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Review of hydrogeological knowledge of the Clyde Basin

Groundwater Systems and Water Quality Programme

Internal Report IR/05/079

BRITISH GEOLOGICAL SURVEY

GROUNDWATER SYSTEMS AND WATER QUALITY PROGRAMME

INTERNAL REPORT IR/05/079

Review of hydrogeological knowledge of the Clyde Basin

B É Ó Dochartaigh

Key words

Clyde Basin, Glasgow, hydrogeology.

Bibliographical reference

Ó DOCHARTAIGH B É. 2005. Review of hydrogeological knowledge of the Clyde Basin. *British Geological Survey Internal Report*, IR/05/079. 21pp.

Keyworth, Nottingham British Geological Survey 2005

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Parent Body

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A short review of the current hydrogeological knowledge of the Clyde Basin, including the city of Glasgow, has been carried out, and activities to address knowledge gaps have been proposed.

The hydrogeological datasets available or potentially available within BGS, Glasgow City Council and other sources are identified. These include national datasets such as maps of aquifer productivity, superficial deposits permeability and thickness, likely depth to water in superficial deposits, and groundwater vulnerability; and databases such as water boreholes, groundwater chemistry and aquifer properties. They also include local datasets such as mine plans, historical mine water pumping data, groundwater levels and groundwater discharges, and groundwater contamination events.

The complex hydrogeology of the Clyde Basin is poorly understood. Groundwater flow in most of the bedrock aquifers, both sedimentary and volcanic, occurs dominantly in fractures. Extensive mining in many of the Carboniferous sedimentary rocks has significantly changed natural hydrogeological conditions. Groundwater flow paths in the sedimentary aquifers are likely to be relatively deep and long, with Glasgow acting as the focal point for much of the groundwater discharge from the Clyde coalfield area. Groundwater flow systems in Carboniferous volcanic rocks are likely to be predominantly local, with discharge occurring as baseflow to local rivers. The natural chemistry of groundwater in Carboniferous sedimentary aquifers is often moderately to highly mineralised. Groundwater quality was also affected by mining in the 19th century. There is little recent information on groundwater chemistry in either the sedimentary or volcanic aquifers.

Little is known of the hydrogeology of the superficial deposits across the area, although they are likely to play an important role in controlling recharge to the underlying bedrock aquifers, and in influencing surface water drainage.

Consultation with representatives from Glasgow City Council has highlighted the following hydrogeological issues: sustainable urban drainage (the role of groundwater in flooding and the potential for discharging surface water to the subsurface); the lack of good quality groundwater data; the hydrogeological characteristics of made ground; the hydrogeological impacts of mining; and the potential presence of poor quality groundwater.

Improving understanding of the hydrogeology of the Clyde Basin, and addressing the hydrogeological issues, will require the development of hydrogeological conceptual models of the superficial deposits and the bedrock aquifers. Effective conceptual model development will depend on the availability and quality of data, and should be staged so that simple models are produced first to cover the whole area, which can be refined as new information becomes available. The development of more complex hydrogeological models should be linked to the current development by BGS of detailed 3D geological models for a small pilot study area in eastern Glasgow, whereby that the existing geological models are attributed with hydrogeological parameters and used as the basis for a numerical groundwater model.

The creation of robust conceptual models will require the collection of new groundwater data, including monitoring of groundwater levels and chemistry. Existing data in borehole and site investigation records should also be digitally captured so that it is easily available.

1 Introduction

This report details the findings of a review of the hydrogeological understanding of the Clyde Basin. The area of interest includes Glasgow city, the Clyde estuary and the downstream part of the River Clyde catchment. The approximate boundaries of the upper and lower Clyde catchments are shown in Figure 1, with the approximate study area highlighted.

The current study was initiated as part of the wider Clyde Basin Environmental Project, a partnership between the British Geological Survey (BGS), Glasgow City Council and the Scottish Environment Protection Agency (SEPA). This project aims to produce a comprehensive database of geoscience solutions to address environmental problems within the Clyde catchment, its estuary and the inner Firth of Clyde. Project tasks already completed or underway include geochemical surveys of the Clyde estuary and Clyde tributaries; digitisation and integration of borehole data; and digital 3D geological modelling. Future tasks include the updating of digital 1:10 000 scale superficial and bedrock geology maps; and the development of digital data on shallow mine workings and superficial deposits thickness.

The objectives of the current study were to review the available hydrogeological data for and current hydrogeological understanding of the Clyde Basin, and to identify the scope for future hydrogeological work in the area.

Previous studies of the hydrogeology of Glasgow and the Clyde Basin have largely occurred as part of wider geological or environmental investigations. A review of groundwater resources and hydrogeology in the Glasgow district is included in Hall et al (1998). A brief description of the hydrogeology of the Carboniferous aquifers of the Glasgow – Alloa area is given in Ball (1999). A review of the chemistry of groundwater in the western part of the Midland Valley, including the Clyde Basin area, is given in Robins (1986).

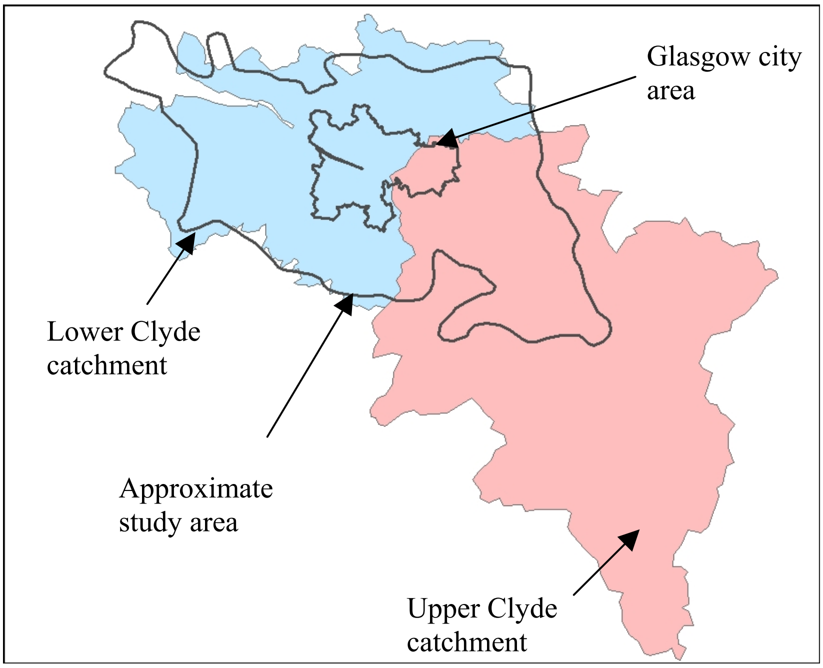

Figure 1 The upper and lower Clyde catchments shown with the Glasgow city boundary and the current study area

2 Summary of the geology of the Clyde Basin

The bedrock geology of the study area is dominated by Carboniferous sedimentary rocks, including the Coal Measures, the Passage Formation, Lawmuir Formation, and the Limestone Coal, Lower Limestone and Upper Limestone formations. These consist largely of repetitive, cyclical sedimentary sequences of sandstone, siltstone and mudstone, with thin bands of coal. Contemporaneous igneous rocks include the basaltic lava flows of the Clyde Plateau Volcanic Formation that form the terraced plateau of the Campsie Fells and the escarpments of the Kilpatrick Hills, which were formed as part of large scale volcanic eruptions in early Carboniferous times. Later igneous intrusive rocks, largely doleritic dykes and sills, date from the late Carboniferous and early Permian. Small outcrops of volcaniclastic sedimentary rocks (the Kirkwood Formation) also occur.

Superficial deposits in the Clyde Basin are dominated by glacial till, normally resting on bedrock and comprising a matrix of clay, sand and silt with pebbles, cobbles and boulders. The till, deposited during successive glaciations, is often heavily compacted. Overlying the till in many areas and dating from the end of the last glacial period are glaciofluvial sands and gravels, deposited by meltwater streams, and deltaic sands and gravels and glaciolacustrine silts and clays, deposited in ice-marginal lakes. Following deglaciation, when relative sea levels were higher than today, extensive spreads of raised marine deposits – sands, gravels, clays and silts – were laid down along the low ground adjacent to the present River Clyde. Once relative sea levels were closer to those seen today, alluvium began to be deposited on the flood plain of the River Clyde and other rivers in the area. The other main post-glacial deposit is peat, which occurs largely over upland areas.

3 Available groundwater datasets for the Clyde Basin

Most of the available data on groundwater in the Clyde Basin is found in national datasets at scales of approximately 1:100 000. At the other end of the spectrum there are data at very local scales, derived from site-specific investigations, although most of this information is not currently readily available. There is little information at intermediate scales, such as on the scale of Glasgow city or different regions within the city.

BGS has developed a number of national (Scotland-wide) hydrogeological datasets that allow a general characterisation of the hydrogeology of the Clyde Basin. Organisations other than BGS may hold a number of other datasets that could provide useful hydrogeological data for Glasgow and the Clyde Basin. The datasets are described in brief here.

3.1.1 Superficial deposits permeability

BGS has produced a GIS map of the permeability of superficial deposits (Figure 2) for Scotland, designed to be used at a scale of 1:100 000. Superficial deposits have been divided into three classes: high, moderate or low permeability. The superficial deposits were classified primarily by reference to BGS superficial deposits maps and lithological descriptions. Glacial till and moraine deposits were then subdivided according to the permeability of the soil parent material as described in the Scottish Soils Database developed by the Macaulay Institute, and their spatial distribution assigned using the Hydrology of Soil Types (HOST) spatial dataset (Ball et al, 2004; Ó Dochartaigh et al, 2005).

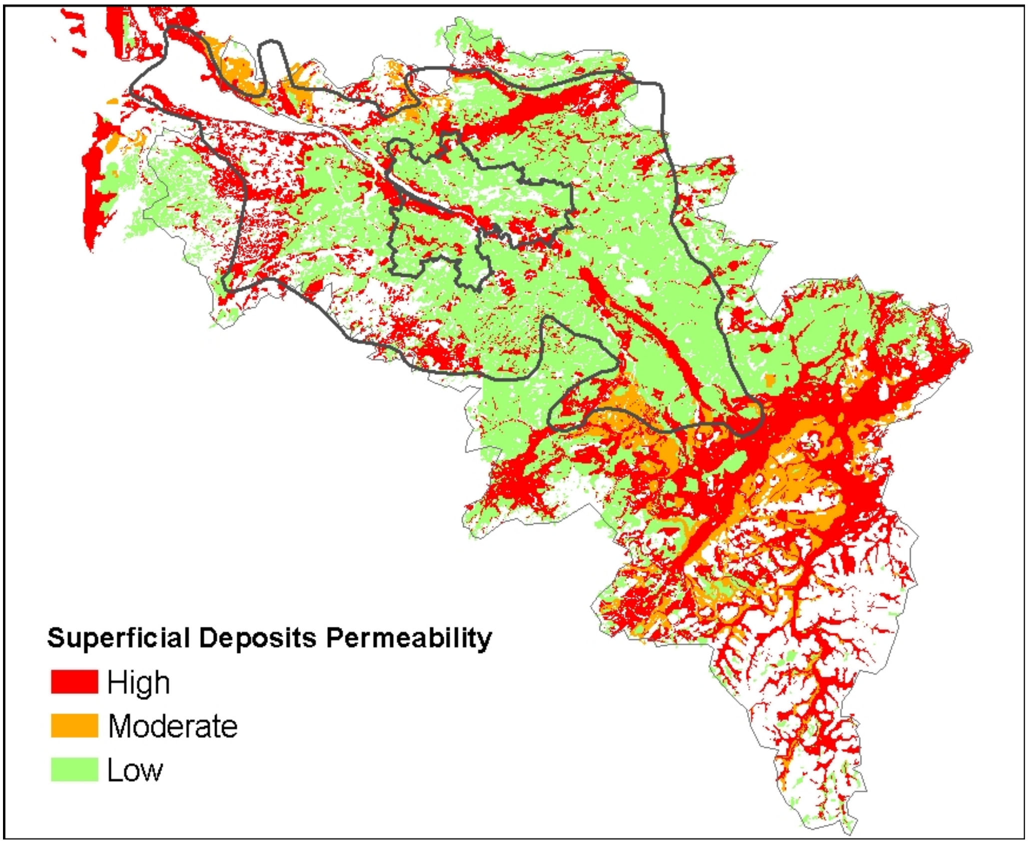

Figure 2 Superficial deposits permeability in the Clyde Basin (Ball et al, 2004; Ó Dochartaigh et al, 2005)

3.1.2 Aquifer productivity

BGS has produced GIS maps of aquifer productivity for both bedrock and superficial deposits in Scotland, designed to be used at a scale of 1:100 000 (MacDonald et al, 2004). Aquifer productivity describes the potential of an aquifer to sustain various levels of borehole supply. Boreholes in aquifers classed as having very high productivity have the potential to provide yields of more than 20 litres/second (l/s). Low productivity aquifers typically provide yields of less than 1 l/s.

The bedrock aquifer productivity map (Figure 3) has five productivity classes, ranging from very high to very low. The map also classifies bedrock aquifers in terms of the dominant groundwater flow type, with three categories: dominantly intergranular flow, mixed fracture/intergranular flow and fracture flow.

The Carboniferous sedimentary rocks underlying most of the Clyde Basin typically form moderate productivity dual porosity aquifers, in which groundwater moves dominantly by fracture flow, with a subordinate component of intergranular flow. The Passage Formation is thought to form a high productivity aquifer in which groundwater moves dominantly by intergranular flow. The volcanic rocks of the Clyde Plateau Volcanic Formation form low productivity, fracture-flow aquifers, and the intrusive igneous rocks are thought to form very low productivity, fracture-flow aquifers. Volcaniclastic rocks and tuffs are thought to form low productivity aquifers with groundwater moving by both fracture and intergranular flow.

Superficial deposits are classed as either non-aquifers or as high, moderate or low productivity aquifers. All superficial aquifers are assumed to have primarily intergranular groundwater flow. The classifications were made using BGS data, geological descriptions and the HOST classifications of the Macaulay Institute. Superficial aquifers are further subdivided into two categories based on the likelihood of them being saturated and, therefore, containing a groundwater resource. This was done using two further datasets: superficial deposits thickness and depth to water, which are described below.

The map of superficial aquifer productivity (Figure 4) shows that the bulk of the superficial deposits in the Clyde Basin are non-aquifers, largely low permeability clay-rich tills. Small outcrops of more granular tills, which can support small groundwater abstractions, are classed as low productivity aquifers. Small outcrops of granular raised marine deposits along the Clyde estuary are classed as moderately productive aquifers. Spreads of glaciofluvial and alluvial sands and gravels along the Clyde and other major river valleys are classed as highly productive aquifers.

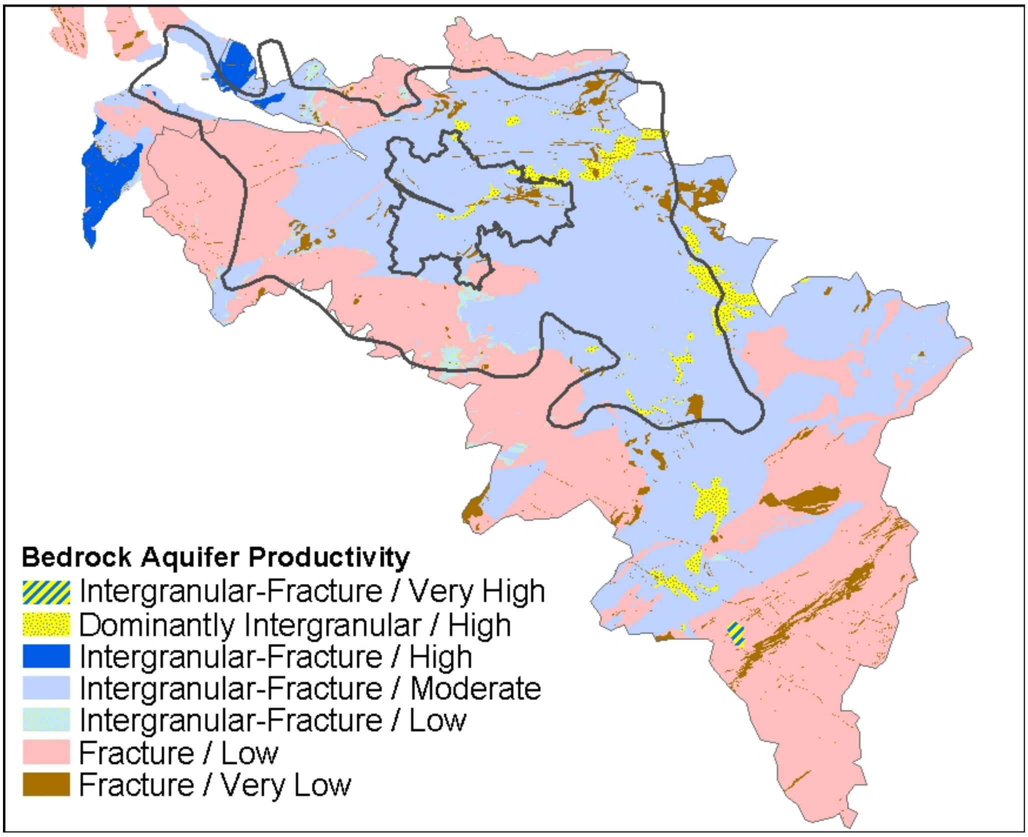

Figure 3 Bedrock aquifer productivity of the Clyde Basin (MacDonald et al, 2004)

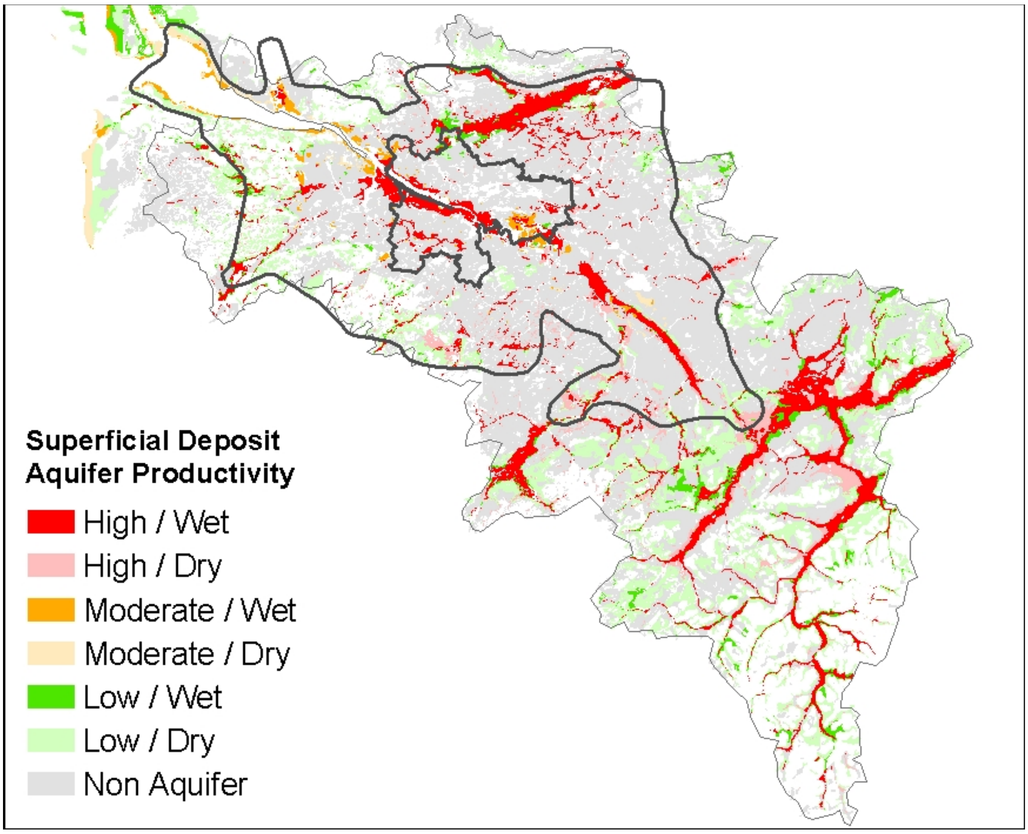

Figure 4 Superficial aquifer productivity of the Clyde Basin (MacDonald et al, 2004)

3.1.3 Superficial deposits thickness

A GIS map of superficial deposits thickness has been developed within BGS, using information on depth to rockhead from borehole records to contour the thickness of superficial deposits (Ball et al, 2004; Ó Dochartaigh et al, 2005) (Figure 5). This map was based on the BGS Geohazard database, modified using a combination of available data and expert judgment. Within the current study area, this map is most reliable in the Glasgow area, where there are sufficient borehole data to constrain the Geohazard model.

3.1.4 Depth to water in superficial deposits

In the absence of sufficient data on groundwater levels, a methodology was developed by BGS to estimate the maximum depth to water in superficial deposits (Ball et al, 2004; Ó Dochartaigh et al, 2005). The methodology was based on a digital terrain model (DTM) and river elevation, and improved by including zones where certain soil classes indicate the presence of a shallow water table, using HOST data.

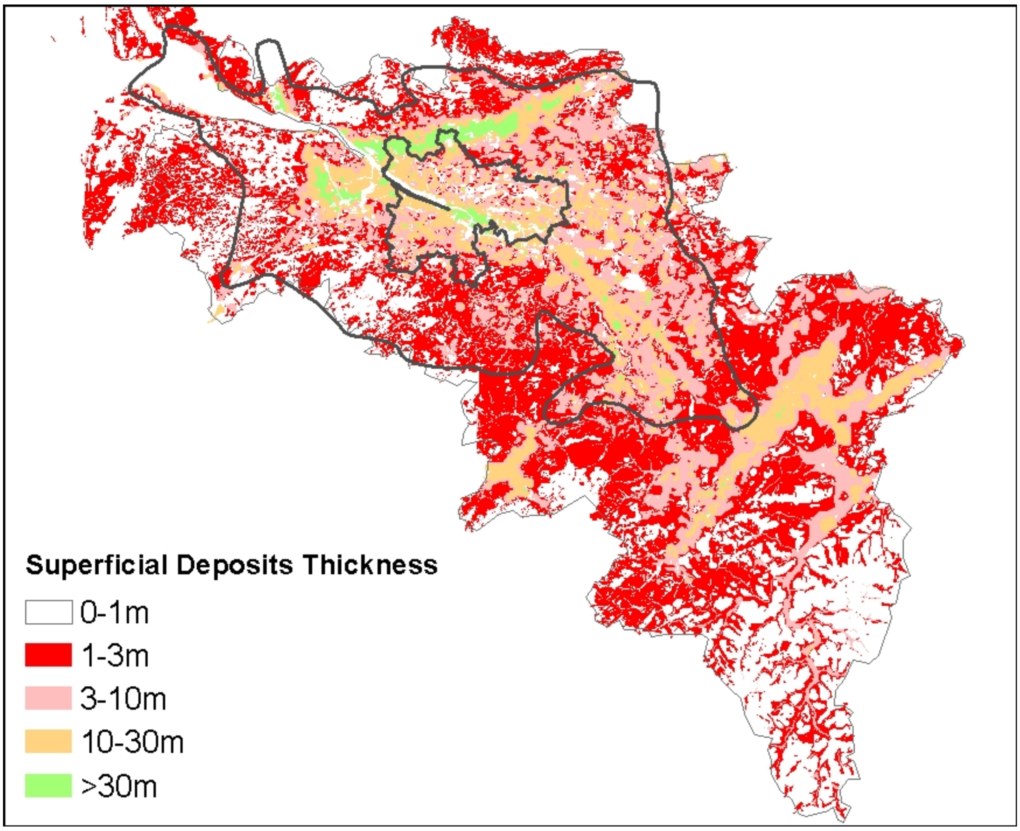

Figure 5 Superficial deposits thickness in the Clyde Basin area (Ball et al, 2004; Ó Dochartaigh et al, 2005)

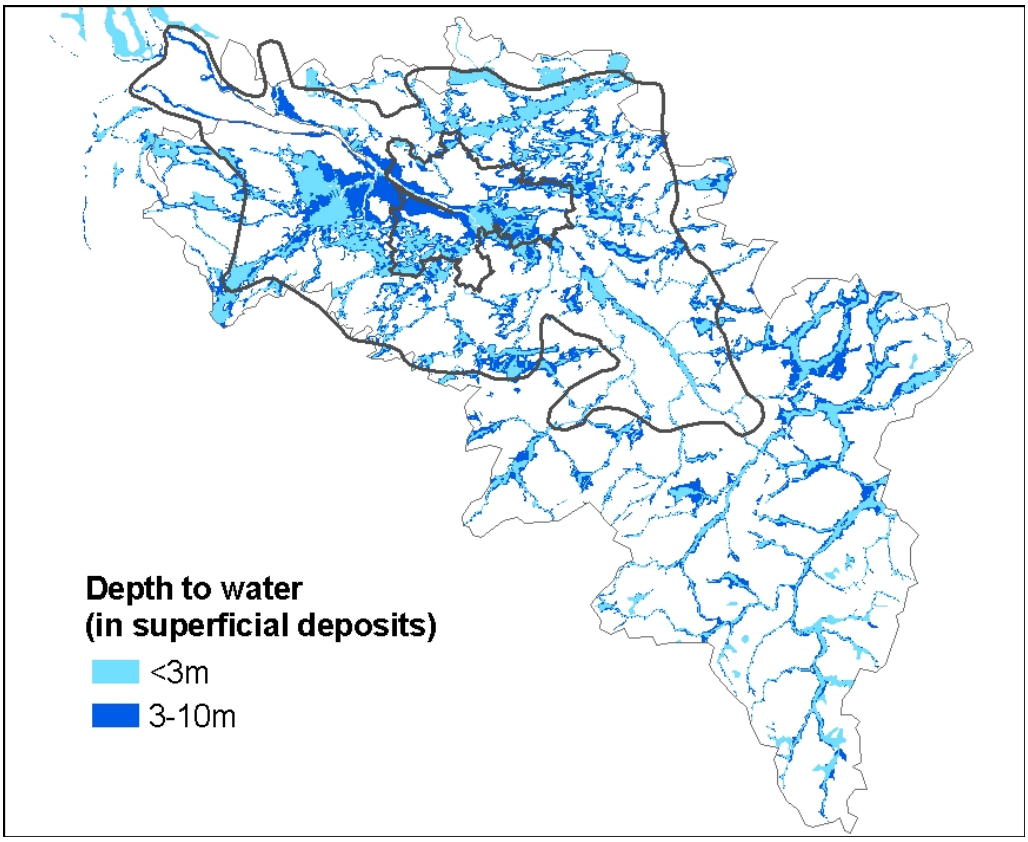

Figure 6 Estimated maximum depth to water in superficial deposits in the Clyde Basin (Ball et al, 2004; Ó Dochartaigh et al, 2005)

3.1.5 Groundwater vulnerability

A new GIS map of groundwater vulnerability in Scotland has been produced by BGS and the Macaulay Institute to meet the requirements of the Water Framework Directive (Ball et al, 2004; Ó Dochartaigh et al, 2005). The map is designed to be used at a scale of 1:100 000 (Figure 7). The map is based on a new methodology that assesses the vulnerability of groundwater in the uppermost aquifer to the vertical downward movement of a non-specific contaminant from the ground surface. It considers the intrinsic properties of the pathway between the ground surface and the water table. The key difference from previous vulnerability maps in Scotland and the rest of the UK is that the new method assesses vulnerability in all geological deposits, regardless of aquifer resource potential.

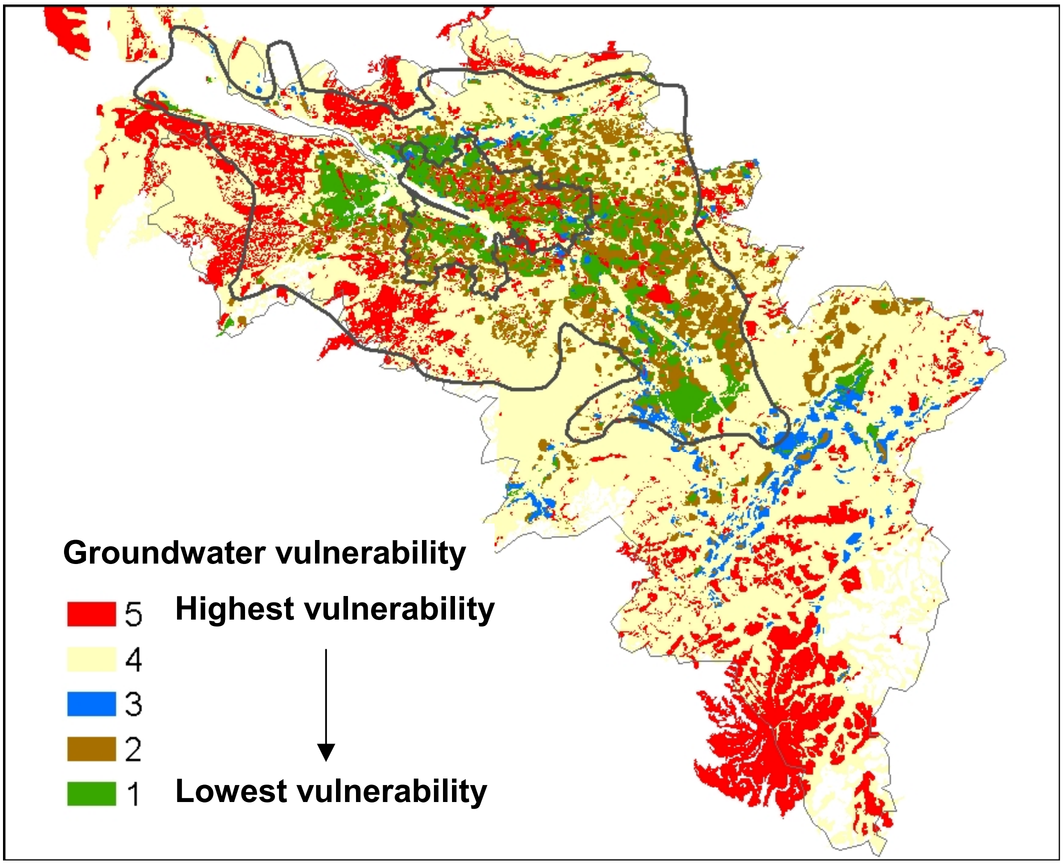

Figure 7 Groundwater vulnerability in the Clyde Basin (Ball et al, 2004; Ó Dochartaigh et al, 2005)

3.1.6 Water boreholes

The National Well Record Collection in BGS contains records of water boreholes, wells and springs across the UK. In Scotland, detailed digital data on approximately 3 000 of these groundwater sources, mostly from records predating 1990, have been captured digitally in Wellmaster, the relevant BGS corporate database. Most of the Scottish records acquired by BGS in the past 10 years are currently held only in a paper archive, pending registration and digitisation. Additionally, BGS also holds an unknown number of historical paper records of water boreholes in Scotland (mostly pre 1970) that have not yet been registered or captured digitally.

Within the Clyde Basin area there are records of approximately 380 boreholes, wells and springs (Figure 8), although only a small number of these (probably less than 20) are currently in use for groundwater abstraction or monitoring. Most of the boreholes (approximately 350) were drilled before 1965. Of those boreholes for which data are available, most were drilled into Carboniferous sedimentary aquifers, mainly the Coal Measures and the limestone formations, with at least 2 boreholes in the Passage Formation. There are also at least 20 boreholes drilled into Devonian sandstones and 10 boreholes in superficial deposits. At least 50 of the boreholes are sited within areas where bedrock geology is mapped as Carboniferous volcanic rocks, but for many of these the aquifer is recorded only as 'Carboniferous' or 'Calciferous Sandstone Measures' (the former name for Strathclyde and Inverclyde Groups). There are 329 recorded values for borehole and shaft depths, ranging from less than 1 m to 559 m, with a median value of 29 m.

The uses of abstracted water included agriculture, baking, bottling, brewing, cooling and condensing, dairy, distilling, domestic purposes, dye works, food processing, forge, ice rink, ironworks, milling, mine dewatering, nursery, paper mills, print works, sewerage and shipbuilding, as well as other unspecified industry.

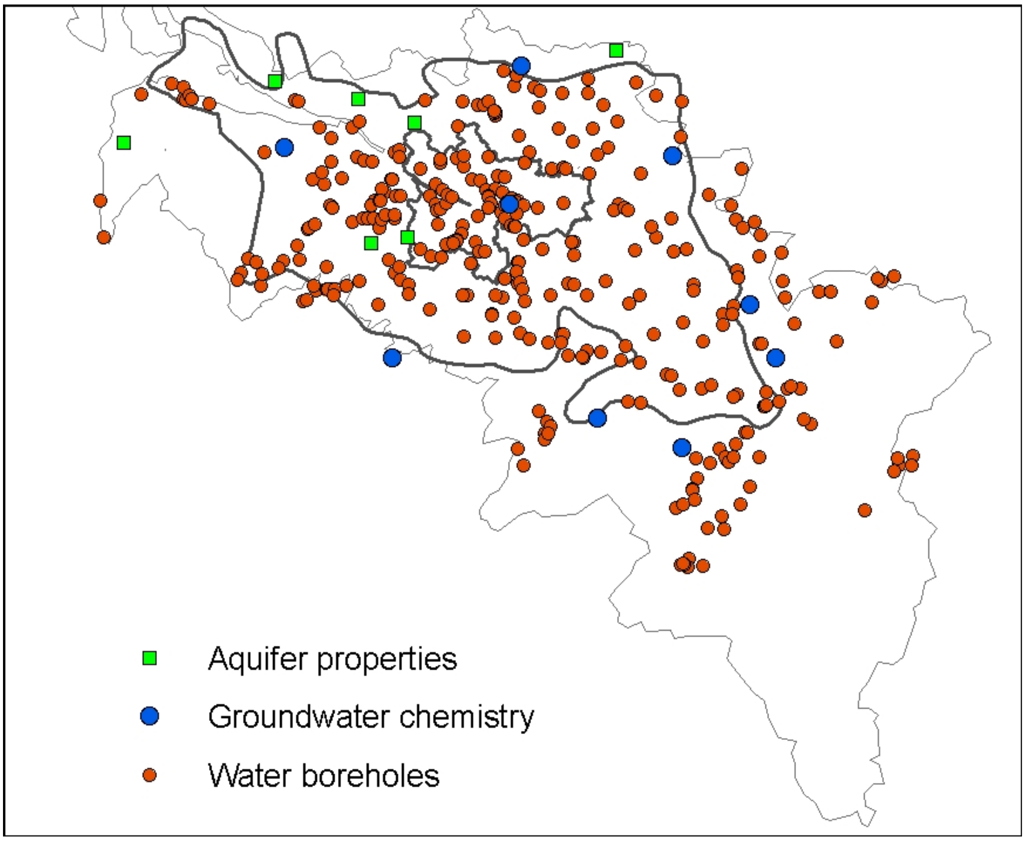

Figure 8 Water boreholes and locations of groundwater chemistry and aquifer properties data in the Clyde Basin. Note that there is more than one borehole at some sites.

3.1.7 Geology boreholes

There are numerous geological investigation borehole records and site investigation reports held by BGS that occasionally include information on groundwater. Outside BGS, Glasgow City Council also holds numerous geological and site investigation records that may have similar hydrogeological data.

A separate task within the Clyde Basin project focuses on the digital capture of geological data from existing paper borehole records. Options are being explored to facilitate the capture of any hydrogeological data in these borehole records. Because the geological data are being captured within a BGS corporate database that does not allow explicit or easy storage of hydrogeological data, it is recommended that a separate small database, specifically designed to store hydrogeological data and compatible with Wellmaster, is created as an 'add-on' to the corporate geological database.

Hydrogeological data in the paper records is usually limited to water strike levels, and occasional rest water levels, pumping and chemistry data. It is recommended that the following data should be captured, if present in the records:

- Elevation (e.g. ground level, casing top)
- Water strike level(s) (m below datum)
- Rest water level (m below datum)
- Top and bottom of screened interval (m below datum)
- Pumping test yield
- Pumped water level (m below datum)
- Any other pumping data (Y/N)
- Any chemistry (Y/N)
- Comments (e.g. details of any pumping/chemistry data)

3.1.8 Groundwater chemistry

There are few known analyses of groundwater chemistry in the Clyde Basin, either within BGS datasets or from external sources. There are available records of chemical analyses from nine boreholes in or immediately outside the Clyde Basin area (Figure 8). Of these, five are in Carboniferous aquifers, two in Devonian aquifers and two in volcanic rock aquifers. Most of the analyses date from the mid 1980s. There are not sufficient data to make generalisations about groundwater chemistry.

3.1.9 Aquifer properties

BGS hold laboratory test results for hydraulic conductivity and porosity for samples from ten boreholes in the Middle Coal Measures and from three boreholes in the Lower Carboniferous Strathclyde and Inverclyde Groups. These data give an average porosity of 15 % for the Middle Coal Measures and 17 % for the Strathclyde and Inverclyde Groups; and an average hydraulic conductivity of 0.02 m/d for the Middle Coal Measures and 0.35 m/d for the Strathclyde and Inverclyde Groups. Other studies state that the hydraulic conductivity for the more arenaceous horizons is on the order of 1 m/d, but in the mudstones and coals it may be only 10^{-2} m/d or less (Hall et al, 1998). However, in undisturbed rock, groundwater flow is dominantly via fractures, and so field values are often likely to be significantly higher than the laboratory-measured hydraulic conductivity.

The water borehole data held by BGS include some pumping test and other borehole yield information. Within the records there are 119 recorded rest water level values, ranging from overflowing at 2.5 m above ground level to 82 m below ground level (mbgl), with a mean value of 7 mbgl and a median value of 4 mbgl. There are 88 recorded values for groundwater abstraction rate, ranging from 0 (the borehole was dry) to 257 l/s, with a mean value of 30 l/s and a median value of 11 l/s. Within this, yields from Carboniferous sedimentary aquifers range from less than 1 to 257 l/s, and yields from the Clyde Plateau Volcanic Formation are generally between 0.8 and 5 l/s. Pumping water levels are rarely recorded at the same time as rest water levels, but where they are, recorded values for pumping induced drawdown ranged from 0.5 to 20 m. Only eight values for specific yield are available, ranging from 8.6 m^3/d/m to 864 m^3/d/m, with a mean value of 173 m^3/d/m and a median value of 56 m^3/d/m.

3.1.10 Geotechnical database

Hydrogeological data is also held on the BGS Geotechnical database. Relevant data includes permeability and porosity from in situ and laboratory tests, pumping test data, water strikes, moisture content variations with depth, and fracture indices.

3.1.11 Mine plans

The location of adit and mine openings for the area of the BGS Glasgow Environmental Geology maps are available digitally. The availability and location of mine plans showing the extent of underground mining is unclear. These may be available through the Coal Authority.

3.1.12 Historical mine water pumping data

There is likely to be very little data on mine water pumping regimes in Glasgow. Most mine drainage reportedly occurred before 1900, when few records were made (Robins, *pers comm*).

3.1.13 Groundwater levels

There are very few groundwater level data for Glasgow and the Clyde Basin. A few historical measurements of water levels in bedrock aquifers exist in the stand-alone database holding much of the water borehole data for Scotland (see Section 3.1.6). Groundwater levels were monitored at one time in the Daldowie sewage works borehole near the river Clyde (Robins, *pers comm*). A recent study has obtained limited groundwater level measurements from piezometers in superficial deposits close to the River Clyde (Glasgow City Council, *pers comm*).

3.1.14 Groundwater discharges

There is little information on the location or volume of groundwater discharges, either to surface water or to mine workings or other tunnels. Some anecdotal evidence on natural groundwater discharges and possible mine water discharges to surface water is known to Glasgow city council. Strathclyde Public Transport are known to be concerned about water ingress to tunnels in some parts of Glasgow (e.g. near Buchanan Street and Kelvinbridge stations). At least some of these inflows may be associated with flows in mine workings. Scottish Water may also hold some information about groundwater flows to tunnels.

3.1.15 Groundwater contamination events

A small number of groundwater contamination incidents are known of, either from information on record in Glasgow City Council or reported in the published literature (Farmer et al, 2002; Whalley et al, 1999). They are usually related to mine water rebound or contaminated land sites.

4 Summary of the current hydrogeological understanding of the Clyde Basin

4.1 GROUNDWATER USE

Groundwater has never been widely used for water supply in the Clyde Basin area, partly due to the abundance of surface water supplies and partly to the generally poor quality of groundwater from Carboniferous aquifers. A number of boreholes abstracted groundwater for industrial use during the 19th century, including three breweries. However, deteriorating groundwater quality, often due to the impact of mining, meant that groundwater abstraction was gradually abandoned from the 1860s onwards, in favour of surface water supplies from Loch Katrine (Hall et al, 1998).

From the 18th to the early 20th centuries, much groundwater was abstracted from mine workings as part of dewatering activities (Ball, 1999; Hall et al, 1998).

4.2 BEDROCK HYDROGEOLOGY

The limited available information suggests that the bedrock hydrogeology of the Clyde Basin is complex. The Carboniferous sedimentary aquifers that underlie a large part of the area are dominated by fracture flow, and although little is known about the large-scale groundwater flow system, it is likely that groundwater flow paths are relatively deep and long. Previous studies have concluded that Glasgow is the focal point for much of the groundwater discharge from the central coalfield, with prevailing groundwater flow from the east, northeast and southeast (Hall et al 1998). The limited available data on groundwater chemistry in the sedimentary aquifers indicates that the natural chemistry of groundwater is often moderately to highly mineralised, often with abundant iron and manganese in solution (Hall et al, 1998; Robins, 1986; Ball, 1999).

Many of the rocks have been extensively mined, leading to significant changes in the natural groundwater flow regime and notable deterioration in groundwater quality (Hall et al, 1998). Haphazard post-mining measures are also likely to have impacted on groundwater flow and chemistry. Mine dewatering, which continued throughout mining activities, finally ended in the 1980s (Robins, *pers comm*). There are no known problems caused by rising groundwater levels in the study area, but the lack of modern records of groundwater level in the bedrock aquifers means that current groundwater levels in the bedrock aquifer are largely unknown. Acid mine water discharge is not currently a known problem in the Glasgow city area, and investigations at a number of sites showed good quality groundwater in abandoned mine workings (GCC, pers. comm.). Parts of former mine workings have been infilled, which may cause diversions in groundwater flow, leading to groundwater discharge and/or chemical degradation in unexpected places.

In the Clyde Plateau Volcanic Formation, groundwater flow is likely to be predominantly local, from high ground towards lower-lying areas, where discharge is likely to occur as baseflow to rivers. The chemistry of groundwater in the volcanic aquifers is unknown.

4.3 SUPERFICIAL DEPOSITS HYDROGEOLOGY

Little is known of the hydrogeology of the superficial deposits across the area. It is likely that there is significant interaction between groundwater in bedrock and superficial aquifers, and between superficial aquifers and surface waters. The superficial deposits may play an important role in controlling recharge to the underlying bedrock aquifers, and in influencing surface water drainage. Representatives from Glasgow City Council report that flooding along the tributaries of the River Clyde has caused problems in some areas, but a lack of hydrogeological understanding means that the role of groundwater in such flooding is unknown. Glasgow City Council is also interested in the possibility of discharging wastewater to the ground as part of managing a sustainable urban drainage system.

4.4 ISSUES HIGHLIGHTED BY GLASGOW CITY COUNCIL

Consultation meetings with staff of Glasgow City Council have highlighted the following groundwater-related issues:

- Sustainable urban drainage: the role of groundwater in surface flooding and the interaction between surface water and groundwater, particularly in superficial deposits and made ground; and the potential for discharging surface water to the subsurface.
- Environmental impacts of mining and post-mining measures: the effects of rising groundwater levels, and changing groundwater flows and quality, particularly in bedrock aquifers.
- Impacts of groundwater on surface streams: the influence of poor quality groundwater, e.g. deriving from contaminated land or waste water drainage, on the chemical and ecological status of surface waters.

The current lack of good quality groundwater data obtained from site investigations and hydrogeological monitoring means that solutions to the above issues cannot yet be found.

5 Recommendations for future hydrogeological work in the Clyde Basin

In order to improve hydrogeological knowledge of Glasgow and the Clyde Basin, and address the issues identified in Section 4.4, there is scope for a large amount of hydrogeological investigation. The work falls into two main areas:

- Understanding the hydrogeology of superficial deposits across the area, including groundwater-surface water interaction, interaction with underlying bedrock aquifers, and groundwater chemistry.
- Understanding the hydrogeology of the various bedrock aquifers across the area, including the current and historic impacts of mining, groundwater chemistry, and interaction with overlying superficial deposits.

In both areas, hydrogeological work should focus on producing hydrogeological conceptual models that describe the current understanding of the groundwater characteristics of bedrock aquifers and superficial deposits. The conceptual models should address the physical properties of aquifers and other geological units; the nature of, and spatial (lateral and vertical) and temporal changes in groundwater flow and storage; groundwater levels and abstraction; interaction between aquifers at different depths and between groundwater and surface water, including recharge; and groundwater chemistry. Conceptual models of bedrock aquifers should also address the impacts of mining.

The development of conceptual models will depend on the availability and quality of data. The current lack of hydrogeological data means that model development should be staged. In the first instance, the available data should be used to produce simple hydrogeological conceptual models covering the whole of the study area. These will provide a necessary overview and also act as the basis for future development of more complex models when data become available. One of the practical outputs from the conceptual model may be a hydrogeological domains map based on 3D hydrogeological information, which could be used as a planning tool.

The development of more complex models should be linked to the development of detailed geological models. BGS are currently developing detailed 3D models of bedrock and superficial geology for a 10 km square area in eastern Glasgow (Sheet number NS66SW). These models could be attributed with hydrogeological data and used as the basis for a numerical groundwater model or models that would address issues such as those described in Section 4.4.

The development of detailed hydrogeological models will require much more data than are currently available. Therefore, the collation and collection of reliable hydrogeological field data should be a priority. This data will help to characterise the physical and chemical properties of the important lithologies. Data collection should include the following activities:

- The digital capture of groundwater data from available borehole and site investigation records, including, where available, groundwater levels, aquifer properties and groundwater chemistry.
- Monitoring of groundwater levels in bedrock and superficial deposits. Ideally, this would be done using a long-term groundwater level monitoring network to provide consistency of data. Such a network should be carefully designed in order to address issues such as the multi-layered nature of the Carboniferous sedimentary aquifers, and

the extensive mine workings, and the heterogeneity of the superficial deposits. For example, monitoring of water levels at different depths (e.g. by multi-level piezometers) may be required.

- Monitoring of groundwater chemistry in bedrock aquifers and superficial deposits, including contaminated land sites. Ideally, this should also be done using a long-term groundwater quality monitoring network to provide consistency of data.

The new hydrogeological data should be collected using standard protocols to ensure its quality. To this end, BGS could provide guidelines for groundwater investigations based on standard procedures, such as BS5930. These would include advice on the siting and design of investigation and monitoring boreholes, data collection during borehole drilling and testing, and groundwater sampling and wellhead chemistry monitoring.

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Most of the references listed below are held in the library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the library subject to the current copyright legislation.

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