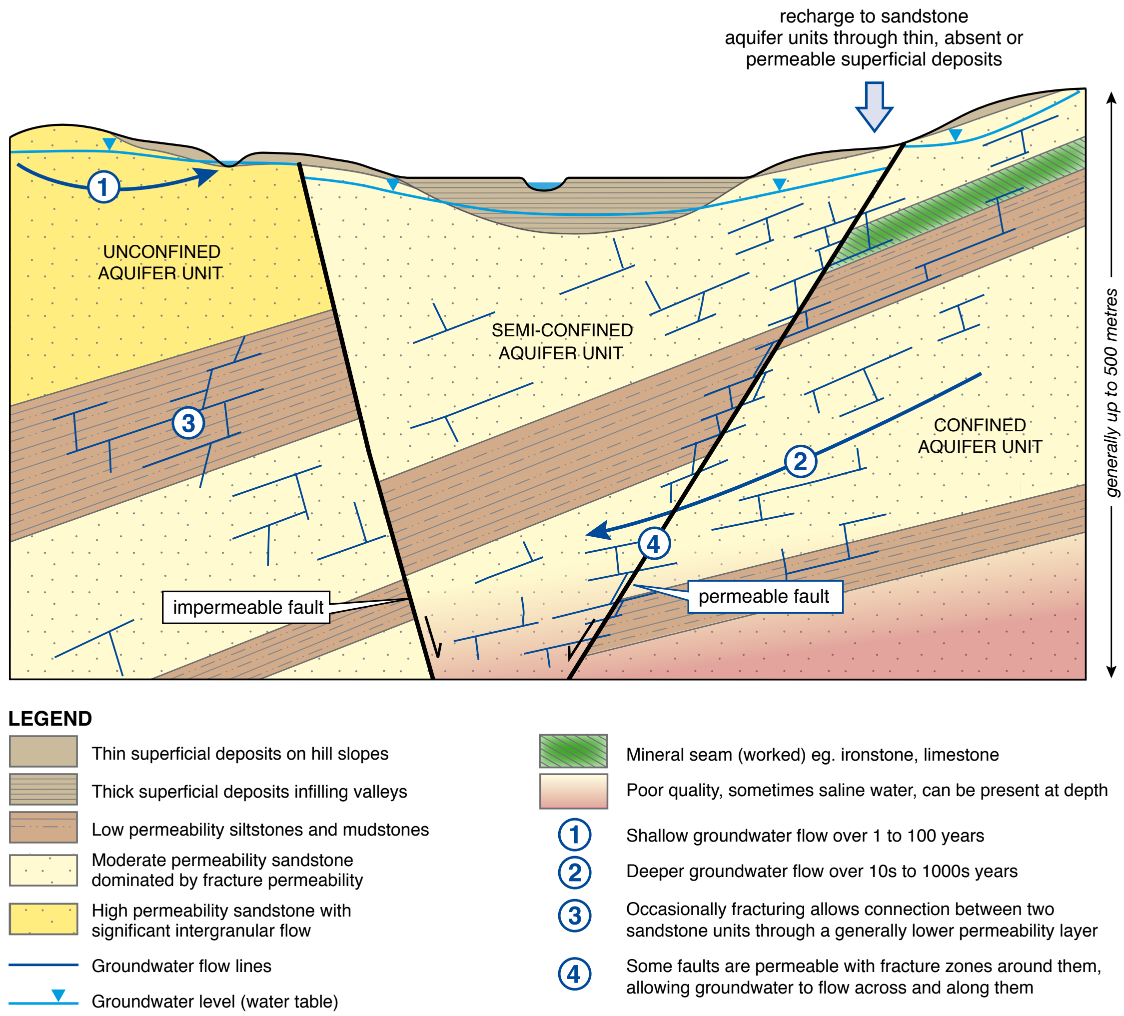


Figure 10 Schematic cross-section of the hydrogeology of Carboniferous aquifers in Scotland not extensively mined for coal.

Table 6 Summary of available aquifer properties data for Carboniferous sedimentary aquifers not extensively mined for coal.

	Porosity (%)	Matrix hydraulic conductivity (m/d)	Transmissivity (m^2/d)	Specific capacity (m3/d/m)	Operational yield (m^3/d)
Carboniferous aquifers – not extensively mined for coal	12–17 (34)	0.0003–0.1 (37)	10–1000 * (5)	48–132 * (46) (minimum 0.43; maximum 1320) *	131–418 (348)

* May refer to both mined and nonmined aquifers
Ranges of values refer to mean and median values except where indicated
Number of values indicated in brackets
Data from the British Geological Survey

5.3.3 Summary of baseline chemistry

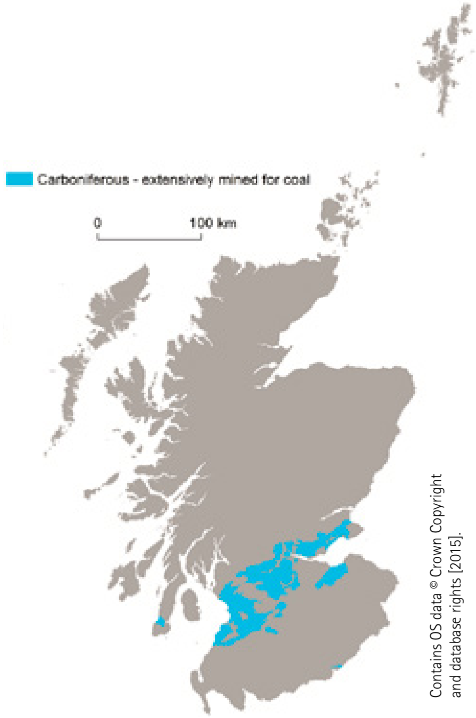
The baseline chemistry of groundwater in Carboniferous aquifers which have not been extensively mined for coal is described in detail in Ó Dochartaigh et al. (2011) for the Midland Valley and MacDonald et al. (2008) for southern Scotland. A summary for groundwater from these aquifers across both the Midland Valley and southern Scotland is provided in Table 7.

Table 7 Summary of baseline chemistry of Carboniferous sedimentary aquifers not extensively mined for coal.

Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	55	0	35.5	43.8	58.7	76.2	154
Cl	mg/L	54	0	9.67	18.1	36.8	52	98.8
DO_2	mg/L	21	0	0.8	1.85	2.76	6.11	9.3
Fe	µg/L	52	9	3	6	46	300	921
HCO_3	mg/L	54	0	166	213	256	318	382
K	mg/L	54	0	1.4	2.08	4.42	7.75	9.48
Mg	mg/L	55	0	12.2	18.9	27.2	36.7	53.3
Na	mg/L	55	0	6.58	12.4	27.9	51.8	146
NO_3 as NO_3	mg/L	36	8	0.04	0.07	3.21	17.24	30.98
pH		50	0	6.69	7.02	7.3	7.68	8.04
SEC	µS/cm	50	0	353	516	694	976	1450
SO_4	mg/L	55	0	5.03	22	38.5	74.6	175

[a] number of samples
[b] number below detection limit

5.4 CARBONIFEROUS SEDIMENTARY AQUIFERS — EXTENSIVELY MINED FOR COAL



Carboniferous - extensively mined for coal

Groundwater flow type	Fracture (minor intergranular)
Aquifer productivity	Moderate
Groundwater flow path length	1–10 km; dominated by impacts of historical mining
Groundwater flow depth	Hundreds of metres +
Groundwater age	Months to millennia
Baseline groundwater chemistry	Often anoxic; generally moderately to highly mineralised
Overlying strata	Generally low permeability. Thick in valleys, thinner elsewhere

5.4.1 Geological summary

Carboniferous sedimentary rocks which have been extensively mined for coal in Scotland are largely found in the Midland Valley, with minor outcrops in southern Scotland. The aquifers have often been significantly altered by mining, with remnant voids and/or enhanced fracturing causing hydraulic connections over potentially large volumes of aquifer.

The main geological formations which have been mined for coal are the Scottish Coal Measures Group and parts of the Clackmannan Group (with the significant exception of the Passage Formation, which does not contain significant coal seams and is not extensively mined for coal; see Section 5.3). They comprise repetitive sequences dominated by sandstone and siltstone beds, interbedded with thinner mudstones, limestones and coals. The thickness of the formations varies from less than 500 m in south-west Scotland up to 2000 to 3000 m in the Midland Valley.

5.4.2 Physical aquifer properties and groundwater flow

In their unmined state, these coal bearing rocks form essentially the same kinds of aquifers as Carboniferous sedimentary rocks which have not been extensively mined for coal (Section 5.3): the main difference is that unmined coal seams act as additional low permeability layers, restricting groundwater flow between more permeable sandstone aquifer units. However, the productivity of mined aquifers depends not only on the nature of natural fracturing but often more significantly on the extent and nature of mining impacts. The generally moderate productivity of Scottish Carboniferous sedimentary aquifers not extensively mined for coal is the lower limit of the productivity of Carboniferous aquifers subject to extensive coal mining (Table 7). Mine voids (shafts and tunnels) can artificially and greatly increase aquifer transmissivity, sometimes across large areas and depths, and can link formerly separate groundwater flow systems, both laterally and vertically (Figure 11). Aquifer storage can also be locally increased. Even where mine voids (e.g. tunnels) have subsequently collapsed, deformation of the surrounding rock mass is likely to have caused further changes in transmissivity and, to a lesser degree, storage (Younger and Robins, 2002).

Quantitative aquifer properties data from test pumping are rare for boreholes intercepting former mines. However, records of specific capacity from boreholes drilled in aquifers which have been extensively mined, many of which intercept mine workings, give an indication of the range in aquifer properties and how this varies from the unmined aquifers (Table 8). There are also many records of yields from mine dewatering boreholes (Table 8). The higher yield and specific capacity values for these boreholes are likely to reflect the productivity of Carboniferous aquifers subject to extensive coal mining.

Groundwater flow paths are likely to be even more complex than in Carboniferous aquifers not extensively mined for coal, due partly to preferential flow in the naturally layered aquifers, and partly to mining impacts. Groundwater may be present under unconfined or confined conditions, at various depths, and different groundwater heads are seen in different aquifer layers and/or mining levels. Groundwater residence times are often in excess of 60 years (Ó Dochartaigh et al., 2011).

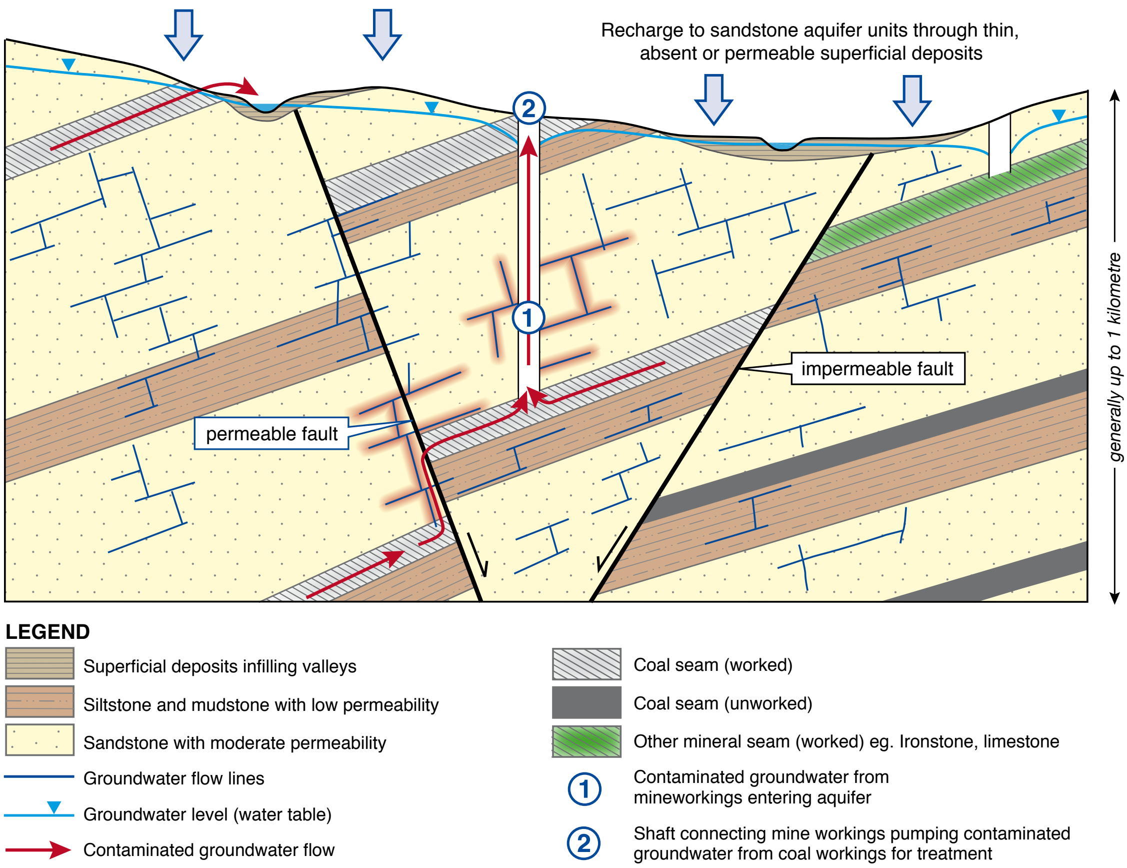


Figure 11 Schematic cross-section of the hydrogeology of Carboniferous aquifers in Scotland which have been extensively mined for coal.

Table 8 Summary of available aquifer properties data for Carboniferous sedimentary aquifers extensively mined for coal.

	Porosity (%)	Matrix hydraulic conductivity (m/d)	Transmissivity (m^2/d)	Specific capacity ($m^3/d/m$)	Operational yield (m^3/d)
Carboniferous aquifers – extensively mined for coal			10–1000 * (5)	48–132 * (46) (minimum 0.43; maximum 1320) *	1987–3279 (171) (minimum 41; maximum 22 248)

* May refer to both mined and nonmined aquifers
Ranges of values refer to mean and median values except where indicated
Number of values indicated in brackets
Data from the British Geological Survey

5.4.3 Summary of baseline chemistry

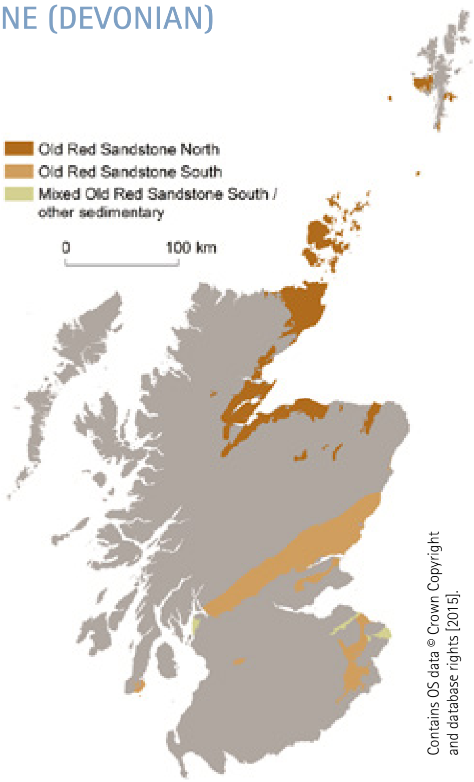
The chemistry of some mining-impacted groundwaters from Carboniferous aquifers in the Midland Valley which have been extensively mined for coal is described in detail in Ó Dochartaigh et al. (2011). A summary is provided in Table 9.

Table 9 Summary of baseline chemistry of Carboniferous sedimentary aquifers in Scotland that have been extensively mined for coal.

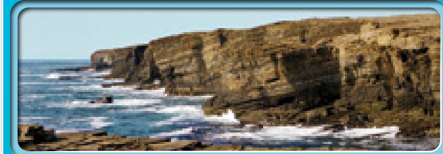
Element	Units	n[a]	n <dl[a]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	56	0	30.9	41.5	71	113	245
Cl	mg/L	56	0	10.7	14.4	23.4	63.4	1140
DO_2	mg/L	36	4	NA	0.3	1.2	2.99	5.96
Fe	µg/L	54	0	31.3	106	675	3730	9360
HCO_3	mg/L	54	0	100	206	324	467	581
K	mg/L	54	0	1.51	2.52	4.26	11.3	26.3
Mg	mg/L	56	0	7.42	15	28.2	48	102
Na	mg/L	56	0	11	13.2	27.6	132	519
NO_3 as NO_3	mg/L	52	24	0.04	0.09	0.13	1.33	8.84
pH		52	0	6.3	6.58	7	7.46	7.69
SEC	µS/cm	52	0	311	470	740	1240	1700
SO_4	mg/L	56	0	10.8	32.9	73	118	270

[a] number of samples
[b] number below detection limit

5.5 OLD RED SANDSTONE (DEVONIAN)

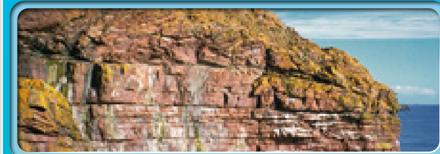


Old Red Sandstone North



Groundwater flow type	Fracture (minor intergranular)
Aquifer productivity	Low to High
Groundwater flow path length	1 km +; usually follows major surface water catchments
Groundwater flow depth	Tens to hundreds of metres
Groundwater age	Decades to centuries
Baseline groundwater chemistry	Often anoxic; moderately mineralised; Ca HCO_3 dominated
Overlying strata	Variable: thick & low permeability in Caithness; generally higher permeability elsewhere

Old Red Sandstone South



Groundwater flow type	Fracture (minor inter-granular)
Aquifer productivity	Moderate to Very High
Groundwater flow path length	1 km +; usually follows major surface water catchments
Groundwater flow depth	Tens to hundreds of metres
Groundwater age	Decades to centuries
Baseline groundwater chemistry	Generally oxic; moderately mineralised; Ca(Mg) HCO_3 dominated
Overlying strata	Generally thick, moderate to high permeability

5.5.1 Geological summary

Rocks of the Old Red Sandstone sedimentary succession crop out across large parts of north, north-east, central and south-east Scotland. It is a terrestrial red-bed sequence, dating from the late Silurian to the early Carboniferous but dominantly Devonian, formed predominantly of fluvial and alluvial fan sandstones, with variable proportions of conglomerates, siltstones and mudstones. Volcanic rocks, including lavas and volcaniclastic rocks, are significant in parts of the otherwise dominantly sedimentary succession, forming a distinct aquifer type, described in Section 5.6, below.

Old Red Sandstone rocks in Scotland were deposited in two distinct basins: a northern, 'Orcadian', basin, including outcrops in Shetland, Orkney, Caithness, Morayshire and Aberdeenshire; and a southern basin including outcrops in Aberdeen; the Vale of Strathmore, from Loch Lomond to Stonehaven; in Fife; and in the Scottish Borders. The maximum total thickness of Old Red Sandstone rocks can exceed 2000 m (Trewin and Thirlwall, 2002).

5.5.2 Physical aquifer properties and groundwater flow

Sandstones form the most productive aquifers within the Old Red Sandstone succession. The youngest sandstones in the sequence are found in Fife, and form some of the most highly productive bedrock aquifers in Scotland. These sandstones are typically well cemented, with relatively low intergranular porosity and permeability (Table 3). Fracture flow dominates groundwater movement (Figure 12), with at least 80 per cent of borehole inflows from fracture flow (Ó Dochartaigh, 2004). Aquifer properties data for these and other Old Red Sandstone aquifers are summarised in Table 9.

Away from Fife, sandstones within the Upper Old Red Sandstone, and older sandstones and conglomerates of the Middle and Lower Old Red Sandstone, generally form moderately, and occasionally highly, productive aquifers (Table 10). In Caithness and Orkney there are extensive fine grained flagstones, within which groundwater flow is concentrated along bedding planes, and which tend to form only moderately productive aquifers at best. Where lower permeability siltstones or mudstones separate sandstone beds, they tend to act as barriers to groundwater flow, except where permeable faults cut through the sequence.

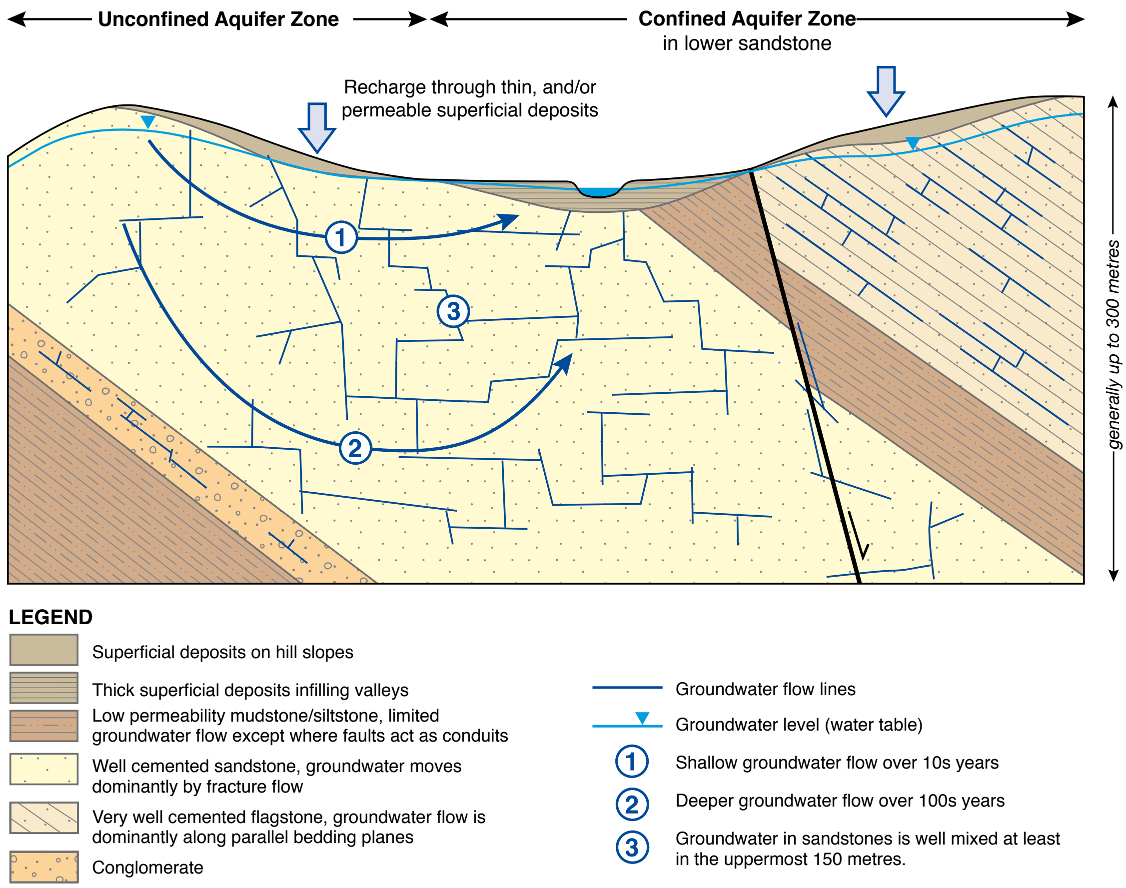


Figure 12 Schematic cross-section of the hydrogeology of Old Red Sandstone aquifers.

Table 10 Summary of available aquifer properties data for Old Red Sandstone sedimentary aquifers.

	Porosity (%)	Hydraulic conductivity (m/d)	Transmissivity (m^2/d)	Specific capacity (m^3/d/m)	Storativity	Operational yield (m^3/d)
Upper Old Red Sandstone (Fife)	20 (7)	0.5 (7)	200–300 (12)	90–175 (13)	~0.002–0.01 (8)	>1000 (34)
Upper Old Red Sandstone (away from Fife); Middle Old Red Sandstone	~10% (16)		150–200 (12)	50–120 (13)	~0.001 (8)	800–1000 (Moray and Aberdeenshire) (19)
Lower Old Red Sandstone (largely Strathmore; some Moray)	~10% (2)	0.01–2 (2)	50–150 (6)	40–100 (23)	~0.0001 (8)	200–400 (Strathmore and Midland Valley) (183)

Ranges of values refer to mean and median values
Number of values indicated in brackets
Data from the British Geological Survey

The predominance of fracture flow means groundwater transport can be rapid, and groundwater is generally well mixed in the top 50 m or so, but groundwater residence times of several decades are typical.

5.5.3 Summary of baseline chemistry

The baseline chemistry of groundwater in Old Red Sandstone aquifers in the Moray Basin is described in detail in Ó Dochartaigh et al. (2010). A summary is provided in Table 11. The baseline chemistry of groundwater in Old Red Sandstone aquifers in Fife is described in detail in Ó Dochartaigh et al. (2006), and of Old Red Sandstone aquifers in southern Scotland in MacDonald et al. (2008). A summary is provided in Table 12.

Table 11 Summary of baseline chemistry of Old Red Sandstone North aquifers in the Moray Basin.

Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	99	0	26.6	47.3	61.6	79.5	99.1
Cl	mg/L	99	0	17.5	26.9	46	72.7	92.6
DO_2	mg/L	49	14	NA	NA	1.22	5.59	8.16
Fe	µg/L	91	19	2.1	4	28.8	300	857
HCO_3	mg/L	99	1	77	127	193	250	327
K	mg/L	98	1	1.3	1.8	2.6	3.8	5.8
Mg	mg/L	99	0	2.3	3.67	8.1	17.4	23.8
Na	mg/L	99	0	11.7	15.3	25.5	41.2	56.9
NO_3 as NO_3	mg/L	82	20	NA	0.18	2.92	15.91	27.54
pH		97	0	6.5	6.8	7.2	7.45	7.7
SEC	µS/cm	94	0	240	374	547	708	890
SO_4	mg/L	99	0	6.13	10.6	19.6	35.9	54.5

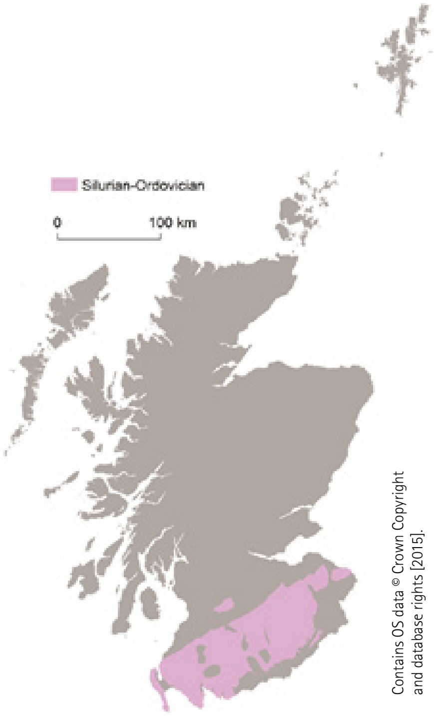
[a] number of samples
[b] number below detection limit

Table 12 Summary of baseline chemistry of Old Red Sandstone South aquifers.

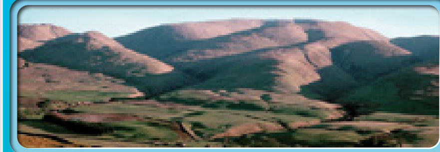
Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	125	0	25.5	38	47.5	60.9	84.3
Cl	mg/L	125	0	13.3	17.6	25.3	43.6	68.4
DO_2	mg/L	64	2	1.4	3.2	6.64	8.2	9.02
Fe	µg/L	105	46	2	2	11	44	158
HCO_3	mg/L	124	0	89.8	128	162	214	257
K	mg/L	125	1	0.9	1.45	2.1	3.22	5.1
Mg	mg/L	125	0	5.72	9.82	14.4	22.2	34
Na	mg/L	125	0	7.48	11.5	16	25.3	66.3
NO_3 as NO_3	mg/L	93	3	0.88	5.75	17.68	45.08	78.23
pH		113	0	6.77	7.02	7.41	7.7	7.8
SEC	µS/cm	108	0	296	386	498	610	821
SO_4	mg/L	124	0	9.01	13.3	21.2	33.2	60.3

[a] number of samples
[b] number below detection limit

5.6 SILURIAN AND ORDOVICIAN



Silurian-Ordovician



Groundwater flow type	Fracture
Aquifer productivity	Low
Groundwater flow path length	0.1 – 1 km +; usually follows local surface water catchments
Groundwater flow depth	Tens of metres
Groundwater age	Years to centuries
Baseline groundwater chemistry	Oxic, weakly to moderately mineralised. Ca (Mg) HCO_3 dominated. Some highly mineralised localities (Na-K-Cl)
Overlying strata	Thin, low permeability on hillslopes; thicker and permeable in valleys

5.6.1 Geological summary

Rocks of Silurian and Ordovician (early Palaeozoic) age dominate southern Scotland but are essentially absent from the rest of the country. They comprise mainly turbiditic sandstones (called greywackes) and siltstones, with variable proportions of conglomerates, mudstones, cherts, volcaniclastic rocks and marine lavas. The total sequence is many thousands of metres thick, and reflects varying marine depositional environments associated with an oceanic subduction zone. The rocks are divided into structural tracts by major north-east to south-west trending faults. Their northern boundary is marked generally by the Southern Uplands Fault, although smaller outcrops of Ordovician rocks occur to the north of this into the Midland Valley.

5.6.2 Physical aquifer properties and groundwater flow

The dominantly fine-grained, well-cemented nature of the rocks means intergranular permeability is generally low. Apart from a sometimes well-developed weathered zone at rockhead, in which intergranular permeability is enhanced, fractures in the rocks are thought to contribute virtually all groundwater storage and flow (Figure 13). There are no transmissivity or hydraulic conductivity data for the aquifer, reflecting the dominance of low yielding, private supply use – the aquifer has never been investigated in detail for public water or large scale industrial supply. Analysis of recorded operational borehole yields suggests that borehole yields are typically low, with an overall median of 0.3 l/s and a mean of 0.6 l/s.

Groundwater flow paths are likely to be controlled by fracture patterns and to be generally relatively shallow, with groundwater appearing to be well mixed in the top 50 metres or so. In general, flow paths are likely to be relatively short and localised, but in some cases there may be connectivity over several kilometres from higher ground to valleys, and groundwater is often resident in the aquifer for several decades (MacDonald et al., 2008).

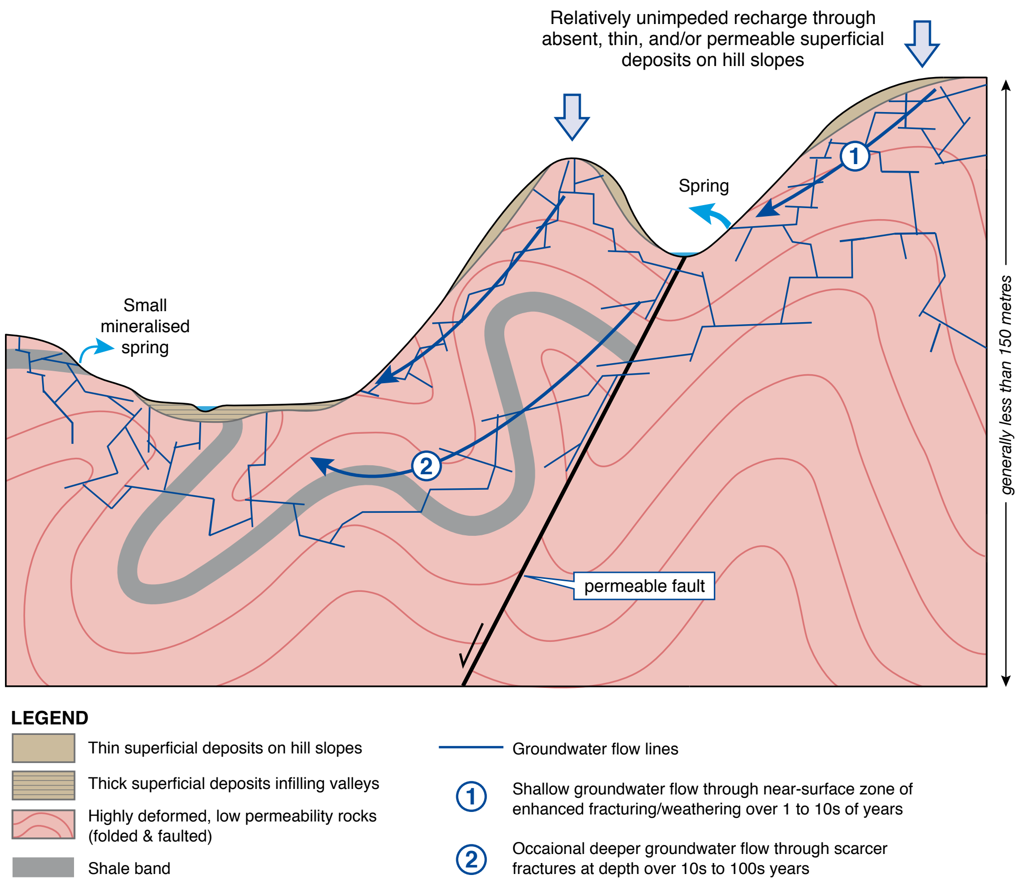


Figure 13 Schematic cross-section of the hydrogeology of Silurian and Ordovician aquifers in Scotland.

5.6.3 Summary of baseline chemistry

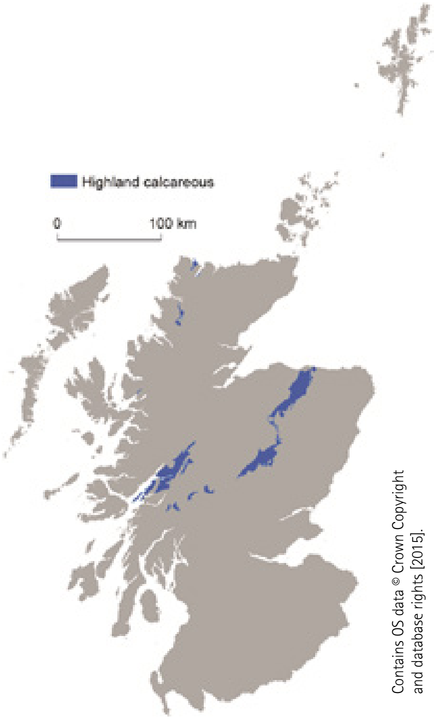
The baseline chemistry of groundwater from Silurian and Ordovician aquifers in Scotland is described in detail in MacDonald et al. (2008). A summary is provided in Table 13.

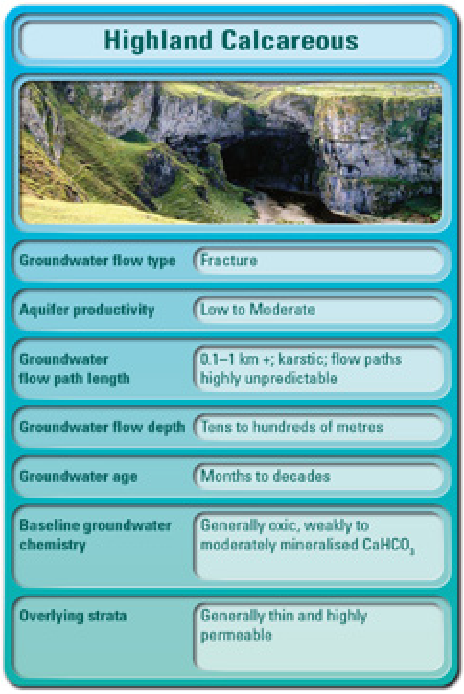
Table 13 Summary of baseline chemistry data for Silurian and Ordovician aquifers.

Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	73	0	10	19.7	39.1	54.6	70
Cl	mg/L	72	0	7.05	10.5	14.4	28.7	49.6
DO_2	mg/L	48	1	0.14	1.5	3.68	5.1	8.1
Fe	µg/L	66	27	7.5	7.5	13	41	419
HCO_3	mg/L	73	1	13	56.7	134	207	273
K	mg/L	72	2	0.5	0.86	1.2	2.27	3.4
Mg	mg/L	73	0	2.64	5.66	12.5	17.9	25.1
Na	mg/L	73	0	5.45	7.4	10.5	15.7	23.9
NO_3 as NO_3	mg/L	70	1	0.51	1.54	11.09	21.30	43.93
pH		72	0	6.04	6.7	7.09	7.48	7.76
SEC	µS/cm	73	0	116	190	340	536	655
SO_4	mg/L	73	0	0.71	5.45	9.38	14.7	28.3

[a] number of samples
[b] number below detection limit

5.7 HIGHLAND CALCAREOUS: DOMINANTLY CALCAREOUS PRECAMBRIAN AND CAMBRO-ORDOVICIAN





5.7.1 Geological summary

Most rocks in Scotland are dominantly siliceous, but a few, mostly Precambrian and Cambro-Ordovician in age and in the Highlands, are dominantly calcareous, which has significant impacts on the chemistry of groundwater stored in and flowing through the rocks. Calcareous rocks occur within the Appin, Argyll and Southern Highland Groups of the Dalradian Supergroup (within the Precambrian South aquifer group), and include calcareous pelites, calcsilicates, and metalimestones (Strachan et al., 2002). The calcareous horizons are often relatively thin — sometimes only a few metres thick — and are interbedded with greater thicknesses of other, noncalcareous metamorphic rocks.

The younger Durness Group, of Cambro-Ordovician age, is a dominantly carbonate sequence which crops out along a narrow belt some 250 km long just inland from the north-west coast. It can be seen as a moderate productivity, fracture flow aquifer in this area in Figure 3. It is usually no more than a few hundred metres thick, although reaches 1300 m at its thickest (Robins, 1990). Only part of the group is dominated by the limestones in this aquifer group; the rest is dominated by dolostones with intervals of subordinate chert (Park et al., 2002).

5.7.2 Physical aquifer properties and groundwater flow

Calcareous Precambrian rocks have low intergranular porosity and permeability, but dissolution of carbonate along fractures in the rock can produce secondary karstic permeability (Figure 14). Where karstic permeability becomes very well developed, these rocks can have higher transmissivity than noncalcareous Precambrian aquifers (Robins, 1990).

Cambro-Ordovician limestones show significant karst development in places, thought to be concentrated along fault planes, and including cave sequences at least 3 km long, through which large flows of up to 00 l/s discharge (Robins, 1990). However, the scarce available data indicate that where karst is poorly developed, the aquifer has relatively low productivity, similar to Precambrian aquifers (Section 5.8).

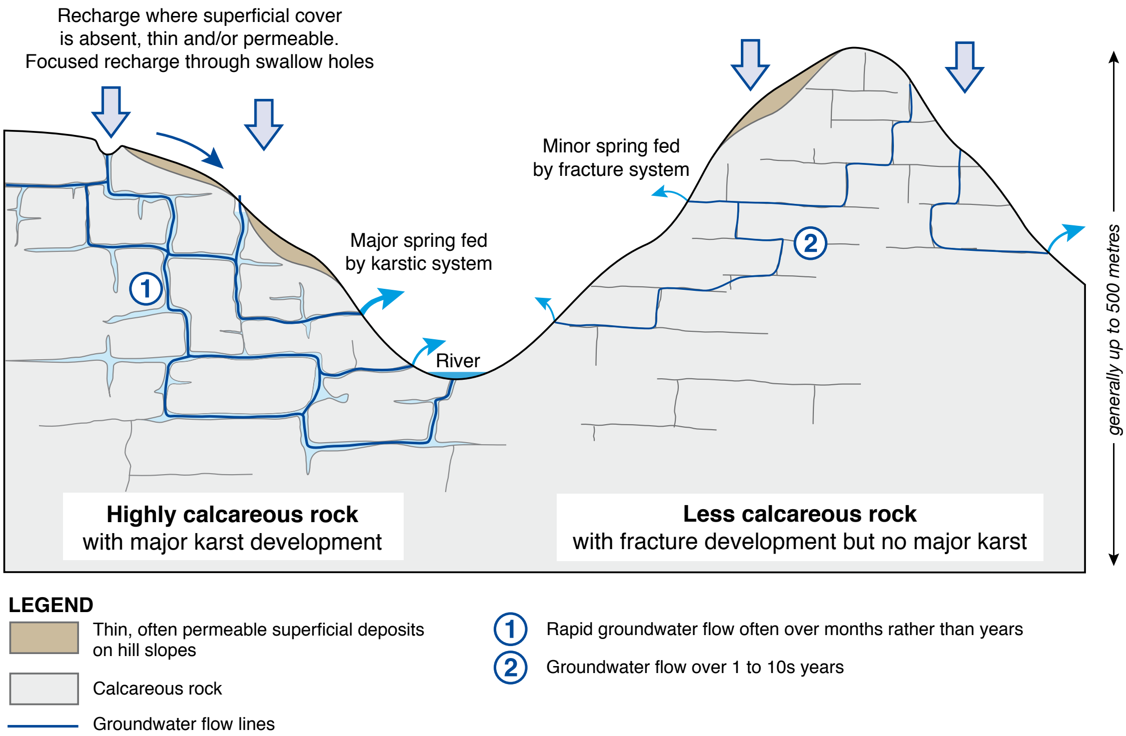


Figure 14 Schematic cross-section of the hydrogeology of calcareous aquifers (dominantly Precambrian and Cambrian) in Scotland.

5.7.3 Summary of baseline chemistry

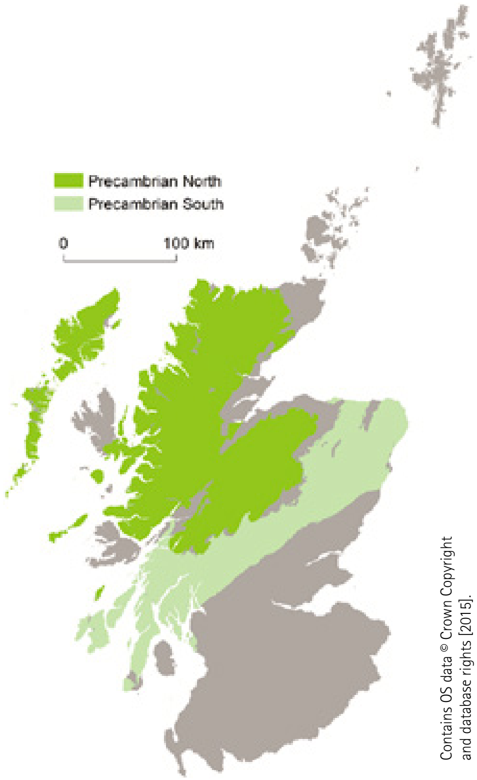
A summary of the baseline chemistry of groundwater in Highland Calcareous aquifers is provided in Table 14.

Table 14 Summary of baseline chemistry of Highland Calcareous aquifers.

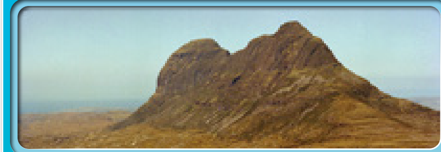
Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	18	0	12.5	25	62.8	78.1	121
Cl	mg/L	18	0	6.27	10.5	16.2	29.8	38.1
DO_2	mg/L	18	0	3.59	5.56	7.86	9.28	10.5
Fe	µg/L	18	3	1	2	10	69	271
HCO_3	mg/L	18	0	46.4	54.3	194	344	377
K	mg/L	18	0	0.877	1.02	2.35	3.48	4.4
Mg	mg/L	18	0	2.89	3.51	4.8	10.4	28.4
Na	mg/L	18	0	4.47	6.88	8.8	14.4	23.2
NO_3 as NO_3	mg/L	18	0	0.93	1.51	6.90	26.56	83.98
pH		18	0	6.46	6.7	7.2	7.42	7.72
SEC	µS/cm	18	0	86.1	279	471	576	656

[a] number of samples
[b] number below detection limit

5.8 PRECAMBRIAN

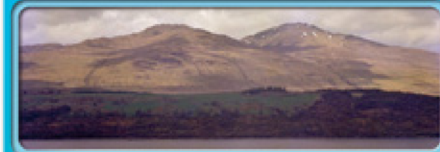


Precambrian North



Groundwater flow type	Fracture
Aquifer productivity	Very Low to Low
Groundwater flow path length	0.1–1 km; usually follows local surface water catchment
Groundwater flow depth	Tens of metres
Groundwater age	Years to decades
Baseline groundwater chemistry	Variable redox conditions, weakly mineralised, Ca-(Na) HCO_3 (Cl)
Overlying strata	Thin, low-moderately permeable on hillslopes; thicker and permeable in valleys

Precambrian South



Groundwater flow type	Fracture
Aquifer productivity	Very Low to Low
Groundwater flow path length	0.1–1 km; usually follows local surface water catchments
Groundwater flow depth	Tens of metres
Groundwater age	Years to decades
Baseline groundwater chemistry	Variable redox conditions, weakly mineralised, Ca-(Na) HCO_3 (Cl)
Overlying strata	Thin, low-moderately permeable on hillslopes; thicker and permeable in valleys

5.8.1 Geological summary

Precambrian rocks cover most of Scotland north and west of the Highland Boundary Fault, geologically divided into a number of tectonostratigraphical terranes divided by major faults. From a hydrogeological point of view they can be divided into a northern and a southern division. They are divided here into Precambrian North and Precambrian South.

Precambrian North aquifers are typified by massive metamorphic rocks, including highly metamorphosed Lewisian gneiss, largely unmetamorphosed Torridonian sandstone, metamorphosed Moine schists, and Dalradian Grampian Group schists.

Precambrian South aquifers are typified by Dalradian metasedimentary schists of the Southern Highland and Argyll groups, which are typically more layered and less massive than Precambrian north aquifers.

Both Precambrian aquifer groups are variously intruded by igneous rocks.

5.8.2 Physical aquifer properties and groundwater flow

Scottish Precambrian rocks, both North and South, typically form low or very low productivity aquifers, with negligible intergranular porosity (less than 1 per cent — Robins, 1990) and low permeability. Weathering of the uppermost few metres of rock, often most pronounced in areas of intensive fracturing, can create enhanced intergranular permeability, but in general groundwater flow and storage is entirely within fractures (Figure 15). These fractures are generally more common at depths of up to approximately 100 m. Often a single fracture, or at most three or four fractures, provide all of the inflow to a borehole, with individual fracture flows up to approximately 0.3 l/s, although typically lower than this.

Very little quantitative aquifer properties data are available for Precambrian aquifers in Scotland. For the Precambrian North, scarce records of operational borehole yields indicate that the largely unmetamorphosed Torridonian sandstone typically has the highest yields, transmissivity and specific capacity of the different Precambrian geological units (Table 15).

In parts of Aberdeenshire, the rare preservation of deep Tertiary weathering products — unlike in the rest of Scotland, where glacial erosion removed most pre-Quaternary weathering debris — has left tens of metres thickness of moderately to highly weathered Precambrian metamorphic, and in some cases intrusive igneous, rock, with enhanced permeability. This special case is treated as a form of regolith — weathered, or superficial, aquifer — and is discussed in Section 5.12.

Table 15 Summary of available aquifer properties data for Precambrian aquifers.

		Transmissivity (m^2/d)	**Specific capacity ($m^3/d/m$)**	**Operational yield (m^3/d)**
Precambrian North	Lewisian	0.2-1.3 median 0.2 (3)	0.3–0.7 median 0.49 (4)	5–11 median 10.5 (4)
	Torridonian	13–37 median 16 (3)	2.7 – 64 median 8 (5)	60–135 median 86 (5)
	Moine	0.2 (1)	0.7 – 1.8 (2)	23–328 median 38 (4)
Precambrian South	Dalradian	1.4 (1)	0.3 – 1.3 median 0.8 (2)	0–864 median 51 (88)

Ranges refer to total range in values
Number of values indicated in brackets
Data from the British Geological Survey

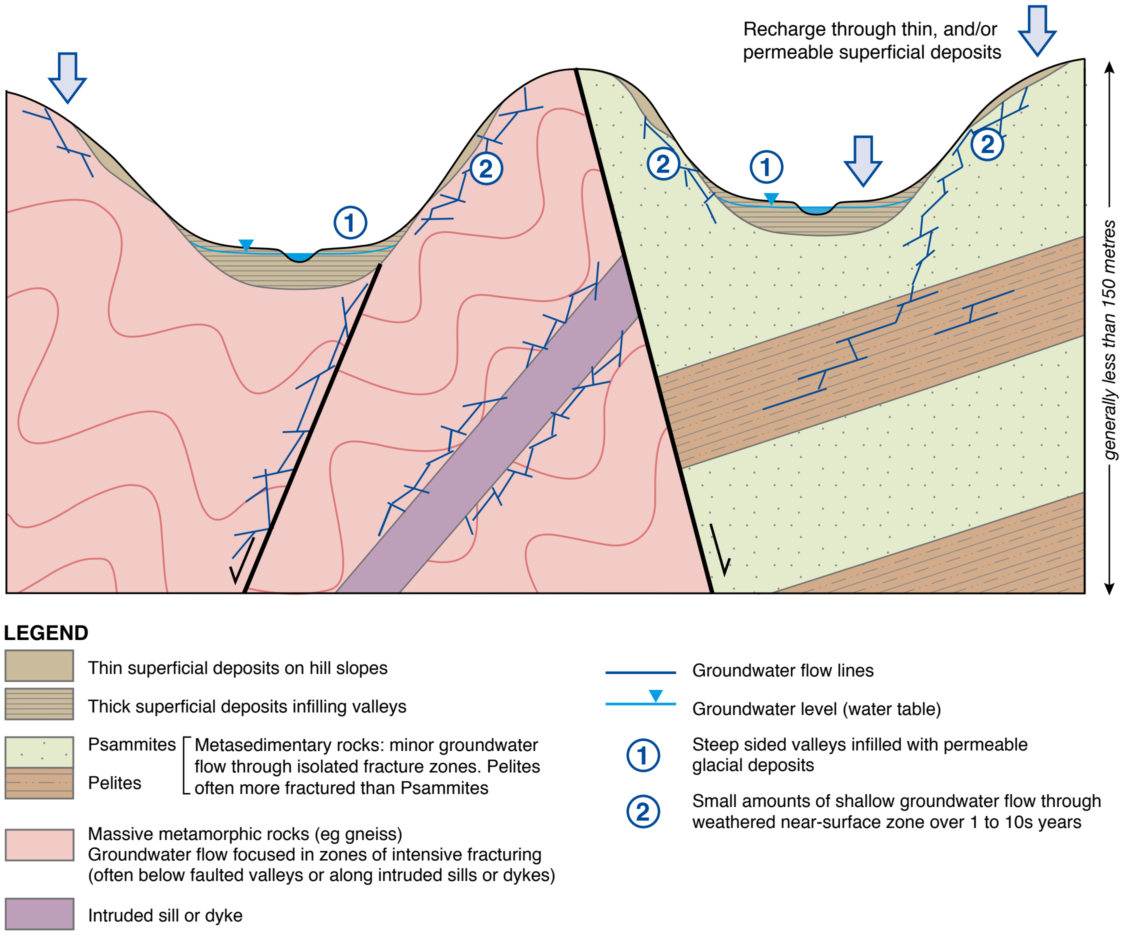


Figure 15 Schematic cross-section of the hydrogeology of Precambrian aquifers in Scotland.

5.8.3 Summary of baseline chemistry

A summary of the baseline chemistry of groundwater in Precambrian North aquifers is provided in Table 16. The baseline chemistry of groundwater in Precambrian South aquifers in Aberdeenshire is described in detail in Smedley et al. (2009). A summary is provided in Table 17.

Table 16 Summary of baseline chemistry of Precambrian North aquifers.

Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	41	0	9	13.3	20.9	34	64.6
Cl	mg/L	41	0	10.1	14	22	37	67.1
DO_2	mg/L	23	0	0.114	0.34	2.06	6.12	9.11
Fe	µg/L	40	1	2	9	41	208	1100
HCO_3	mg/L	41	0	27	46.9	72	116	221
K	mg/L	41	0	0.95	1.33	1.91	2.6	4.1
Mg	mg/L	41	0	1.18	2.1	3.73	5.9	7
Na	mg/L	41	0	7.4	11.3	18	29	35
NO_3 as NO_3	mg/L	38	4	0.15	0.18	1.25	9.90	17.46
pH		38	0	6.07	6.27	6.68	7.28	8.09
SEC	µS/cm	33	0	110	161	227	317	544
SO_4	mg/L	41	0	2.27	4.54	7.67	10.5	12

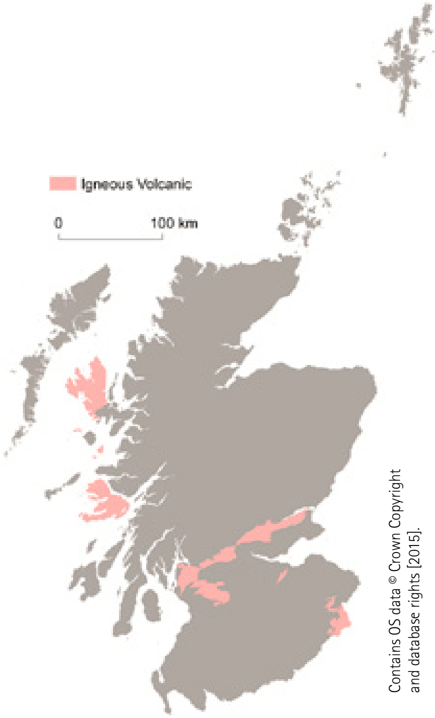
[a] number of samples
[b] number below detection limit

Table 17 Summary of baseline chemistry of Precambrian South aquifers.

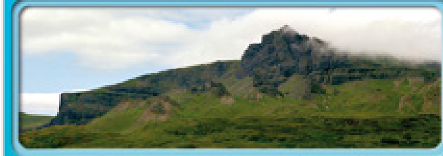
Element	Units	n[a]	n < dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	39	0	6.4	10.8	17.4	28	44.3
Cl	mg/L	39	0	3.76	4.73	15.4	30.1	39.3
DO_2	mg/L	32	2	1.09	3.32	5	7.76	9.78
Fe	µg/L	39	5	5	10	35	120	508
HCO_3	mg/L	38	0	10.8	18.2	37	108	155
K	mg/L	39	0	0.7	1.04	1.51	2.45	3.34
Mg	mg/L	39	0	1.2	2.41	4.53	7.72	11
Na	mg/L	39	0	3.06	5.51	13.7	22.6	28.9
NO_3 as NO_3	mg/L	34	2	0.18	1.99	7.96	26.70	45.08
pH		39	0	5.71	6.06	6.65	7.54	8.13
SEC	µS/cm	37	0	83.5	149	241	330	449
SO_4	mg/L	39	0	4.53	5.86	10.9	15.9	25

[a] number of samples
[b] number below detection limit

5.9 IGNEOUS VOLCANIC



Igneous Volcanic



Groundwater flow type	Fracture
Aquifer productivity	Low
Groundwater flow path length	0.1 – 1 km; usually follows local surface water catchments
Groundwater flow depth	Tens to hundreds of metres
Groundwater age	Months to decades
Baseline groundwater chemistry	Oxic, weakly to moderately mineralised; Ca HCO_3 dominated
Overlying strata	Generally thin or absent

5.9.1 Geological summary

There are innumerable outcrops of volcanic rocks across Scotland, from all time periods in the Phanerozoic. They were dominantly formed as lava flows that range from a few centimetres to many kilometres in size. Three periods in particular saw large volumes of volcanic lavas extruded: the Devonian (within the Old Red Sandstone sequence), Carboniferous and Tertiary. Volcaniclastic and, rarely, pyroclastic deposits are sometimes interlayered with the lavas; weathered layers and palaeosols within the sequence are also common.

5.9.2 Physical aquifer properties and groundwater flow

Volcanic rocks in Scotland typically form low productivity aquifers. In their unweathered state they have negligible intergranular porosity and permeability. The main controls on aquifer permeability are the degree and nature of rock fracturing, and the degree of weathering along junctions between individual lava flows (Figure 16). Highly weathered zones can have relatively highintergranular permeability, transmitting significant amounts of groundwater. Fractures in the intervening more massive rock can connect these zones and increase the overall productivity of the aquifer. Water bearing fractures are generally more common in the near surface, and are thought to become less common with depth: fracture inflows to boreholes at depths of more than 100 m do occur, but are rare.

The fractured and therefore heterogeneous nature of volcanic rock aquifers means there is a wide range in recorded borehole yields. Recorded yields range from <1 m³/d to >1300 m³/d, based on a total of 93 recorded values, with a mean of 145 m³/d and a median of 50 m³/d. The lowest recorded yields are from Devonian lavas (median 17 m³/d) and the highest from Tertiary (median 65 m³/d) and Carboniferous (median 57 m³/d) lavas. Specific capacity values for all volcanic rocks range from less than 1 to nearly 400 m³/d/m, with a median of 5 m³/d/m, based on a total of 17 values.

There are several notable abstractions for mineral water from Scottish volcanic rocks, and the aquifer is also used locally for private water supply. A number of springs from Tertiary lavas in the Highlands, particularly on Skye, are used for public water supply.

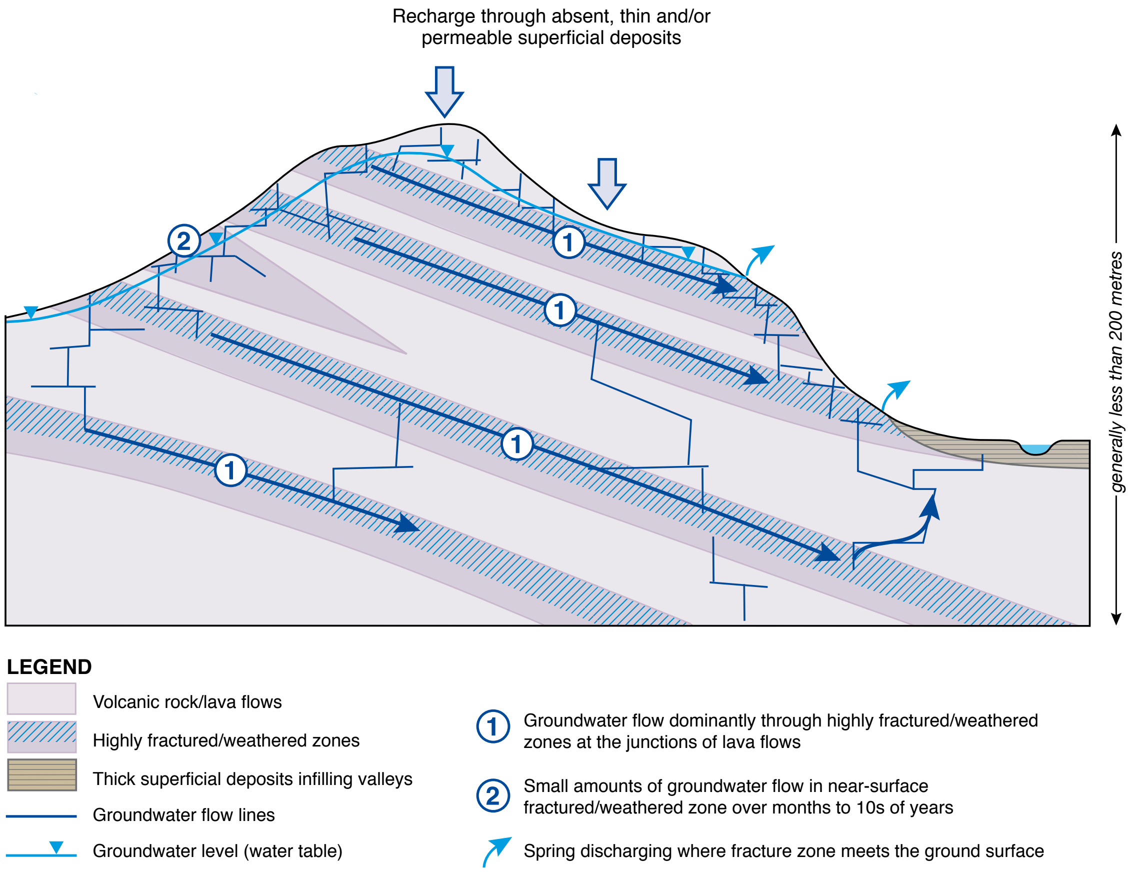


Figure 16 Schematic cross-section of the hydrogeology of volcanic igneous aquifers in Scotland.

5.9.3 Summary of baseline chemistry

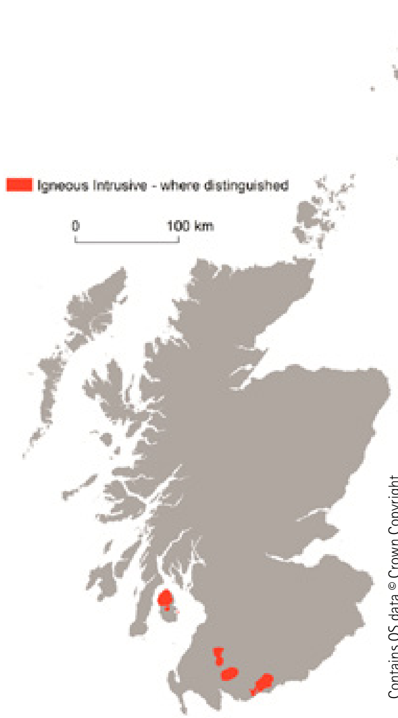
A summary of the baseline chemistry of groundwater in Igneous Volcanic aquifers is provided in Table 18.

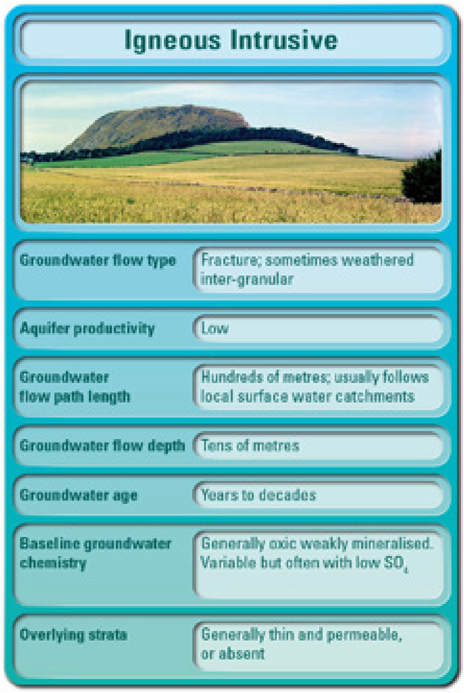
Table 18 Summary of baseline chemistry data for igneous volcanic aquifers.

Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	43	0	14.4	22.8	42.2	69	116
Cl	mg/L	43	0	7.59	10.2	22	44.1	77.7
DO_2	mg/L	24	1	1.48	2.31	5.46	6.9	9.17
Fe	µg/L	39	3	4	5	26	92	300
HCO_3	mg/L	43	0	55.7	94	158	211	245
K	mg/L	43	2	0.51	0.71	1.1	2.18	6.9
Mg	mg/L	42	0	2.31	7.57	11.5	19.3	36
Na	mg/L	43	0	9.17	12	22.5	38.1	83.4
NO_3 as NO_3	mg/L	35	0	0.72	1.69	16.00	54.81	141.44
pH		37	0	6.62	6.94	7.3	7.71	8.14
SEC	µS/cm	37	0	178	254	383	605	704

[a] number of samples
[b] number below detection limit

5.10 IGNEOUS INTRUSIVE





5.10.1 Geological summary

There are many major and innumerable minor igneous intrusions across Scotland, ranging from linear dykes a few millimetres wide to granitic batholiths many kilometres across. They date from all time periods in the Phanerozoic, but certain eras saw major periods of igneous activity, in particular the Devonian and Carboniferous.

5.10.2 Physical aquifer properties and groundwater flow

Intrusive igneous rocks typically form low or very low productivity aquifers. In their unweathered state, primary intergranular porosity and permeability are negligible, and groundwater flow and storage occurs entirely in fractures (Figure 17). In near-surface zones where the rocks are weathered, particularly for granitic rocks, intergranular permeability can be enhanced. Across most of Scotland, glacial erosion has removed most pre-Quaternary weathering, and these zones are rarely more than few metres thick, but in parts of Aberdeenshire and the Cairngorms, many metres, sometimes tens of metres, of weathered intrusive igneous rocks have been preserved. This special case is treated as a form of regolith – weathered, or superficial, aquifer – and is discussed in Section 5.12.

Few good quantitative aquifer properties data are available. The range in recorded operational yields from all intrusive igneous rocks, based on 47 recorded values, is from <1 m^3/d to 600 m^3/d, with a mean of 110 m^3/d and a median of 44 m^3/d.

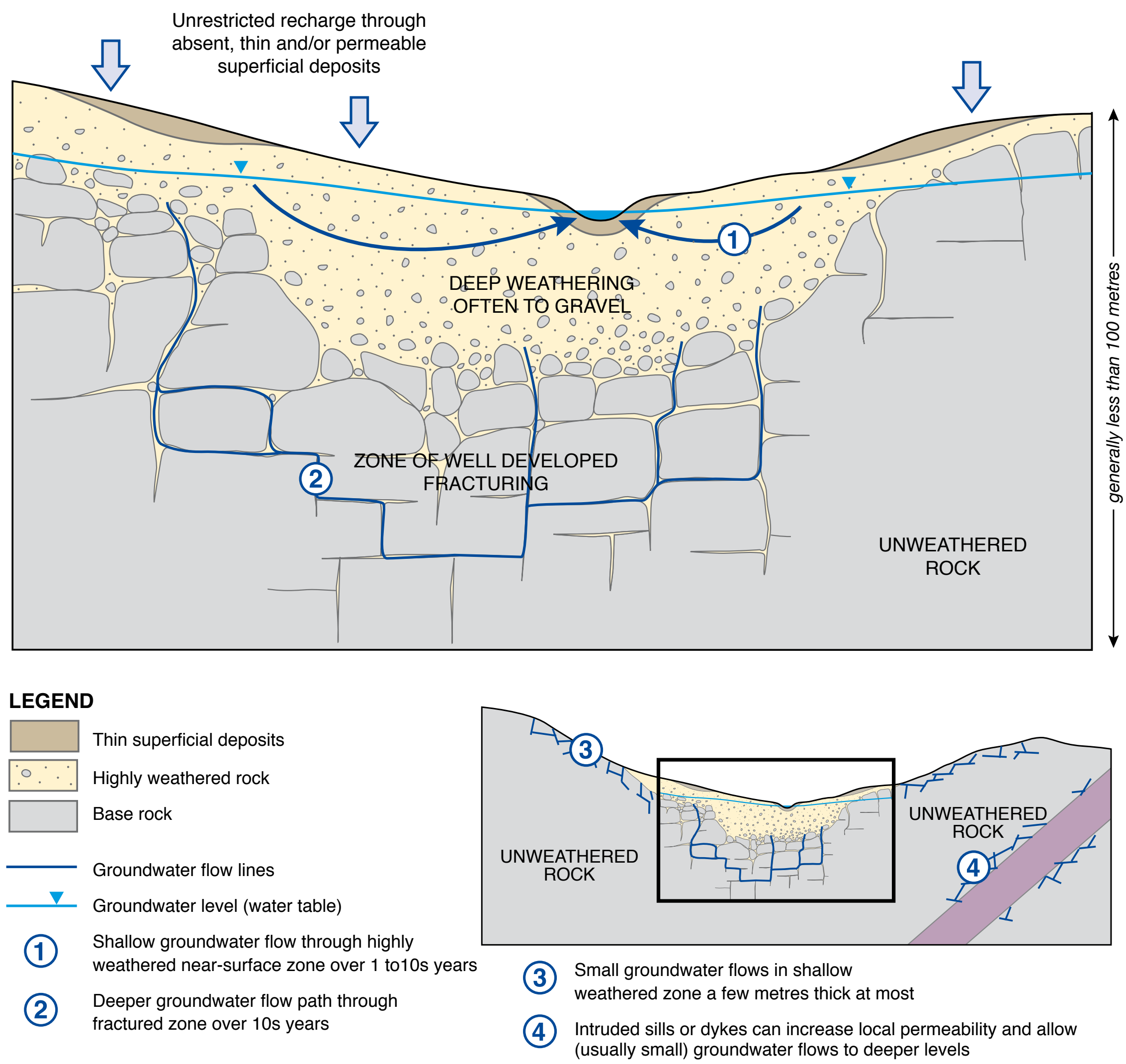


Figure 17 Schematic cross-sections of the hydrogeology of intrusive igneous aquifers in Scotland.

5.10.3 Summary of baseline chemistry

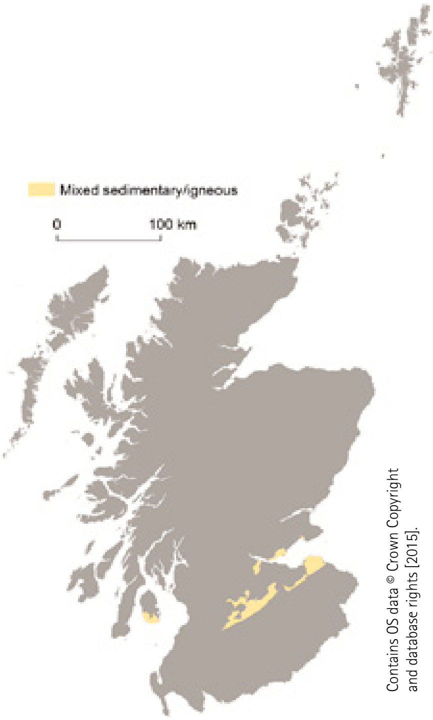
The baseline chemistry of groundwater in igneous intrusive aquifers in Aberdeenshire is described in Smedley et al. (2009). A summary is provided in Table 19.

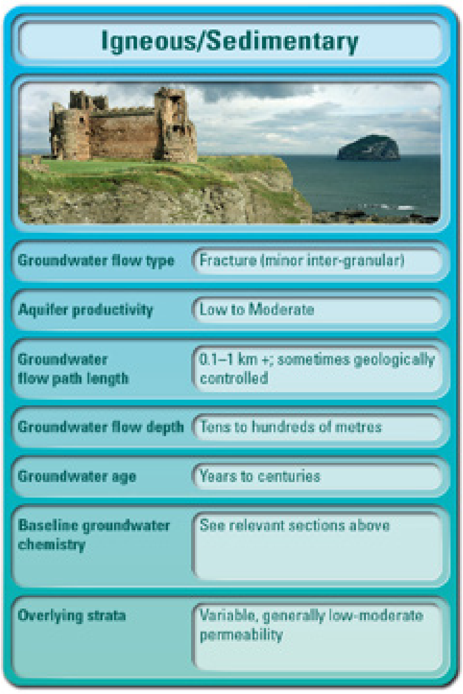
Table 19 Summary of baseline chemistry data for igneous intrusive aquifers.

Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	34	0	3.93	10.9	20	33.9	45.2
Cl	mg/L	34	0	7.4	13.5	25	41.4	68.1
DO_2	mg/L	23	0	3.26	4.55	7.6	8.39	9.7
Fe	µg/L	34	15	NA	NA	16	100	250
HCO_3	mg/L	34	1	8	17.1	37	106	204
K	mg/L	34	2	0.4	1.02	1.4	2.84	4.19
Mg	mg/L	33	0	1.08	3.6	6.69	9.29	13.1
Na	mg/L	34	0	5.21	10.5	16.5	24.7	37.6
NO_3 as NO_3	mg/L	31	3	0.04	0.75	13.30	54.81	64.09
pH		33	0	5.69	6.19	6.63	7.04	7.32
SEC	µS/cm	29	0	63.5	168	271	334	430
SO_4	mg/L	34	0	1.03	7.25	11.8	18	22.3

[a] number of samples
[b] number below detection limit

5.11 IGNEOUS/SEDIMENTARY





Igneous/Sedimentary	
Groundwater flow type	Fracture (minor inter-granular)
Aquifer productivity	Low to Moderate
Groundwater flow path length	0.1–1 km +; sometimes geologically controlled
Groundwater flow depth	Tens to hundreds of metres
Groundwater age	Years to centuries
Baseline groundwater chemistry	See relevant sections above
Overlying strata	Variable, generally low-moderate permeability

5.11.1 Geological summary

In some parts of Scotland, particularly within Carboniferous and Old Red Sandstone rocks, there are thick sequences — often many hundreds of metres in total — of interbedded sedimentary and igneous volcanic rocks. The individual volcanic or sedimentary rock layers are no different from those described in other relevant sections here (e.g. Sections 5.3, 5.5 and 5.9), but the combined sequence can behave differently as an aquifer.

5.11.2 Physical aquifer properties and groundwater flow

The individual properties of the sedimentary and volcanic layers are generally the same as for the relevant rock where it occurs separately, but as a whole sequence there are differences. Sandstone beds tend to have the highest permeability and storage, with fracture and inter-granular permeability throughout them, and can therefore contain larger volumes of groundwater than volcanic layers. However, groundwater flow that does occur through volcanic rocks can be faster, restricted to narrow, highly weathered zones (Figure 18).

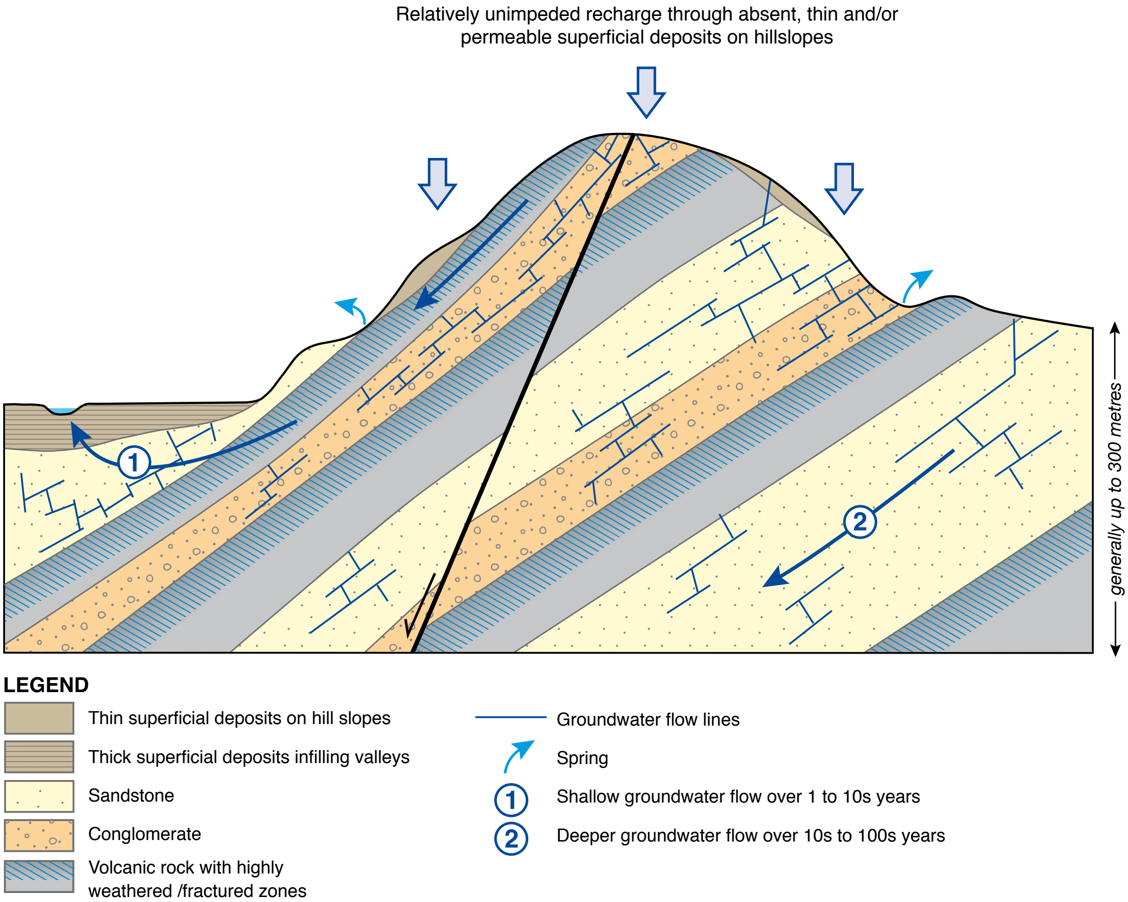
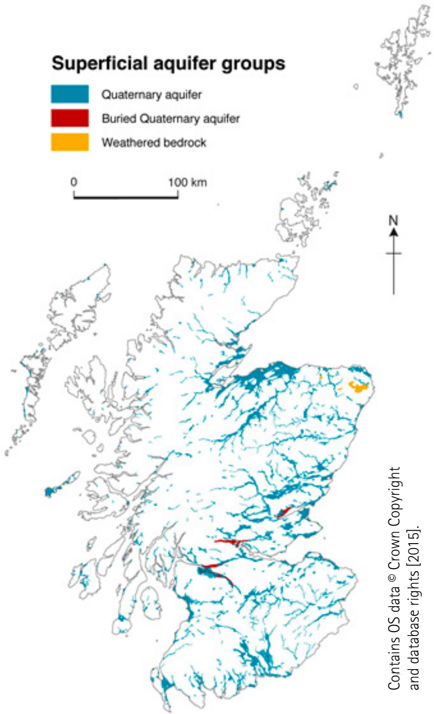


Figure 18 Schematic cross-section of the hydrogeology of mixed igneous–sedimentary aquifers in Scotland.

5.11.3 Summary of baseline chemistry

The chemistry of groundwater in this aquifer depends on the local proportion of sedimentary and igneous rocks. For the range of expected chemical parameters see the relevant sections: Section 5.9 for Igneous Volcanic aquifers; Section 5.3 for Carboniferous sedimentary aquifers not extensively mined for coal; Section 5.5 for Old Red Sandstone sedimentary aquifers and, where relevant, Section 5.1 for Permo-Triassic sedimentary aquifers.

5.12 SUPERFICIAL AQUIFERS IN SCOTLAND



Superficial Aquifers

Groundwater flow type	Intergranular
Aquifer productivity	Moderate to High
Groundwater flow path length	0.01–1 km; usually follows major surface water catchments
Groundwater flow depth	Tens of metres
Groundwater age	Weeks to years
Baseline groundwater chemistry	Variable redox conditions, weakly to moderately mineralised with a wide range of water types, but often Ca (Na) HCO3 (Cl)
Overlying strata	Generally absent

Some of the most productive aquifers in Scotland are formed of superficial deposits. However, superficial aquifers vary widely in productivity, due to their highly variable lithology, depositional history and therefore parameters such as sediment sorting, and also, importantly, 3D geometry (the lateral extent and thickness of the deposit). The thickest superficial aquifers in Scotland exceed 80m, where thick sequences of gravels and sands infill deep valleys eroded by glaciers from bedrock. Superficial aquifers have been divided into three categories according to their age, provenance and whether they crop out at the ground surface or are hidden, described in more detail in Section 3.2: Quaternary deposits mapped at the surface; buried aquifers; and deeply weathered bedrock (regolith).

5.12.1 Quaternary aquifers that crop out at the ground surface

The distribution and productivity of Quaternary aquifers that crop out at the ground surface is shown in the map above. The dominant control on aquifer properties is the mode of sediment deposition, which determines the grain size, sediment sorting and density, which in turn control permeability (MacDonald et al., 2012). The 3D geometry of the aquifers is also a key control on the hydrogeology: the thickness and extent of Quaternary deposits can be highly variable, which means that aquifers do not persist over large areas. The highest productivity aquifers are usually glaciofluvial deposits; alluvium typically forms moderate to highly productive aquifers; and coastal deposits of various kinds typically form low to moderate productivity aquifers. Key characteristics of each of these are summarised in Table 20.

Table 20 Summary of key features of the main Quaternary aquifer types (Boulton et al., 2002).

Aquifer type	Key features
Glaciofluvial deposits	Deposited by glacial meltwater rivers towards the end of the last glacial period. Widespread in occurrence, commonly infilling deeply eroded bedrock valleys, to more than 80 m deep (e.g. in the lower Spey valley), or forming broad outwash spreads across many kilometres (e.g. along the Moray coast, around Forfar in Angus, and in the Nith valley north of Dumfries). Dominated by gravel and sand but can have variable composition. Gravel channels can be very thick and highly permeable; but can be interbedded with finer grained, lower permeability deposits.
Alluvial deposits	Deposited by rivers since the end of the last glacial period, forming floodplains Typically mixed sequences with interbedded silt, clay, sand and gravel. Often overlie glaciofluvial deposits. Groundwater flows naturally towards rivers; groundwater is often in hydraulic contact with river.
Raised marine deposits	Deposited by marine action around the end of the last glacial period, when sea levels were higher. Variable composition, from coarse shingle to thick clay. Gravel beds tend to be thin and irregular, but highly permeable. Often thick clay beds. Low lying and shallow water table.
Blown sand	Typically forming sand dunes along coasts. Well-sorted sand, which can be moderately to highly permeable, but can be thin and laterally restricted

5.12.2 Buried Quaternary aquifers

Buried Quaternary aquifers are those that do not crop out at the ground surface, but are overlain by nonaquifer deposits such as clays and silts. The locations of significant buried Quaternary aquifers are shown in Figure 6. They are all dominantly formed of glaciofluvial deposits, laid down by glacial meltwater rivers in deep, pre-existing eroded bedrock valleys towards the end of the last glacial period (Table 19). Little exploration of the deposits has been done, but they are known to exceed 80 m thickness in places. They may form significant local aquifers, with large volumes of groundwater storage and flows.

5.12.3 Weathered bedrock aquifers

Significant weathered bedrock aquifers occur in lowland parts of north-east Scotland (Figure 6). The deep weathering, of both intrusive igneous (granitic) and Precambrian South rocks is thought to have occurred under the humid temperate environments of the Pliocene and warmer periods of the Pleistocene. It is common in some parts of north-eastScotland to find extensive areas with few, if any, unweathered rock outcrops. The depth of weathering commonly extends to between 10 and 20 m, and can exceed 50 m. Significant variation in weathering thickness occurs laterally (Merritt et al., 2003). Weathered rock has often been wrongly identified as superficial deposits in borehole logs, and its true extent may be much greater than is shown on this map.

The regolith — weathered rocks — varies widely in grain size, geochemistry and clay mineralogy, controlled largely by parent rock type and the degree of chemical alteration during weathering. Two distinct types are identified. The most common is dominantly sandy, with limited fine-grained material. Clay mineralogy is closely controlled by rock type, with granitic saprolites containing kaolinite-mica mineral assemblages, basic igneous saprolites containing a wide range of clay minerals, acid metamorphic rocks containing kaolinite and mica clays, and metalimestones dominated by smectite. Less common is a more evolved saprolite that has elevated clay content (more than 6 per cent) with clay mineralogy dominated by kaolinite and haematite (Merritt et al., 2003).

The regolith has significantly higher permeability and storage than the unweathered parent bedrock. Although few systematic hydrogeological studies have been done, the aquifer supports many private water supplies in Aberdeenshire.

5.12.4 Baseline chemistry of superficial aquifers

Fewer data are available on the chemistry of groundwater from superficial aquifers in Scotland, as the *Baseline Scotland* project collected data only on bedrock aquifers. However, a total of 111 samples of groundwater from Quaternary aquifers have been collected by BGS and analysed at BGS laboratories since 1984. These data have been subject to preliminary quality assurance, and the results have been interpreted to characterise key chemical parameters of groundwater from superficial aquifers across Scotland (Table 21). Threshold values were calculated using the 5th and 95th percentile of the dataset, and the median is also quoted.

Superficial aquifers are highly heterogeneous lithologically, in their size and distribution across Scotland, and the baseline chemistry of groundwater in the aquifers is also highly variable. These summarised results are therefore only a general description of the chemistry of groundwater in Scotland's superficial aquifers, but do provide threshold values within which most superficial groundwater is likely to fall.

Table 21 Summary chemistry data for all superficial aquifers in Scotland. Data from the Baseline Scotland project.

Parameter	n[a]	$P_{0.05}$	$P_{0.5}$	$P_{0.95}$
Ca mg/L	106	6.4	35.1	77.5
Cl mg/L	98	8.5	27.4	120.2
K mg/L	97	0.3	2.23	4.29
Mg mg/L	63	1.6	4.2	20.45
Na mg/L	95	6.19	14.5	71.7
NO_3 as NO_3 mg/L	61	0.44	9.68	70.4
SO_4 mg/L	61	2.4	13.8	140
HCO_3 mg/L	109	10.4	76.9	210.6
Fe mg/L	47	0.005	0.04	0.31
Mn mg/L	47	0.001	0.04	0.36
SEC uS/cm	107	105	316	737
Dissolved oxygen mg/L	62	0.4	4.8	11.3
pH	106	5.8	6.71	7.74
Temperature °C	98	7.38	9.95	12.1
Eh mV	69	12.2	296	458

[a] number of samples above detection limit

6 Conclusion

Scotland's groundwater is a hugely valuable resource, which among other things underpins much of Scotland's private drinking water supplies and the bottled water and whisky industries. Groundwater bodies are the fundamental management units for Scotland's groundwater under the Water Framework Directive (2000/60/EC) and in a River Basin Management framework, providing a risk-based framework for preventing new problems and the prioritisation of action to address existing problems. Groundwater bodies were first defined for Scotland in 2007 (SEPA, 2009b). This report describes how the delineation of groundwater bodies has been reviewed and revised during the second River Basin Management cycle, using the latest geological, hydrogeological, hydrological and pressures information, and experience gained from the first River Basin Management cycle.

This has been a collaborative project by the British Geological Survey and the Scottish Environment Protection Agency. This report includes both a record of the groundwater body review and revision process, and a summary of the physical and chemical hydrogeology of Scotland's main aquifers for use by technical specialists.

The key features of Scotland's groundwater bodies are:

- Groundwater bodies define areas of groundwater that behave in a similar way, both naturally and in response to pressures from human activity.
- Groundwater bodies have been divided into two layers: a shallow layer of superficial aquifers, and a deeper layer of bedrock aquifers. This helps to target action, as shallow bodies are more at risk from activities such as agriculture, while deeper bodies are more at risk from activities such as mining.
- Groundwater bodies are primarily delineated on the basis of geological differences, which are the fundamental control on aquifer hydrogeology. This was based on the best available geological mapping at 1:50 000 scale.
- Superficial groundwater bodies are defined as permeable superficial deposit aquifers with a minimum area of 1 km^2. They are subdivided by large surface water catchments, with a minimum total outcrop area in any one river catchment of 10 km^2, unless they are clearly linked to a groundwater dependent feature such as a wetland or large drinking water abstraction. Where necessary to maintain a relationship between bedrock and their overlying superficial groundwater bodies, they are also subdivided by bedrock groundwater body boundaries.
- Bedrock groundwater bodies are defined primarily by bedrock aquifer type, which reflects key characteristics such as aquifer properties, groundwater flow characteristics and groundwater chemistry. Bedrock aquifer groups have been subdivided into smaller groundwater bodies or amalgamated into larger bodies where necessary, according to known pressures from human activity – mostly from mining and agriculture – and management requirements. Subdivision was done on hydraulic criteria, either based on surface water catchment boundaries, or on geological and structural features, such as faults. The minimum bedrock groundwater body size is 10 km^2.

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Glossary

Abstraction, Q [m^3/d, m^3/a]
The removal of water from a groundwater reservoir, usually by pumping.

Aquiclude
A geological formation that may be capable of storing water but is unable to transmit it in significant amounts.

Aquifer
A geological formation that is sufficiently porous and permeable to yield a significant quantity of water to a borehole, well or spring. The aquifer may be unconfined beneath a standing water table, or confined by an overlying impermeable or weakly permeable horizon.

Artesian groundwater
Groundwater in a confined aquifer that is under pressure, so that when tapped by a borehole or well it is able to rise above the level at which it is first encountered. It may or may not flow out at ground level. The pressure in such an aquifer commonly is called artesian pressure.

Artificial recharge
The deliberate replenishment of the groundwater by means of spreading basins, recharge wells, irrigation, or other means to induce infiltration of surface water.

Baseflow

Natural discharge of groundwater from an aquifer, via springs and seepages, to rivers. It is baseflow that sustains the low flow of surface steams and rivers during prolonged dry weather.

Baseflow index (BFI)
An estimate of the contribution of groundwater to surface flow, taken as a proportion of total streamflow. BFI varies with time, so comparisons are only valid for the same period of for long-term averages.

Bulk hydraulic conductivity
This term is used to represent the average hydraulic conductivity of a section of aquifer, and is made up of matrix and fracture components.

Bypass flow
Movement of recharge water (usually intermittently) through fractures in the unsaturated zone of a dual-porosity aquifer.

Confined aquifer
An aquifer whose upper and lower boundaries are low permeability rocks or unconsolidated deposits that confine the groundwater in the aquifer under greater than atmospheric pressure. Groundwater in these aquifers can become artesian, where the piezometric or potentiometric surface is above ground level, resulting in overflow under artesian pressure.

Conjunctive use
The managed use of both surface and groundwater to meet variable demand. A common feature of conjunctive use schemes is the use of groundwater storage during dry periods to augment surface supplies thus creating more storage capacity to be replenished during the subsequent recharge period.

Drawdown
The reduction of the pressure head in an aquifer as the result of the withdrawal of groundwater.

Effective rainfall [mm]
The proportion of rainfall that is available for run-off and groundwater recharge after satisfying actual evaporation and any soil moisture deficit.

Ephemeral stream
An ephemeral stream is one that remains dry during some of the year. Ephemeral flow may result from a rising water table intersecting the stream bed, or from periods of rainfall and surface flow.

Evapotranspiration [mm/d, mm/a]
The amount of water that would be lost from the ground surface by evaporation and transpiration from plants if sufficient water were available in the soil to meet the demand is termed Potential Evapotranspiration (PE). The proportion of PE that is actually evapotranspired under the prevailing soil moisture conditions is termed Actual Evapotranspiration (AE).

Fracture
The term fracture is often used to refer to any parting in a rock. The term does not imply any particular orientation or origin, except that of brittle failure. Thus, joints and faults are fractures, but a fracture is only referred to as a joint or fault if the relevant mode of formation is known. The term fissure is commonly used by hydrogeologists, but its meaning is imprecise.

Fracture flow
The preferential flow of groundwater through dilated cracks, joints, bedding planes or other features of secondary porosity within an aquifer. It does not include preferential groundwater flow through a thin high-permeability horizon of an aquifer.

Flow path or flow pattern
The line or group of lines that indicate the direction of groundwater flow in an aquifer and which reflect the movement of groundwater from a recharge zone to a discharge zone.

Good groundwater status
The status achieved by a groundwater body when both its quantitative status and its chemical status are at least 'good', as defined by the Water Framework Directive.

Groundwater body
A distinct volume of groundwater within an aquifer or aquifers, as defined under the Water Framework Directive.

Groundwater flooding
Groundwater flooding is the emergence of groundwater at the ground surface or the rising of groundwater, through natural processes, into man-made ground or structures.

Groundwater rebound
Rising groundwater levels resulting from a reduction in abstraction rates following a period of high abstraction during which groundwater levels were kept artificially low. The classic scenario is in cities overlying major aquifers where groundwater levels were depressed by decades of substantial industrial groundwater abstraction, such as London. A decline in industrial activities allowed depressed groundwater levels to recover. Groundwater rebound can cause negative effects, such as a risk of flooding to subsurface infrastructure (e.g. tunnels and the basements of buildings), as well as changes in geotechnical and geochemical properties that could result in settlement and corrosion of deeply founded structures.

Hydraulic conductivity, k [m/d]
For an isotropic porous medium and homogenous fluid, the volume of water that moves in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Commonly, though imprecisely taken to be synonymous with permeability.

Hydraulic gradient
Slope of the water table or potentiometric surface. The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydraulic head [m]
The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a ground water system. For a borehole, the hydraulic head is equal to the distance between the water level in the borehole and the datum plane.

Influent stream
An influent stream or river is one that loses flow to groundwater by percolation through its porous bed. An influent stream that loses substantial amounts of their water may be ephemeral.

Karst
Limestone terrains produced by dissolution of and attrition by groundwater. Karstic limestone is characterised by the absence of surface drainage and by sinks and rising streams connected underground by flow along major fissures or in cave systems.

Licensed quantity
The volume of water, usually expressed as m^3/d, which a user is allowed to withdraw from a groundwater source under the terms of an abstraction license issued by the Scottish Environment Protection Agency.

Nonaquifer
A rock formation that does not form an aquifer: see aquiclude.

Permeability K (specific or intrinsic permeability) [mD (milliDarcy)]
The term permeability, used in a general sense, refers to the capacity of a geological formation to transmit water. Such water may move through the rock matrix (intergranular permeability) or through fractures, fissures, joints, faults, cleavage or other partings (fracture or secondary permeability).

A more strict definition of permeability is a measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient. It is the property of the medium only and is independent of the fluid. Commonly, but imprecisely, Permeability is taken to be synonymous with the term Hydraulic Conductivity, which implies the fluid in question is water.

Piezometric surface
See Potentiometric surface.

Porosity
The ratio of the volume of the interstices to the total volume of rock or superficial deposit expressed as a fraction. Effective porosity includes only the interconnected pore spaces available for groundwater transmission; measurements of porosity in the laboratory usually exclude any void spaces caused by cracks or joints (secondary porosity).

Potentiometric surface
An imaginary surface representing the elevation and pressure head of groundwater and defined by the level to which water rises in a borehole or piezometer. The water table is a particular potentiometric surface. An older term is piezometric surface.

Pressure head
Hydrostatic pressure expressed as the height of a column of water that the pressure can support, expressed with reference to a specific level such as land surface. The hydraulic head is the height of the free surface of a body of water above a given surface or subsurface point.

Pumping test
A field testing procedure to quantify aquifer properties at a site involving pumping water out of (or less commonly injecting water into) an aquifer and measuring the effect on water levels in that aquifer and sometimes in adjacent strata. There are several different procedures employed depending on the physical properties to be quantified. A constant-rate pumping test is conducted at a steady rate of discharge or injection; a step-test increases the discharge in stages to a maximum value; a bailing test is conducted during the drilling process, using the bailer drilling tool as a water withdrawal method.

Recharge [mm, mm/d, mm/a]
Inflow of water to an aquifer from the surface, from sources such as the direct infiltration of rainfall; leakage from an adjacent formation; or leakage from a watercourse overlying the aquifer.

Rest water level
The standing water level in a borehole or well when it is not being pumped.

River basin district
The area of land and sea, made up of one or more neighbouring river basins together with their associated groundwaters and coastal waters, which is identified under Article 3(1) of the Water Framework Directive as the main unit for management of river basins.

Saline intrusion
The entry of sea water into a coastal aquifer. It may be caused by over pumping fresh water from the aquifer or insufficient natural head on the fresh water aquifer. Sea water is more

dense than fresh water and it may form a wedge beneath the fresh water adjacent to the coast.

Specific capacity Q/s [l/s/m, m^2/d, m^3/d/m]
The rate of discharge of water pumped from a borehole divided by the resulting drawdown of the rest water level in the borehole.

Specific storage Ss [m^{-1}]
Specific storage of a saturated aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head.

Specific yield Sy [dimensionless]
The amount of water in storage released from a column of aquifer of unit cross sectional area under unit decline of head. Expressed as a dimensionless proportion of the saturated mass of that aquifer unit. Effectively synonymous with the Storativity in an unconfined aquifer. Equivalent to Effective Porosity.

Storativity (coefficient of storage) S [dimensionless]
The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Swallow hole
The point where a sinking stream goes underground.

Transmissivity T [m^2/d]
The integral of the hydraulic conductivity of an aquifer over its saturated thickness. It relates to the ability of an aquifer to transmit water through its entire thickness.

Unconfined aquifer
A partially saturated aquifer which contains a water table which is free to fluctuate vertically under atmospheric pressure in response to discharge or recharge.

Unconsolidated deposit
A deposit consisting of loose grains that are not held together by cement. River terrace deposits are a typical example of an unconsolidated aquifer.

Unsaturated zone or vadose zone
The zone between the land surface and the water table. It includes the capillary fringe and may contain water under pressure less than that of the atmosphere.

Vulnerability
The sensitivity of a groundwater system to contamination. Intrinsic vulnerability takes into account the hydrogeological characteristics of an area, but is independent of the nature of the contaminants and the contaminant scenario. Specific vulnerability takes these latter factors into account.

Water Framework Directive
The European Water Framework Directive (2000/60/EC; European Parliament, 2000), which came into force in December 2000, is the most significant piece of European legislation relating

to water management for at least two decades. The Directive provides a framework to pull together existing legislation relating to water and expands the scope of water protection to all waters. The main aims of the Directive are to prevent further deterioration of, and promote enhancement of, the status (quality and quantity) of water bodies and related ecosystems. This includes the progressive reduction in the pollution of groundwater.

Water table
The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere. The uppermost surface of a saturated aquifer. The rest (or static) water level in a borehole in an unconfined aquifer is equal to the water table.

Yield Q [l/s, m^3/d]
The volume of water pumped or discharged from a borehole, well or spring.

Appendix 1 Methodology for subdividing bedrock groundwater bodies in Carboniferous sedimentary rocks of the Midland Valley

The Carboniferous sedimentary aquifer in the Midland Valley, in the Central Belt, has more complex aquifer geometry and hydrogeology than other aquifers in Scotland, which have been exacerbated by the effects of mining; it is also in the most highly populated and industrialised part of the country; and because of this and the legacy of mining, is subject to more significant pollution pressures than most of the rest of the country.

Step 1 The Carboniferous sedimentary rocks in the Midland Valley were first subdivided according to whether they are coal bearing and have been extensively mined for coal in the past. Due to the complexity and high spatial variability of Carboniferous geology, certain different aquifer types were combined in the same groundwater body – in particular, mixed sequences of extrusive igneous and sedimentary rocks.

Step 2 Coal-bearing Carboniferous rocks were initially identified as the Clackmannan and Coal Measures groups. In some areas, very small adjacent outcrops of non-coal-bearing Carboniferous rocks were included with the coal bearing rocks for ease of mapping.

Step 3 These areas were subdivided along the lines of significant faults, particularly where available groundwater level information suggested that aquifers on either side of a fault were hydraulically separate.

Step 4 Additional structural information (for example, the location of anticlines) was used to further subdivide the Central and Fife Coalfields. In the Central Coalfield, the location of intrusive igneous dykes, which can act as hydraulic boundaries, were also used to subdivide groundwater bodies.

Step 5 The Passage Formation of the Clackmannan Group was defined as a separate groundwater body because of its significance as a highly productive aquifer with distinct hydrogeological properties – t is one of the only bedrock aquifers in Scotland to show significant intergranular flow.

Step 6 Remaining large groundwater bodies were divided along the boundary between the Clackmannan and Coal Measures groups.