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The Dumfries Basin aquifer

Research Report RR/06/02

BRITISH GEOLOGICAL SURVEY

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Keywords

Permian sandstone, groundwater, resource potential, modelling

Front cover

Large diameter core from the Dupont Borehole showing both the typical breccia and sandstone lithollogies found in the Dumfries Basin Aquifer. Core lies on its axis where it was laid out by the drillers, fifty year previously.

Bibliographical reference

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Preface

The Dumfries Basin aquifer is one of the most important groundwater resources available in Scotland. It is used both for public and private supply. There are known pollution hazards in the Basin and the water quality is variable. A major source of uncertainty has been the relationship of the aquifer to surface waters, and the work reported here focuses on this issue.

The investigation of the Dumfries Basin aquifer was carried out as part of the ongoing National Groundwater Survey within BGS, collaboratively with the Scottish Environment Protection Agency (SEPA) and Scottish Water. Funding was provided by all three collaborators and available data were shared within the project. SEPA also carried out field measurements and monitoring of both surface water flow and groundwater levels from their regional office in Dumfries.

Although the Dumfries Basin aquifer has been a focus of investigation for the last 25 years, work has not previously addressed an integrated approach to understanding the relevant processes. The current study has brought surface and groundwater interests together to develop a better conceptual realisation of the aquifer and its relationship to the rivers that flow across it. Supporting evidence is drawn from water chemistry and groundwater provenance indicators. The resulting conceptual model has been tested with a digital groundwater flow model which utilises the newly developed ZOOM3QD software developed jointly by the BGS, the Environment Agency and the University of Birmingham. The model, although raising some issues of uncertainty, outlines the current understanding of the Dumfries Basin aquifer and is the foundation for SEPA to carry out its forthcoming groundwater source abstraction licensing exercise, and for Scottish Water to better manage and develop its sources.

The Dumfries Basin aquifer study is an important piece of the jigsaw that is the National Groundwater Survey. It represents the first major input from the BGS Science Programme of funding into understanding the overall hydrogeology in Scotland, and with support from both SEPA and Scottish Water ensures that the study has been properly focusses on the needs of the principal stakeholders.

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Executive summary

Investigation of the hydrogeology of the Dumfries Basin aquifer commenced in the late 1970s with the commissioning of the Manse Road Pumping Station. During the 1980s and 1990s piecemeal investigation of the aquifer, focussed on the Permian breccia in the western part of the basin, took place and to a lesser extent of the sandstone in the east. Early attempts to model the groundwater flow system were hindered by lack of information pertaining to the groundwater-surface water regime prevailing over the basin aquifer. In the early 2000s the opportunity has been taken to address data gaps in order to better understand the basin-wide groundwater system. Some new primary data were collected and all the available data have been gathered together to create a new conceptual model of the aquifer which has been tested in a digital groundwater flow model. The key objectives were to define the groundwater flow system, develop a water balance and distinguish those areas currently under stress and those areas available for further exploitation.

The Dumfries Basin aquifer is situated in the lower part of the catchment of the River Nith adjacent to the sea. The basin comprises mainly Permian sediments, is deep and is partly fault-bounded, and is surrounded by weakly permeable Palaeozoic strata. The Permian sediments within the basin are divided into two formations: the Doweel Breccia and the Locharbriggs Sandstone formations. Bedrock is partially covered by superficial deposits including sandy till, sands and gravels, peat and marine clays, the latter adjacent to the sea. It is approximately 20 km long and 10 km wide. Annual rainfall varies from some 1000 mm near the coast to 2000 mm on higher ground towards the western watershed of the Nith catchment. The aquifer is under pressure both in terms of quality and quantity, with industrial and agricultural pollutants present in the area, and intensive local pumping taking place in the central western part of the basin.

The basin comprises two hydraulically distinct parts. In the west, thin sandstone units are interbedded with breccias; fracturing associated with sandstone/breccia boundaries creates the principal pathway for groundwater movement. Groundwater storage is low, but the system is recharged via near vertical fractures principally in the north-west and other areas of higher ground where granular superficial deposits prevail. This contrasts with the eastern part of the Permian basin aquifer where sandstone predominates, groundwater flow is through smaller, less extensive fractures and groundwater storage is high. A covering of silty marine clay over part of the area offers some protection to the eastern basin.

Much of the natural discharge from the Permian aquifer is to the river, via the superficial deposits. Shallow baseflow through the superficial deposits also provides significant baseflow to the rivers. The transmissivity of the Permian aquifer ranges up to 10^3 m^2 d^{-1} in the west, but storage of groundwater, particularly west of the River Nith, is largely restricted to sandstone horizons which account for only 20% of the aquifer thickness in the upper 100 m of the aquifer. In general the hydraulic response is confined except where the aquifer is in contact with permeable superficial deposits beneath which an unconfined response may occur.

The Permian basin receives direct rainfall recharge through alluvial and glaciofluvial sands and gravels and also receives some indirect recharge from losing rivers and streams in the upper part of the basin. Direct recharge from rainfall occurs across the higher ground within the basin to the north and west of Dumfries. In these areas, sand and gravel deposits promote infiltration to the water table. Discharge from the Permian aquifer is principally via superficial gravels to the River Nith north of Dumfries with some also to the Lochar Water and possibly some to the sea.

Groundwater quality derives from maritime rainfall modified by dissolution with carbonate minerals in the aquifer. The groundwater is moderately mineralised and is predominantly of a $Ca\text{-}Mg\text{-}HCO_3$ type. The pH is in the range 7.1 to 7.6 with a median of 7.2. NO_3 is present and samples available have a median of 6.1 mg l^{-1} NO_3.-N. The main source is farming through the increasing application of nitrogen fertiliser and slurry to land. Modern groundwater contains on average 9 mg l^{-1} NO_3-N, whereas the older pre-1950 groundwaters have only 2 mg l^{-1}. Locally around dairy farms concentrations of nitrate can be greater than 12 mg l^{-1} NO_3-N.

The groundwater age determinations, using CFCs as a tracer, indicate that the youngest waters occur in the central western part of the basin where most abstraction takes place and groundwater storage is low, and the oldest waters occur in the east where the percentage of modern water is less than 10%.

The conceptual groundwater flow model has the following features:

- The basin edge is effectively a no-flow boundary given the comparatively limited hydraulic properties of the surrounding Palaeozoic rocks.
- Rainfall recharge occurs to the bedrock aquifer via superficial sands and gravels which principally occur in the north-western and central part of the basin. Rainfall recharge is greatly inhibited in areas underlain by clay or silt grade superficial material and peat.
- The superficial and bedrock aquifers are not always in hydraulic contact.
- Some surface water indirectly recharges the aquifer, probably in the northernmost part of the basin.
- Potentiometry indicates both lateral flow towards the River Nith and groundwater sinks in the western central parts of the basin which are intensively pumped.
- Marine and alluvial silts inhibit discharge from the basin directly to the sea.

Water balance, recharge and groundwater flow modelling in the Dumfries Basin have allowed the conceptual model of groundwater flow to be tested. The modelling has not only confirmed the main features of the conceptual model developed to date but has also both improved it and highlighted where understanding is inadequate.

The water balance for the basin is given by:

> Recharge + runoff + river inflow + urban leakage + irrigation return + fish farm return + sewage return
> = river outflow + groundwater outflow + abstraction + spring discharge
> = 3700 Ml d^{-1}

However, 94% of the total throughflow is river inflow and outflow and recharge to the aquifer is calculated at only 200 Ml d^{-1}, i.e. one sixteenth that of river flow, making groundwater surface water interaction difficult to quantify.

Analysis of the superficial deposits, undertaken in conjunction with the recharge modelling, has shown that they are largely permeable and allow recharge to the groundwater system over much of the basin, although the main area of recharge is centred towards the north-west of the basin.

The major inflow and outflow to the groundwater system is via the rivers. Flow in the River Nith dominates the water balance; however, the flow at the tidal limit of this river is only estimated. Modelling suggests that over the long term the rivers gain water from the aquifer over much of their length.

Whilst the modelling process has enhanced the development of the conceptual model it has also highlighted the processes, which are poorly understood. In particular, deficiencies have been identified regarding recharge processes in the Lochar Water catchment and surface water-groundwater interaction along this river. The main deficiencies in the data are groundwater heads in the north of the basin, between Larchfield and Caerlaverock and, in the east of the basin. It is important that a method of measuring river flows close to the tidal limit of the River Nith is established.

In terms of resource development, firm conclusions are difficult to arrive at due to the uncertainty in the river flow in the Nith. There is no evidence of regional over-abstraction, and there are possibilities for further abstraction, particularly in the east, but development should be accompanied by careful modelling of the impact, and increased monitoring. However, the water balance demonstrates that groundwater abstraction is currently a small component of the inflow to the Dumfries Basin. With continued monitoring the numerical model will provide the spatial framework with which to test and improve the conceptual model, in particular with respect to river–aquifer interaction.

1 Introduction

The Dumfries Basin is located in the lower part of the catchment of the River Nith in south-west Scotland. The basin is a deep, partly fault-bounded outlier of Permian sandstone and breccia, with a partial superficial cover comprising a variety of lithologies which range from gravel to clay. These strata form the Dumfries Basin aquifer, a regionally significant aquifer which provides water for public supply, industry and agriculture as well as a small number of private domestic supplies. There is a complex interaction between the River Nith and the aquifer where the river and its various tributaries cross the basin. The river system and the basin aquifer receive runoff from the surrounding uplands which are underlain by Lower Palaeozoic rocks. The aquifer basin is some 10 km wide by 20 km long. The catchment areas of the rivers Nith and Lochar Water, Hydrometric Area 79, are 1230 km^2 and 150 km^2 respectively. The respective river lengths are 98 km and 36 km (Figure 1.1).

The aquifer is subject to a number of pressures in terms of quality. Of general concern is the widespread use of nitrogenous fertiliser in the catchment, particularly in the western and northern parts of the basin where the aquifer is unprotected by other than superficial sand deposits. Leaking sewers in the inner urban areas of the basin are less of a concern as these are under negative pressure from shallow groundwater in many parts of Dumfries. Industrial pollution of the aquifer in the vicinity of a large former chemical manufacturing complex at Drungans to the west of Dumfries town is also a concern. Groundwater flow paths provide a connection between the pollution plume and the recharge capture zones of a number of important water supply boreholes in the central and western parts of the basin.

The aquifer is also under pressure in terms of quantity. There is increasing evidence that intense pumping in the Terregles area to the west of Dumfries town (see Figure 1.2) has locally reduced the potentiometric head on the aquifer. This in turn has induced lateral inflow of shallow nitrate-rich water that is currently of poorer quality than the water it has displaced. Regulation of abstractors by licensing is not yet carried out in Scotland, although

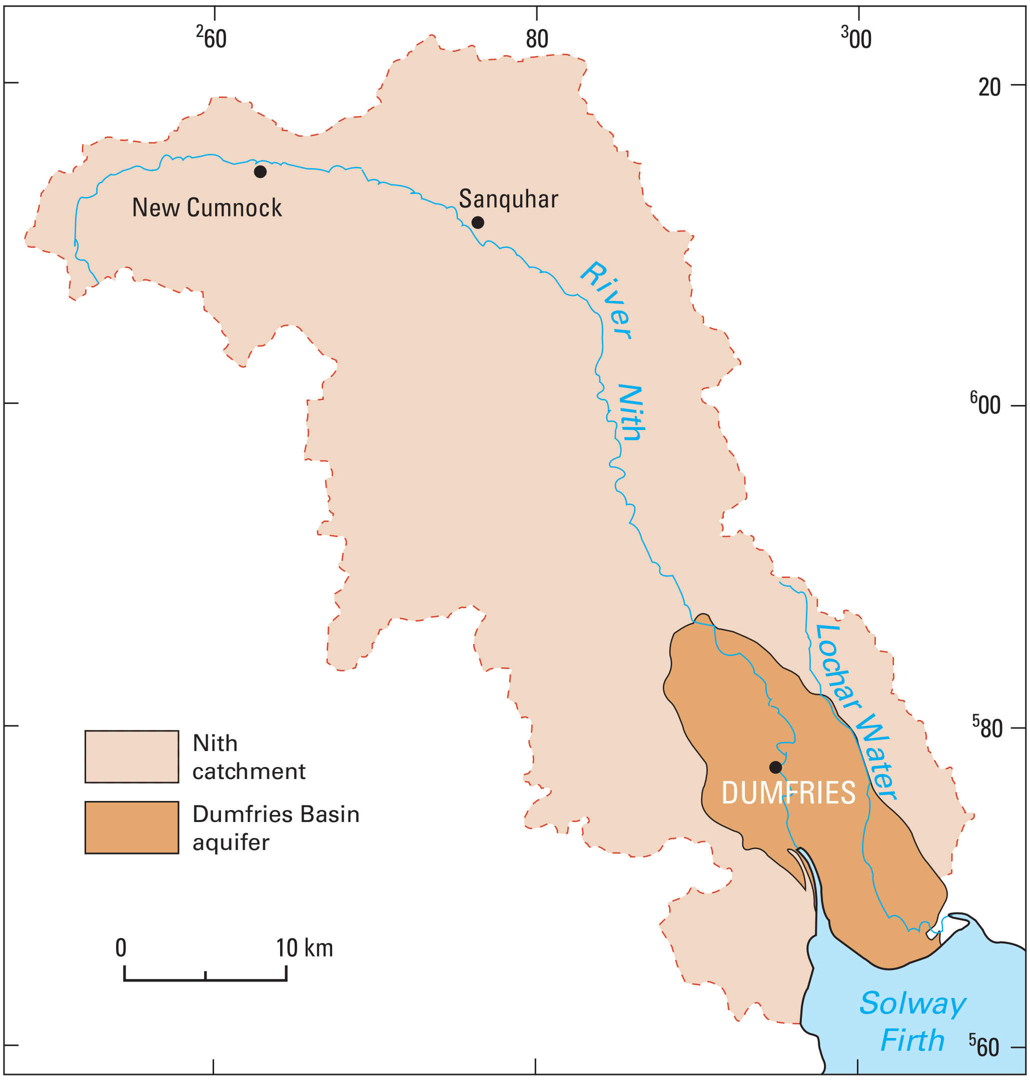
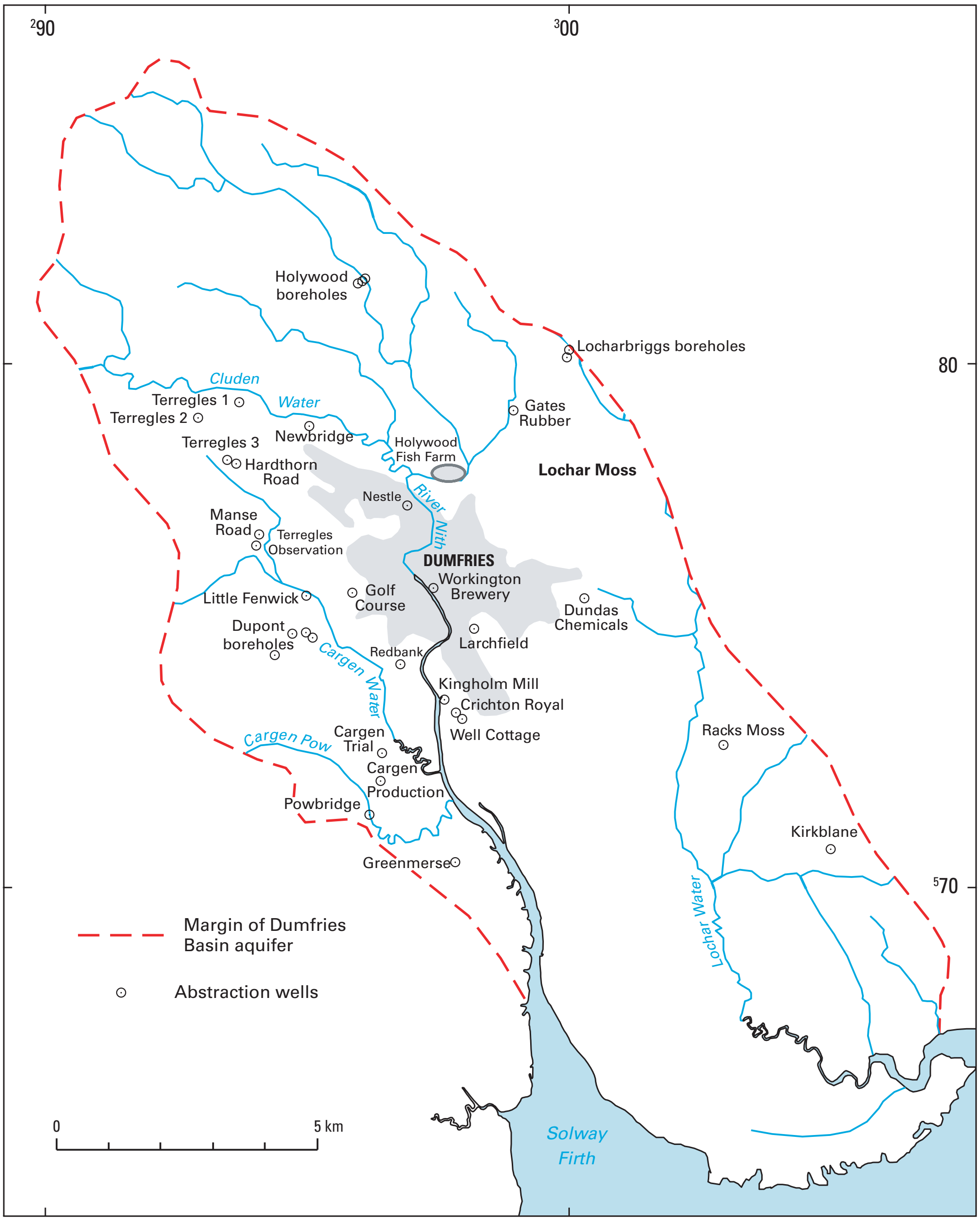


Figure 1.1 The catchments of the River Nith and Lochar Water in relation to the Dumfries Basin aquifer.

Figure 1.2 Place names and topography in the Dumfries Basin aquifer.



provision for abstraction licences in some aquifers is now being considered (see Chapter 7).

The hydrogeology of the Dumfries Basin aquifer is of interest to all groundwater users in the catchment (Table 1.1). Understanding the hydraulics of the basin is of key significance to the Scottish Environment Protection Agency (SEPA). SEPA is the responsible body for the implementation of integrated catchment management through the implementation of the Water Framework Directive (European Union, 2000). SEPA will also be responsible for issuing defensible groundwater abstraction licences in selected catchments which, by definition will undertake to safeguard licensed sources from derogation. Understanding the Dumfries Basin aquifer is also of key significance to Scottish Water (SW) who need to safeguard their existing groundwater pumping station assets and to optimise future use of the groundwater resource. Other interested parties include the fish farming units at Terregles and Holywood, and Dupont at Drungans. Protection of the resource from potentially polluting surface activities is, of course, paramount to all.

With these interests in mind, a major programme of study has been undertaken to identify and address knowledge gaps and to develop a new and robust groundwater flow model for the basin aquifer. The key objective of the study was to determine the total renewable resource available in the Dumfries Basin aquifer as a part of the overall Nith catchment. Further aims included:

- defining the groundwater flow system, its principal recharge and discharge zones
- developing a catchment-scale water balance
- distinguishing those parts of the aquifer that are under stress from those parts which are available for further additional exploitation.

The project design included four key tasks: drilling and monitoring, analytical activities, conceptualisation, and numerical modelling. Both SEPA and SW are stakeholders in the groundwater investigation study which was completed in 2004. This report describes the current understanding of the geology, the development of the conceptual groundwater flow

Table 1.1 Estimates of groundwater abstraction in 2003 in the Dumfries Basin aquifer.

Source name	NGR	Borehole depth (m)	Average yield ($m^3\ d^{-1}$)	Totals by use ($m^3\ d^{-1}$)
Manse Road Public Supply	NX 9400 7680	112	4300	
Cargen Pulic Supply (2 boreholes)	NX 9630 7210	115	2000	Public supply 7400
Larchfield Public Supply	NX 9810 7500	95	1100	
Holywood Fish Farm (8 boreholes)	NX 9760 7780	Aprox. 70	Total: 1300	
Terregles Fish Farm (6 boreholes)	NX 9290 7730	30–130	Total: 8000	Fish farming 9300
Nestle (3 boreholes)	NX 9290 7730	138–183	Total: 1380	
Dupont	NX 9430 7450	71	?	Industry 2980
Gates Rubber	NX 9890 7910	103	800	
Crichton Royal Hospital	NX 9780 7330	150	1000	Hospital 1000
Golf Club	NX 9580 7570	54	300	Recreational 300
Agriculture	various		1000	Agriculture 1000

model, and the numerical simulation model for the aquifer. This knowledge will provide the foundation for all future development and future management of the aquifer, as it is based on a logical and defensible understanding of the workings and processes within the aquifer.

1.1 TOPOGRAPHY

Elevation varies from sea level on flat-lying land by the River Nith estuary around Greenmerse, to 698 m above Ordnance Datum (OD) on Windy Standard at the head of the Afton valley. The Dumfries Basin comprises gently rolling land outwith the flatter river terraces, the local topography being controlled by moundy superficial sands and peat-infilled hollows. A distinct ridge of higher ground to the south of Dumfries from Larchfield, through Crichton Royal towards Caerlaverock Castle near the coast, rises to over 90 m OD, and was formed by selective glacial erosion of the bedrock (Figure 1.2). A similar ridge occurs on the opposite bank of the River Nith between Cargenbridge and Cargen.

The Dumfries Basin is bounded to the west by steeply rising land with hills of up to 250 m OD, and to the south by Criffel which peaks at 569 m OD. The eastern edge of the basin gives way to gently rising and undulating land that rises up to 200 m OD.

The River Nith flows into the Dumfries Basin via a narrow gorge from the Thornhill Basin, another smaller basin of Carboniferous and Permian strata. Above the

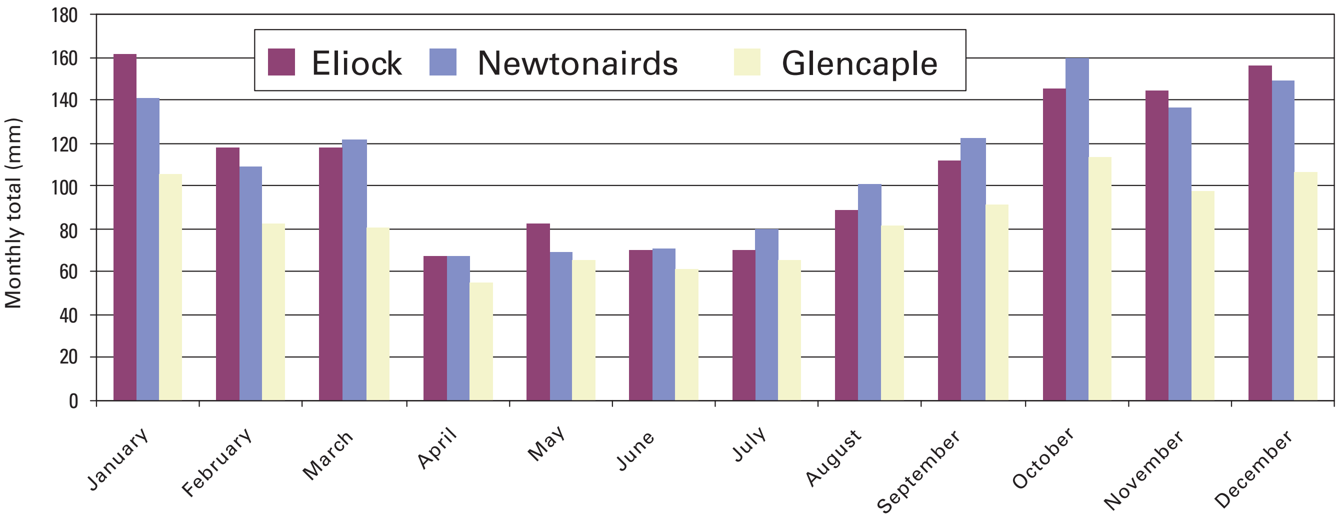


Figure 1.3 Average monthly rainfall for Eliock (Sanquhar), Newtonairds and Glencaple.

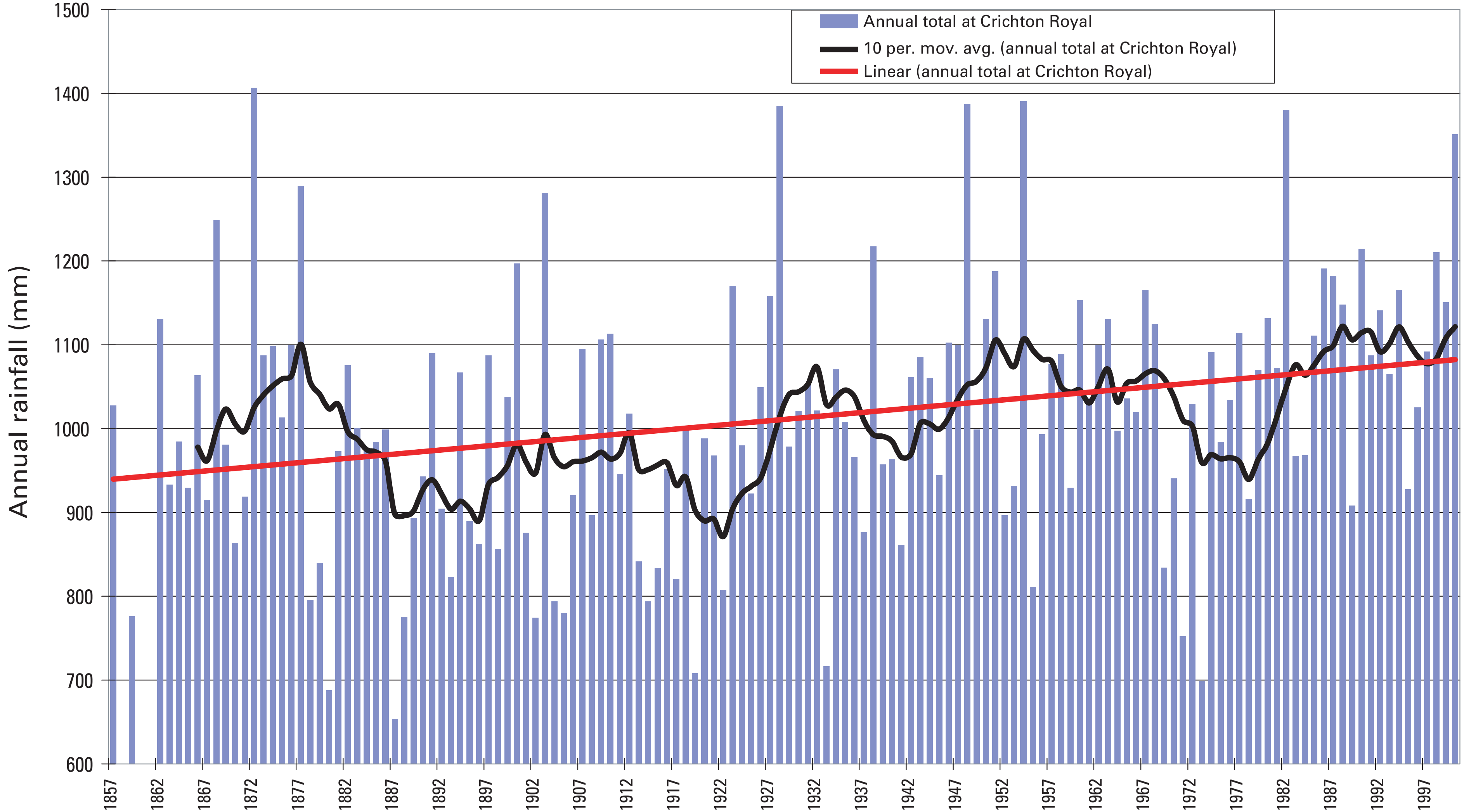


Figure 1.4 Rainfall at Crichton Royal 1857–2002 showing trend lines.

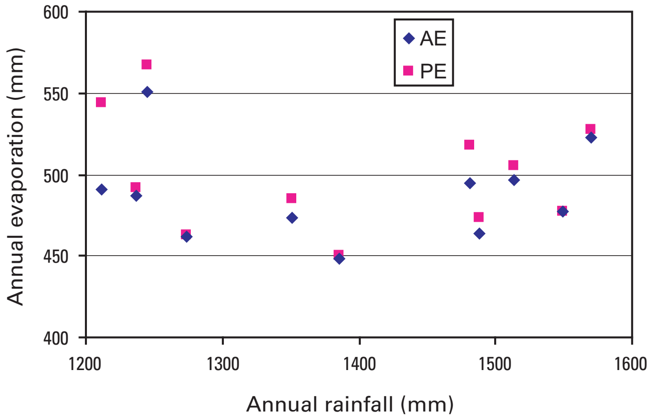


Figure 1.5 Relationship between annual rainfall and annual actual and potential evaporation (AE and PE) for the calender years 1988 to 1998.

Thornhill Basin the river drains the hills of upper Nithsdale, and the Sanquhar Coalfield. These areas are characterised by steeply sloping hillsides typical of much of the Southern Uplands.

1.2 CLIMATE

The prevailing winds are westerly moisture-laden maritime winds. Average daily temperatures in Dumfries are 3 ºC in January and 13 ºC in July. There is an average 3.7 hours sunshine per day.

Annual precipitation totals vary from approximately 1000 mm in coastal areas to more than 2000 mm over the high ground near the western watershed. Some of the winter precipitation falls as snow, with an average of 25 snowfall days per winter. The wettest months are October to March (Figure 1.3). The raingauges are situated at Wanlockhead, Sanquhar (Eliock), Moniaive, Thornhill, Newtonairds, Dumfries and Glencaple, with the longest record dating from 1857. There has been a significant overall increase in annual rainfall (5–15%) over the last fifty years in the catchment, generally as a result of increased winter rainfall (Figure 1.4).

Average potential evaporation is typically in the range 450 to 550 mm a^{-1}. The relationship between annual rainfall, actual evaporation and potential evaporation for the Dumfries Basin is shown in Figure 1.5. The data derive from the eleven years 1988 to 1998 and they show that actual evaporation may only be marginally less than the potential evaporation in some years whilst the difference may be as high as 53 mm in others, but that the differences do not correlate with higher or lower annual rainfall.

1.3 LAND USE

The Nith catchment is the most densely populated and industrialised catchment in Dumfries and Galloway. Surface water quality nevertheless remains high, and the River Nith is a designated salmonid river.

Much of the lowland areas of the Dumfries Basin, the Thornhill Basin and the flatter land in the higher parts of the Nith catchment are devoted to grassland as pasture for cattle, and in the Hardthorn Road area of the Dumfries Basin also for horses. Large areas of the Lochar Water catchment, particularly around Lochar Moss, Craigs Moss and Ironhirst Moss are forested. The remainder of the Dumfries Basin is urban or industrial and there is a large working sandstone quarry at Locharbriggs.

The upland areas of the catchment are largely given over to rough grazing, forestry and moorland.

2 Geology and structure

2.1 GEOLOGY

The bedrock aquifer sequence of the Dumfries Basin comprises the Permian Doweel Breccia and Locharbriggs Sandstone formations (Permian) (Figure 2.1). The Doweel Breccia consists of predominantly sedimentary breccia interbedded with sandstone, and underlies the western part of the basin (Brookfield, 1978, 1980; British Geological Survey, 1996; McMillan, 2002). The formation extends eastwards toward the centre of the basin where it interfingers with the Locharbriggs Sandstone which underlies the eastern and northern parts of the basin. The Locharbriggs Sandstone comprises two facies: distinctive orange-red, cross-bedded sandstones (Plate 1), interpreted to have accumulated as a migrating dune field in arid desert conditions; and thin-bedded and laminated, orange-red, silty sandstone containing pebbles of local derivation generated by fluvial reworking of breccia and sandstone (Brookfield, 1978, 1980; Akhurst and Monro, 1996; McMillan, 2002).

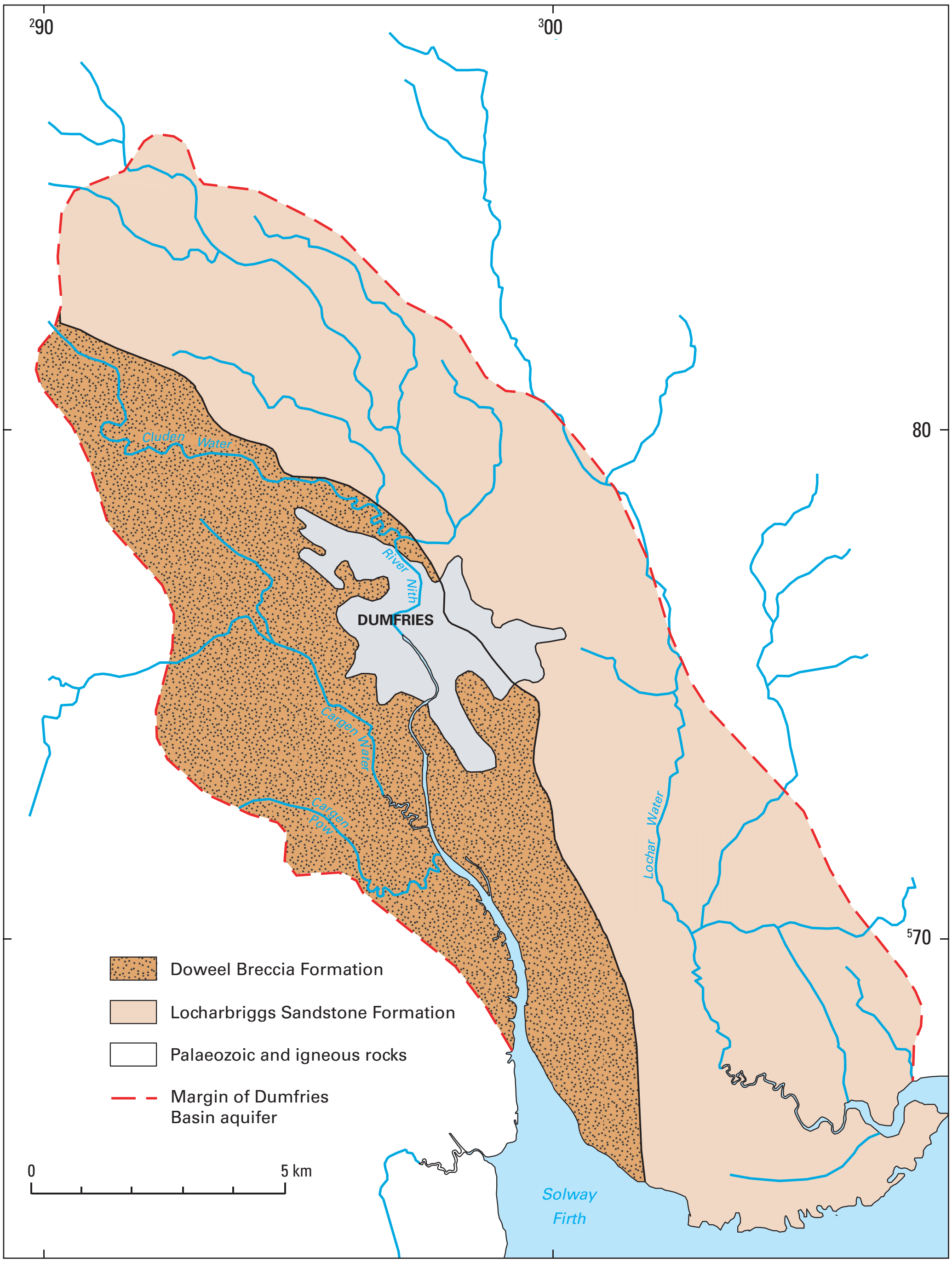


Figure 2.1 Solid geology of the Dumfries Basin.

Plate 1 Locharbriggs Sandsone as a freestone — Church of Scotland building, English Street, Dumfries.

The Permian basin-fill sequence unconformably overlies a steeply dipping succession of grey, fine-grained, wacke sandstone and mudstone of Silurian age that is intruded by the Criffel-Dalbeattie granodiorite to the south-west of the basin (Lintern and Floyd, 2000). Carboniferous strata, continuous with the sequence in the adjacent Annan Basin, unconformably underlie the south-eastern part of the Dumfries Basin (British Geological Survey, 1998; Holliday et al., 2001).

The Permian basin-fill sequence is inferred to have a maximum thickness of between 1.1 and 1.4 km, from modelling of airborne gravity data, with the centre of the basin lying immediately to the north of Dumfries (Kimbell, 2002). The basin is interpreted from Bouger gravity anomaly data, to be fault-bounded by a series of *en echelon* faults along its western margin, and fault-bounded also to the north-east.

The superficial geology of the Dumfries Basin is dominated by an extensive development of glacigenic deposits, both granular and cohesive, formed during the Dimlington Stadial (late Devensian) glaciation (Figures 2.2 and 2.3). To the south-east of Dumfries, ice originating in the Southern Uplands, moulded a streamlined topography of rock ridges aligned north-west to south-east (Plate 2). During deglaciation, active retreat of the Nith glacier took place in a north-westerly direction to pinning points (bedrock highs) at Cargenbridge, Maxwelltown and Locharbriggs. To the north-west of Dumfries, the basal deposit resting on the Permian strata is an overconsolidated sandy diamicton with wacke and sandstone clasts. This deposit is regarded as the lodgement till of the Dimlington Stadial ice sheet. On the lower-lying ground the till is overlain by extensive discontinuous spreads of cobble gravel which form a distinctive landscape of mounds (kames), up to 15 m high, kame terraces and ridges (eskers), the crests of which trend north-west to south-east. These deposits exhibit normal faulting characteristic of an ice-contact origin. They are commonly overlain by a discontinuous thin (usually 1m or less) gravelly flow till.

To the south-east of Locharbriggs (in a more distal position in relation to the retreating ice-front) fine sand, silt and clay, with dropstones, were deposited in ephemeral glacial lakes. These glaciolacustrine deposits are overlain by tabular spreads of cross-bedded sand and pebbly gravel. As deglaciation proceeded, the Nith glacier readvanced resulting in the formation of a moraine, characterised by moundy topography that extends in an arc between Locharbriggs and Cargenbridge. The deposits of the moraine, which locally exceed 30 m in thickness, mainly comprise gravel and till. They also contain beds of sheared glaciolacustrine sand and silt.

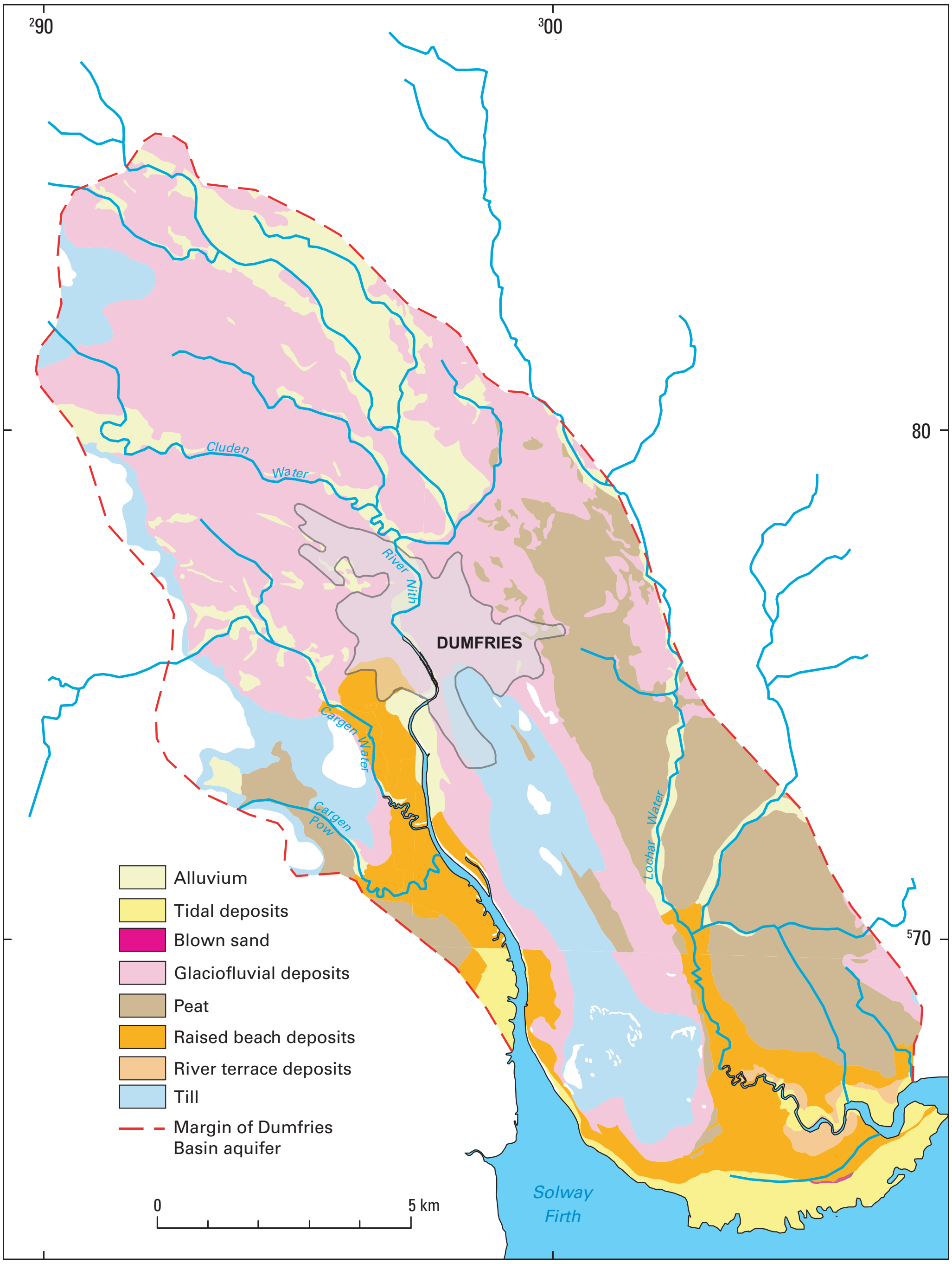
Following deglaciation, a rise in relative sea level resulted in the deposition of extensive late-glacial estuarine deposits of bedded sand, clay and silt to the south of Dumfries. Owing to isostatic rebound, these deposits now form dissected terraces which generally lie at an elevation of 10 to 15 m OD (McMillan, 2002). Marine clays, once worked for brick-making, are overlain by bedded sands of littoral origin south of Cargenholm. During the Holocene, there was renewed estuarine and tidal flat sedimentation associated with the main postglacial transgression. This laid down fine-grained sediments which form flat-lying ground up to about 10 m OD backing the coast (Smith et al., 2003). Extensive peat basins, such as those at Lochar Moss and Kirkconnell Flow, have developed locally on top of the Holocene alluvial, estuarine and tidal-flat deposits. The most recent alluvial sediments of the Dumfries Basin occupy the valley floor floodplain and lowest terraces of the River Nith and its tributaries. These comprise gravel, sand and silt reworked from the glacigenic sequences.

2.1.1 Geological investigation

A summary of research on the Quaternary deposits of the Dumfries Basin was presented by Golledge (in McMillan, 2002). A recent initiative has resulted in the remapping of the Quaternary deposits of the southern half of the Dumfries Basin aquifer area and elsewhere in the Solway district. This is now complete and a new 1:50 000 scale geological map (British Geological Survey, 2004) is available and an accompanying research report is in preparation. Major findings of the new survey in the southern part of Dumfries Basin are:

- The glaciofluvial deposits are more variable in composition and are less extensive than previously interpreted, especially within and to the south of Dumfries (e.g. Institute of Geological Sciences,1980; Goodlet, 1970; Cameron, 1977).
- Although a thin discontinuous flow till forms a surface drape to some of the glaciofluvial deposits (notably those forming kame terraces) there is no evidence of a widespread 'tripartite' till-sand-till sequence, such as is present in the Gretna district and parts of north Cumbria (Trotter and Hollingworth, 1932).
- Streamlined landforms provide evidence that ice flowed from west to east on the interfluves but that in Nithsdale the flow was predominantly from north-west to south-east along the axis of the valley.
- A moraine composed of glacitectonised sediments up to 30 m thick crosses the valley of the Nith between Locharbriggs and Cargenbridge. Lateral moraines, up

Figure 2.2 Superficial deposits in and around the Dumfries Basin.



to 20 m high, are present on the north-west side of the Nith valley between Dalswinton and Duncow.

- Raised beach and estuarine deposits of both late glacial and Holocene age form flat-lying ground on both sides of the Nith estuary downstream of the readvance moraine. They provide evidence of high relative sea level during the late glacial and again during the main postglacial transgression.

The Quaternary hydrogeology is summarised as depositional units or Quaternary domains in Figure 2.4 with domain descriptions given in Table 2.1. Estimated thickness of superficial material is shown in Figure 2.5.

Bedrock is concealed beneath superficial deposits in the south-eastern part of the Dumfries Basin although the thickness of the deposits and elevation of rockhead was not well understood prior to the drilling of the aquifer investigation boreholes. The transect from north-west to south-east both parallel to the basin margin and downstream of the Lochar Water reveals a marked variation in thickness of superficial deposits and elevation of rockhead (Table 2.2). The preserved thickness of superficial deposits thins markedly from 32 m at Lochar Moss and Racks Moss, through 10 m at Ironhirst Moss to only 5 m thickness at Longbridgemuir (Ó Dochartaigh, 2002). The elevation of rockhead proven in the boreholes (Table 3) rises from -21 m OD at Racks Moss to 1 m OD at Ironhirst Moss and is 15 m OD at Longbridgemuir; a shallowing of rockhead by 36 m over a distance of 9.5 km parallel to the basin margin.

Strategic collection and interpretation of geological data within the Dumfries area has greatly enhanced understanding of the bedrock geology on the eastern side of the basin. The basin margin is interpreted from Bouger gravity anomaly data to be partly fault-bounded on its eastern side by the Tinwald Fault. Unlike the western basin margin, Permian strata do not extend to the fault along its entire length but have been eroded from the hanging wall block in the south-eastern part.

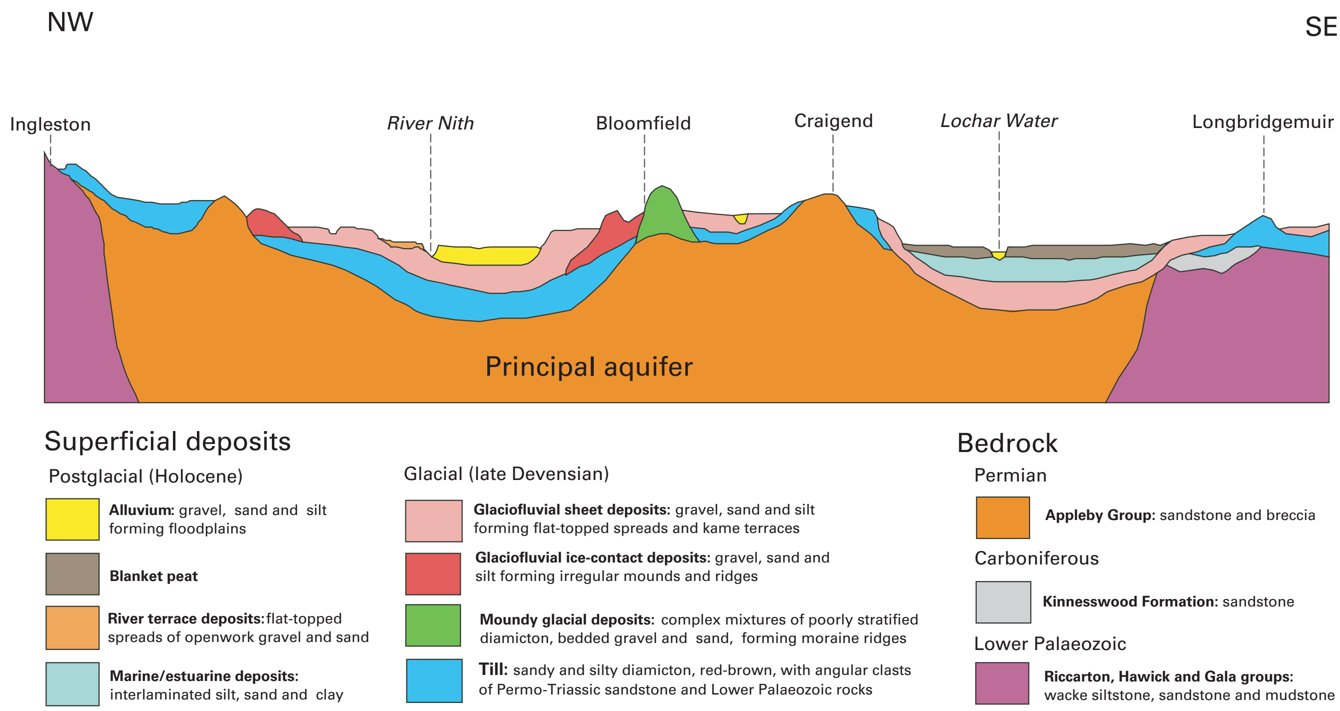


Figure 2.3 Schematic cross-section north-west to south-east showing the superficial deposits.

Data from three partially cored boreholes drilled during this study have placed additional constraints on the bedrock geology that is otherwise concealed beneath superficial deposits in the south-eastern part of the basin. Carboniferous strata have been proven to underlie Permian strata within the basin in the Longbridgemuir Borehole (Table 2.1). Fine-grained and well-sorted, white quartz sandstone characteristic of Carboniferous strata in the region is noted at -57 m OD, underlying a sequence of orange-red pebbly sandstone of the Locharbriggs Sandstone Formation.

Permian strata were previously considered to occur continuously at rockhead within the Dumfries Basin. However, no Permian strata were noted in the Ironhirst Moss Borehole where reddish-grey, well-indurated, poorly sorted sandstone directly underlies superficial deposits at rockhead (1 m OD). The sandstone at rockhead in the Ironhirst Moss Borehole may have been deposited in Siluro-Devonian or Carboniferous times and is distinct from the fine-grained wacke sandstone typical of Silurian formations in the Southern Uplands that is present below -35.5 m OD in the borehole.

Clast composition within the Permian strata very much reflects a local derivation and has been used to distinguish two separate fans of alluvial sedimentation within the Doweel Breccia on the western side of the basin

Plate 2 The northern end of the Larchfield ridge seen from the Police Station at Dumfries with the Tesco Supermarket in the central right area of the picture.

(Brookfield, 1980). Surprisingly, clasts from core in the Locharbriggs Sandstone on the eastern side of the Dumfries Basin are mostly distinctive lithologies including granodiorite eroded from the Criffel-Dalbeattie pluton. Limestone and calcareous sandstone, presumed to be of easterly provenance eroded from the exposed sequence of Carboniferous rocks, are only a minor component of the clast population in the Locharbriggs Sandstone in the Longbridgemuir Borehole. There seems to have been very little debris eroded from the Carboniferous strata to the east supplied to the eastern part of the basin. Pebbles of calcareous sandstone, presumed to be of Carboniferous age, have undergone dissolution to produce secondary mouldic porosity that is partially recemented to form large vuggy pores lined by an equant calcite spar cement.

BOX 1 REGIONAL GEOLOGICAL SETTING

Comparison of Permian and Triassic strata in north-west England and south-west Scotland demonstrates that the Dumfries basin-fill sequence is unlike that in adjacent areas both in terms of thickness and sedimentary facies. Sequences of Permian strata are well-known in north-western England (Arthurton, 1971; Arthurton and Hemingway, 1972; Burgess and Holliday, 1974, 1979; Arthurton et al.,1978; Jackson and Johnson, 1996; Akhurst et al., 1997). Sequences recognised onshore in Cumbria and offshore in the Irish Sea have been correlated with the Carlisle and Annan basins immediately east of the Dumfries Basin (Holliday et al., 2004).

Although Permian strata are geophysically modelled as being 1.1 to 1.4 km thick in the Dumfries Basin (McMillan, 2002), less than 450 m are proven in the Carlisle Basin. Correlation of Permian strata demonstrates a much thinner sequence in the Annan Basin where only strata of Late Permian age, approximately 100 m thick, are preserved. A distinctive sequence of Permian and Triassic formations of similar thicknesses are correlated by Holliday et al. (2004) from sequences in west Cumbria, the Irish Sea, the Vale of Eden, the Carlisle and Annan basins over a distance of 70 km.

However, the character and thickness of Permian strata in the Carlisle and Annan basins cannot be correlated to the Dumfries Basin. Sequences of thin Late Permian evaporites in the Annan Basin and Permian, Triassic and Jurassic formations in the Carlisle Basin contrast with the very thick sequence of sandstone and sedimentary breccias in the Dumfries Basin. This marked contrast in both thickness and sedimentary facies, otherwise traced widely in north-western England, between the immediately adjacent Annan and Dumfries basins, demonstrates independent development of the Dumfries Basin during the Permian and probably also the Triassic (no strata of this age have been proven in the Dumfries Basin).

A major fault structure interpreted from seismic profiles in the Solway, the Waterbeck Fault, bounds the present day margin of the Annan Basin and throws Permian and Triassic strata against pre-Permian rocks. The Waterbeck Fault is inferred to have been active during the Permian and so facilitate the development of the Dumfries Basin independently of the immediately adjacent Annan and Carlisle basins. Thus the basin-fill sequence of the Dumfries Basin extends some way into the shallow offshore but is not continuous with strata of similar age to the south and has an erosional edge on the Carboniferous rocks of the footwall-block of the Waterbeck Fault. Silty mudstones and evaporites of Late Permian age in the adjacent Annan Basin, likely to be of low permeability and poor aquifer quality, are not recorded in the Dumfries Aquifer study boreholes. The contrast in depositional facies between the adjacent basins indicates that such fine-grained strata are unlikely to be present.

Only one steep fracture is noted within Permian strata borehole cores, at -69 m OD in the Racks Moss Borehole, suggesting fracture-fed flow is not a major component of groundwater transport. However, in the Stragglingwath Borehole [NY 0692 6977], approximately 1 km north of the Longbridgemuir Borehole site (Figure 2.1), the Locharbriggs Sandstone is cut by two sets of very steeply inclined fractures. The calcite cement in the later phase of fractures has been corroded to re-open the fractures, demonstrating fracture porosity available to permit active groundwater flow and dissolution of calcite.

2.2 HYDRAULIC CHARACTERISTICS

Surface and subsurface characterisation of the Dumfries aquifer has increased the understanding of the hydrogeology of the western margin of the Dumfries Basin (Wealthall, 2002). The work centred on exploratory drilling and testing at the Dupont industrial site as well as characterisation of fracture density and orientation at outcrop in the western basin area (Figure 2.6).

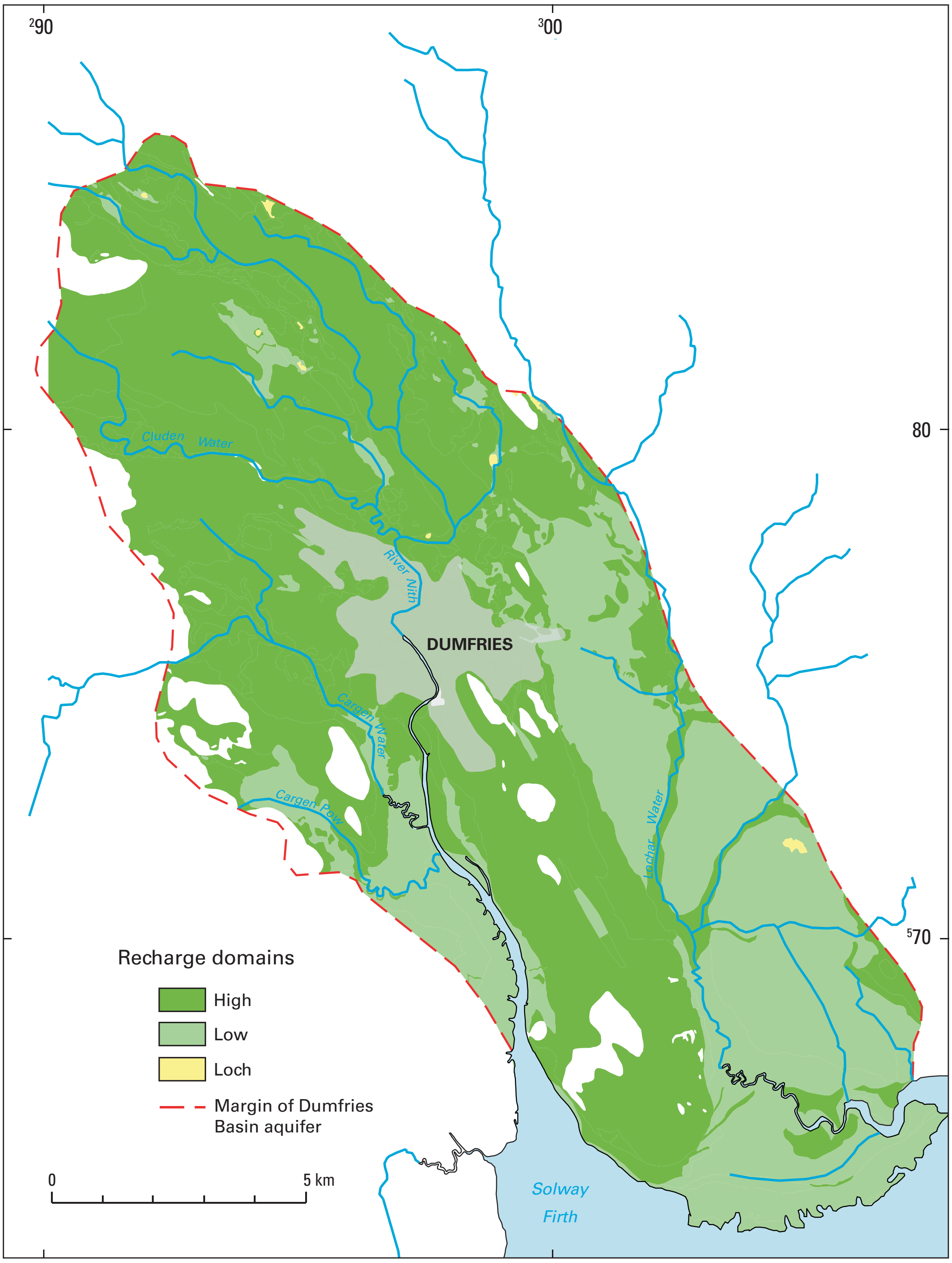
Statistical analysis of available measurements in the Doweel Breccia Formation indicates that the in situ matrix hydraulic conductivity is $7x10^{-5}$ m d^{-1} (Wealthall, 2002) and the bulk hydraulic conductivity is 10^{-3} m d^{-1} increasing to 10^{3} m d^{-1} where it is fractured. Fracture flow concentrates on discontinuities which in most of the Dumfries Basin are dominantly subhorizontal, such as the breaks between sandstone and breccia. As a consequence horizontal permeability is commonly greater than vertical permeability. In the south-west of the basin there is some sub-vertical fracturing which trends parallel to the western boundary, i.e. north-west to south-east. The boundary fault to the north-east of the basin also imparts preferential orientation in the east of the basin. There is evidence in some boreholes, and at outcrop, of shallow water movement in unsaturated bedrock fractures after periods of rain (Wealthall, 2002). This was also noted in the Hardthorn Road boreholes, where fractures up to 20 m below rockhead contributed water to the boreholes immediately after rainfall.

The Doweel Breccia Formation typically has low intergranular permeability and porosity and high secondary (fracture) permeability, and as such is uncharacteristic of Permo-Triassic sandstones in the UK. The transmissive characteristics are closer to the Chalk aquifer of southern England, where the ratio of laboratory (matrix) to field (fractures and matrix) permeability (Table 2.3) is greater than 1:1000 (Price, 1996).

A fully-cored borehole was drilled to characterise the fracture network on the industrial site to supplement the lithological and fracture mapping undertaken at nearby outcrop where approximately 500 m of breccia and sandstones are exposed. Further hydraulic and geological data have been incorporated from an earlier borehole drilled on the field research site. Vertical packer test profiling (Brown and Slater, 1999; El-Naqa, 2001) to a depth of 30 m has been used to determine transmissivity and calculate hydraulic apertures.

Core samples confirmed the succession observed at outcrop, which comprised a 5 m sequence of a reddish-brown sandy glacial till underlain by fractured reddish-brown breccia with less abundant medium- to fine-grained sandstones, which were weathered to highly weathered in the upper 5–7 m. The laboratory measured matrix hydraulic conductivity was $8x10^{-6}$ m d^{-1}, suggesting that the test zone transmissivity reflects the fracture system.

Figure 2.4 Quaternary hydrogeological domains.



Pore throat diameters are listed in Figure 2.7 for the breccia, fine-grained sandstone (f) and medium- to coarse-grained sandstone (m-c). The apparent initial invasion of mercury, present in the plot as a leading tail, results from sample conformance where the mercury invades surface irregularities in the sample caused by sample preparation (Bloomfield et al., 2001; Price et al., 2000).

Pore throat diameters are <10 mm for the sandstones and <1 mm for the breccia. The steep curves for the sandstones indicate less variability in the pore throat size distribution than that observed in the breccia.

Evidence for the structural control of the basin was observed from the western margin where a bounding fault system, inferred from geophysical data, defines a major linear north-westerly trending feature. The fault is not observable at surface due to the cover of superficial deposits. Orientation data from the basin-wide survey indicate that the major fracture trends are aligned sub-parallel to the basin margin fault systems. These data confirm earlier observations (Robins and Buckley, 1988) on the development of directional secondary permeability aligned sub-parallel to the basin-bounding faults.

Four fracture sets were observed at outcrop. Bedding-parallel fractures trend subparallel to regional bedding (6° dip north-north-west). Three high-angled fracture sets were observed (Figure 2.6), with the main set (Set 2) trending north-west (318°). This trend is consistent with the nearby basin boundary fault system which, in the vicinity of the outcrop, trends at northwest 318°. Fracture set 3 trends south-east (147°) and Fracture set 4 trends south-west (218°).

Analysis of the orientation data from the Cargen industrial site boreholes identified three of the four sets observed at outcrop. The bedding-parallel fractures dominated the borehole fracture population and reflected the sampling bias which results from characterising 3D fracture networks by sampling in only one orientation (i.e. the borehole). Set 2, the major high angled set, was present, one fracture from Set 3 was observed, and no fractures were observed from Set 4.

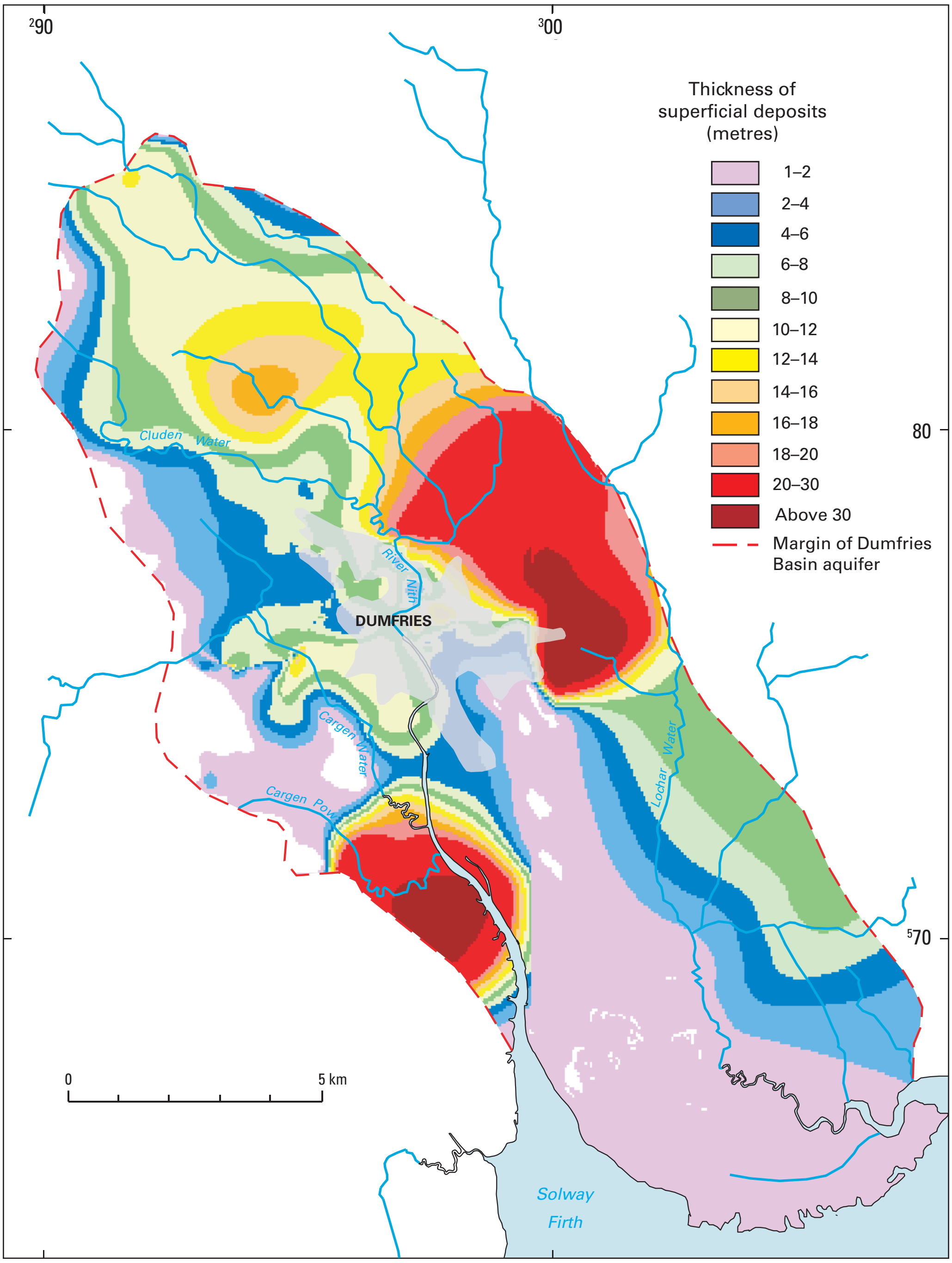
Table 2.1 Quaternary hydrogeological domains identified within in the Dumfries Basin.

Domain	Materials & morphology	Drift thickness	Area
1. Alluvial and river deposits on till	Floodplain sand and gravel, 2–3 m on sand and gravel and/or till	River Nith S of Dalswinton: thick underlying sands and gravels, 17 m at Holywood	N of Dumfries, Nith and tributaries
2. Modern and Flandrian tidal flat, raised tidal flat, saltmarsh and warp deposits on till or rock area	Clay, silt and fine sand with interbedded peat on laterally discontinous till; clay and silt overlain by peat in Lochar Gulf		S of Dumfries: River Nith and Lochar Gulf: Craigs Moss, Racks Moss (centre), Ironhirst Moss
3. Peat on raised tidal flat deposits on glaciofluvial	Peat, 2–3 m on clay, silt and fine sand on ? discontinuous till (possibly on gravel)	Lochar Moss, E of Dumfries: thick sands below peat	Lochar Moss Racks Moss (flanks) Kirkconnel Flow
4. Flandrian and late Devensian raised beach, shoreface and deltaic deposits on till or rock	Sand and gravel (possibly silt) on till or rock	New Abbey Pow BH 4 m gravel on sand; South Carse BH 8 m sand on ?till	Ingleston, Carsethorn, Southerness
5. Glaciolacustrine deposits	Laminated clay and silt with dropstones on till	Thickness not known	Small patch at Holywood; possible concealed
6. Glaciofluvial ice contact morainic deposits on till or rock	Mounds and ridges of sand, gravel and silt; laterally discontinuous — hollows may be occupied by peat on till; moraines S of Locharbriggs glacitectonised sands and silts	10 m+ N of Locharbriggs	Dalswinton, and Locharbriggs flanking Nith valley and tributaries; W of Dumfries, Kirkbean
7. Glaciofluvial sheet deposits on till or rock	Sheets and terraces of sand, gravel and silt	Approximately 10 m around Locharbriggs	Locharbriggs, flanking Lochar Gulf, Kirkbean, Cargenbridge
8. Till on rock	Sandy diamictons, jointed, sandy interbeds	< 5 m	Ridges S of Cargenbridge and SSE of Dumfries; NW of Dumfries
9. Rock at or near surface	Locharbriggs Sandstone Doweel Breccia Lower Palaeozoic wackes and siltstones		

Table 2.2 New drilling in the eastern zone of the Dumfries Basin aquifer.

	Borehole elevation (m aOD)	Borehole depth (m)	Static water level (m aOD)	Test yield ($m^3 d^{-1}$)	Specific capacity ($l s^{-1} m^{-1}$)	Stratigraphy
Racks Moss NY 0297 7273	11	100	9.4	500	0.25	Rockhead -21 m OD; Permian to -89 m OD.
Ironhirst Moss NY 0490 7071	11	100	10.7	120	0.08	Rockhead +1 m OD; Carboniferous/Devonian to -3 m OD; Silurian proved to -89 m OD.
Longbridgemuir NY 0699 6891	20	80	13.6	454	0.35	Rockhead +15 m OD; Permian to -57 m OD; Carboniferous to -60 m OD

Figure 2.5 Estimated thickness of superficial deposits.



Bedding-parallel fracture trace length is defined by a log-normal distribution with a mean value of 15.6 m. High angled fracture length distribution is biased due to truncation at outcrop and is assumed to be a lognormal distribution. The mean fracture trace length of high angle fractures is 7.86, 6.24, 7.30 m for fracture sets 2, 3 and 4 respectively.

The bedding-parallel fractures recorded at outcrop were more widely spaced than those observed in the borehole. The bedding-parallel data from boreholes approximated a lognormal distribution with a mean value of 0.76 m, whilst the data for Set 2 at outcrop approximated a normal distribution with a mean spacing of 5.51 m. Mean fracture spacing for Sets 3 and 4 was 6.75 and 6.60 m respectively. The low sample population for sets 3 and 4 precluded fitting the data to theoretical probability distributions.

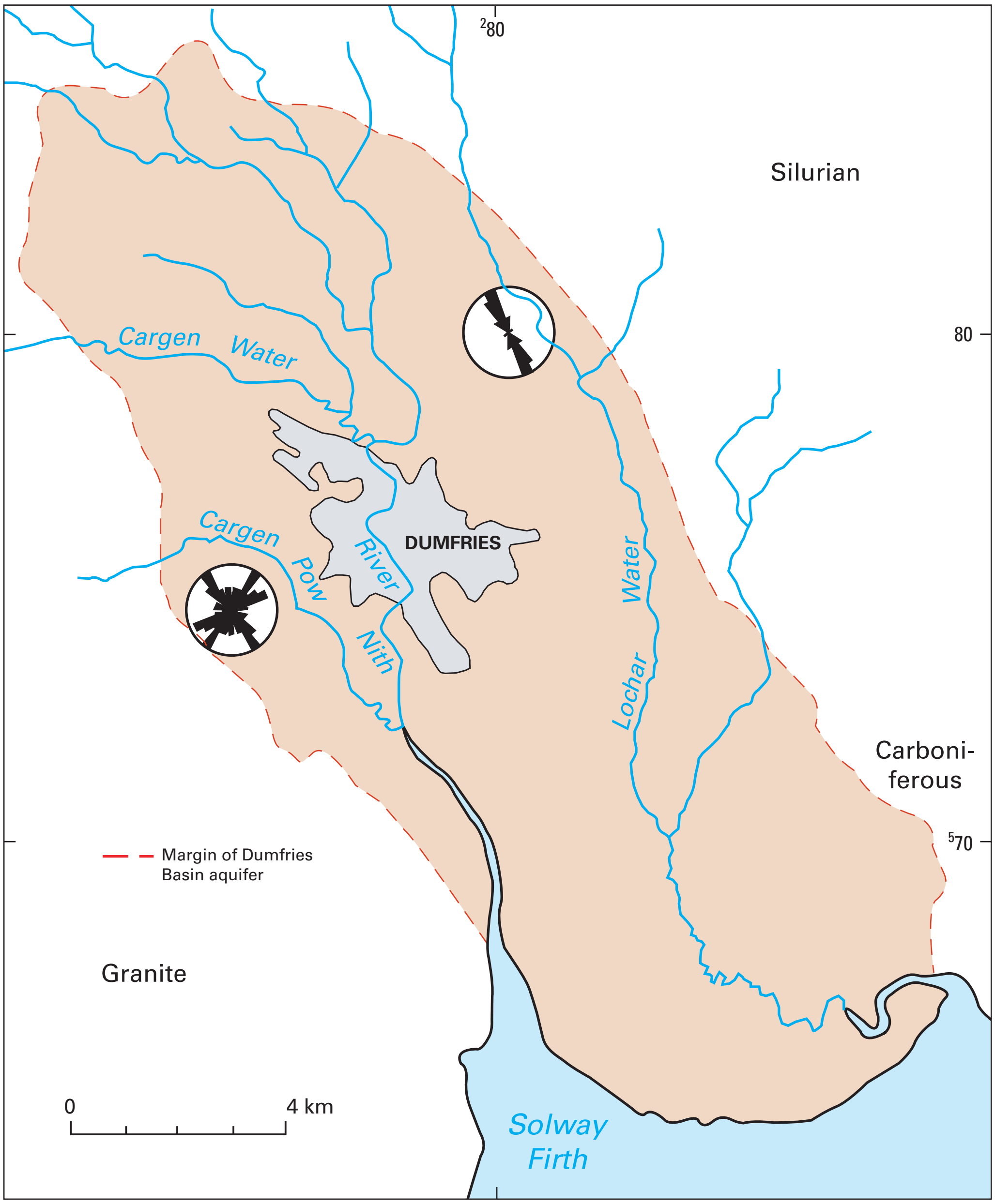
Two types of fracture aperture measurements were undertaken: i) single-plane fracture apertures profiles were measured at outcrop, using an engineer's feeler gauge (Renshaw, 1995), for one bedding-parallel fracture and one high-angled joint, and ii) fracture apertures were determined from the hydraulic tests undertaken in the site boreholes (Figure 2.8).

Table 2.3 Comparison of hydraulic conductivity (K) for Permian breccia, Cretaceous chalk, and Permo-Triassic sandstone.

Aquifer type	Field K (m d^{-1})	Lab K (m d^{-1})	Ratio of field K/lab K
[1] Permian breccia	1	1x10^{-3}	1000
[2] Cretaceous chalk	5	4x10^{-3}	1250
[3] Triassic sandstone	2.2	1.2	1.8

1 (Robins and Buckley, 1988), 2 (Price, 1996), 3 (Allen et al., 1998)

Figure 2.6 Regional structural trends at the west and east margins of the basin.



The mean fracture aperture calculated from the hydraulic tests is approximately one order of magnitude smaller than that measured at outcrop. The outcrop aperture profiles are biased towards larger fracture apertures, as a result of the reduction of overburden pressure, and only the hydraulic test aperture results are presented here.

The apertures determined from the hydraulic tests were lognormally distributed with a mean of 67 µm . Transmissivity ranged between 1×10^{-6} and 1×10^{-1} $m^2 d^{-1}$ (Figure 2.8).

The main conclusions are:

- The orientation of the fracture network at the western margin of the basin is strongly influenced by the north-west trending fault system.
- A well-connected fracture network is defined by a bedding-parallel set and three high-angled fracture sets, although the spatial distribution is poorly constrained at depth.
- Low bulk transmissivity (~ 1 $m^2 d^{-1}$) in the upper 30 m is derived mostly from secondary porosity (fractures).
- The Doweel Breccia Formation is characterised by very low (in situ) matrix hydraulic conductivity ($\sim 10^{-6}$ m d^{-1}).
- Fracture fill is present in the shallow Doweel Breccia Formation and elsewhere in the basin (e.g. Locharbriggs). Fill genesis, distribution and penetration depth is unknown, but if absent at depth this may explain the observed increase in transmissivity with depth.

Figure 2.7 Pore throat size distribution for the breccia and sandstones.

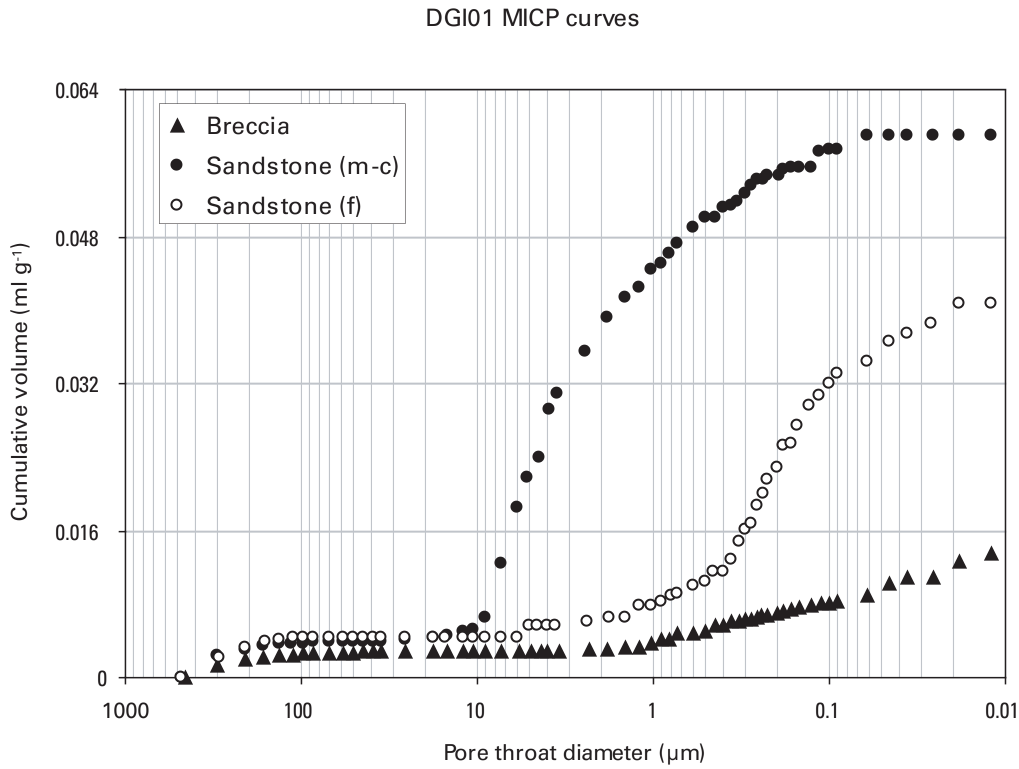
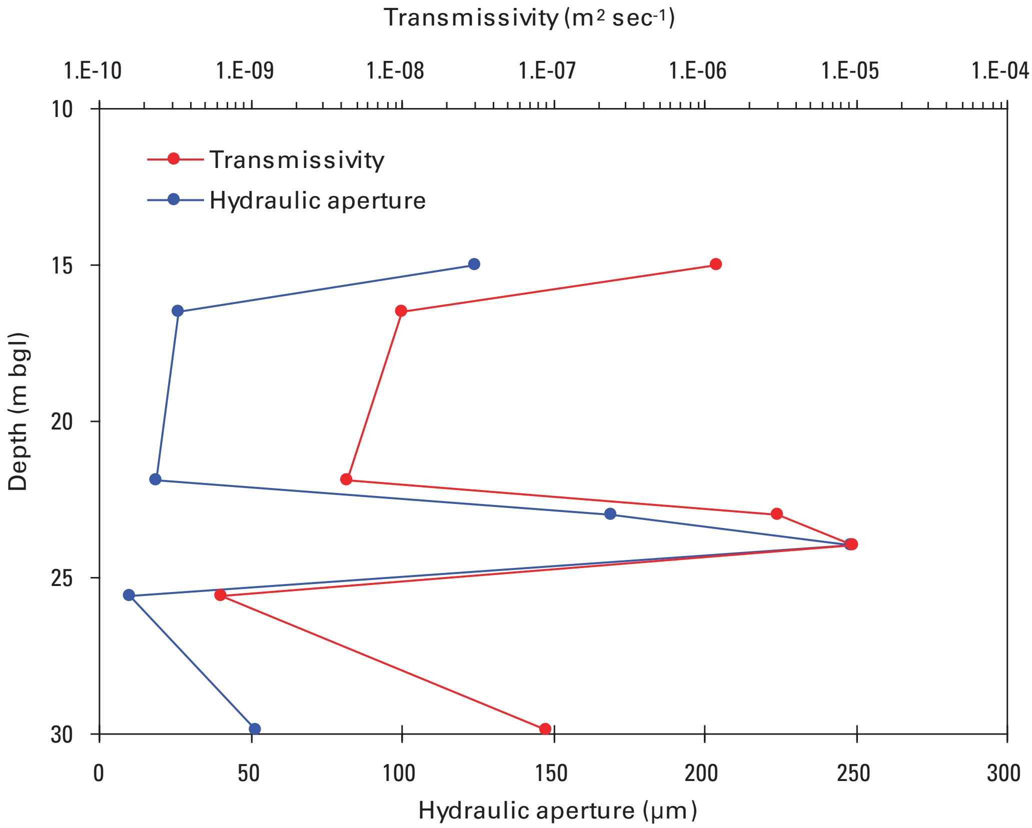


Figure 2.8 Vertical profiles of transmissivity and hydraulic aperture in the Dupont exploratory borehole.



3 The Nith catchment

3.1 GEOMORPHOLOGY OF THE NITH CATCHMENT

The landscape of the Southern Uplands represents the fluvially dissected residual of a pre-Cretaceous surface which gently dipped eastwards (George, 1956). However, the formation of the Nith valley is complex, and represents periods of both rejeuvenation and capture of former tributaries of the Clyde as its course developed. The upper Nith rises in open country above the Ayrshire plain and rather than heading west to the plain, breaks through a water gap at New Cumnock, at an elevation of 195 m OD, into a reach flanked by high hills. It then traverses the Sanquhar Coalfield to Kirkconnel. Below this it traverses the Southern Upland hills within narrow and steep sided walls, having captured cross-flowing streams probably heading at one time to the Clyde, and is broken by small falls and rapids reflecting past rejuvenation of base level. Below Carronbridge to Dumfries it flows south and east of south through the Thornhill and Dumfries basins and is fed by convergent and sub-parallel tributaries, largely on the right bank.

Once the Nith arrives in the Dumfries Basin it follows a mature and long established profile (Plate 3). The topography of the basin is largely controlled by the superficial geology, but to the south of Dumfries ridges of harder breccia have been formed by preferential removal of adjacent softer sandstone by glacial and fluvial erosion to either side.

3.2 RAINFALL RUNOFF RELATIONSHIPS

Annual flow in the River Nith has increased in recent decades (Figure 3.1) as a response to a general increase in winter rainfall (see Chapter 1). The Nith above Friars Carse [NX 921 854], which is where the river enters the Permian basin, is a flashy river with short lag times between rainfall events and runoff response (Jameson, 2001). However, when the catchment is particularly dry, for example during July 1995, the relationship between flow and rainfall is greatly moderated by the need to bring soil moisture back up to field capacity. The flow duration curves for the catchment (Figure 3.2) confirm that high volume flows occur for relatively short periods of time (the steeper slope at high flow rates), and that low flows of longer duration (the tail of the curve) represent the baseflow element of river flow. The 95 percentile flow (Q95) at Friars Carse is 2.8 $m^3 s^{-1}$ and the 10 percentile flow (Q10) is 67.6 $m^3 s^{-1}$; the long term base flow index (BFI) is 0.38 (CEH/BGS, 2003).

Calculated BFIs from annual flow data for the River Nith at Friars Carse are listed in Table 3.1. In general terms a BFI > 0.6 indicates a mature lowland river with a significant groundwater contribution, and a BFI < 0.3 reflects an upland catchment with little contribution from groundwater.

3.3 SURFACE WATER QUALITY

Jameson (2001) reported that total dissolved solids (TDS) concentration in the River Nith varies proportionately with river stage. Alkalinity concentrations may peak at up to 70 mg l^{-1} during periods of high flow, but are typically in the range 20 to 30 mg l^{-1} at times of low flow and occasionally less than 10 mg l^{-1} following an exceptional period of flood. Part of the source of mineralisation is former, now abandoned, coal mines above Blackaddie in the Sanquhar Coalfield. Here alkalinity concentrations of up to 109 mg l^{-1} have been recorded (9 August 2001), diminishing with dilution to only 80 mg l^{-1} at Thornhill. On the same date samples from the Cluden, which is not connected with the coalfield, had a concentration of

Plate 3 The River Nith above Dumfries looking north.

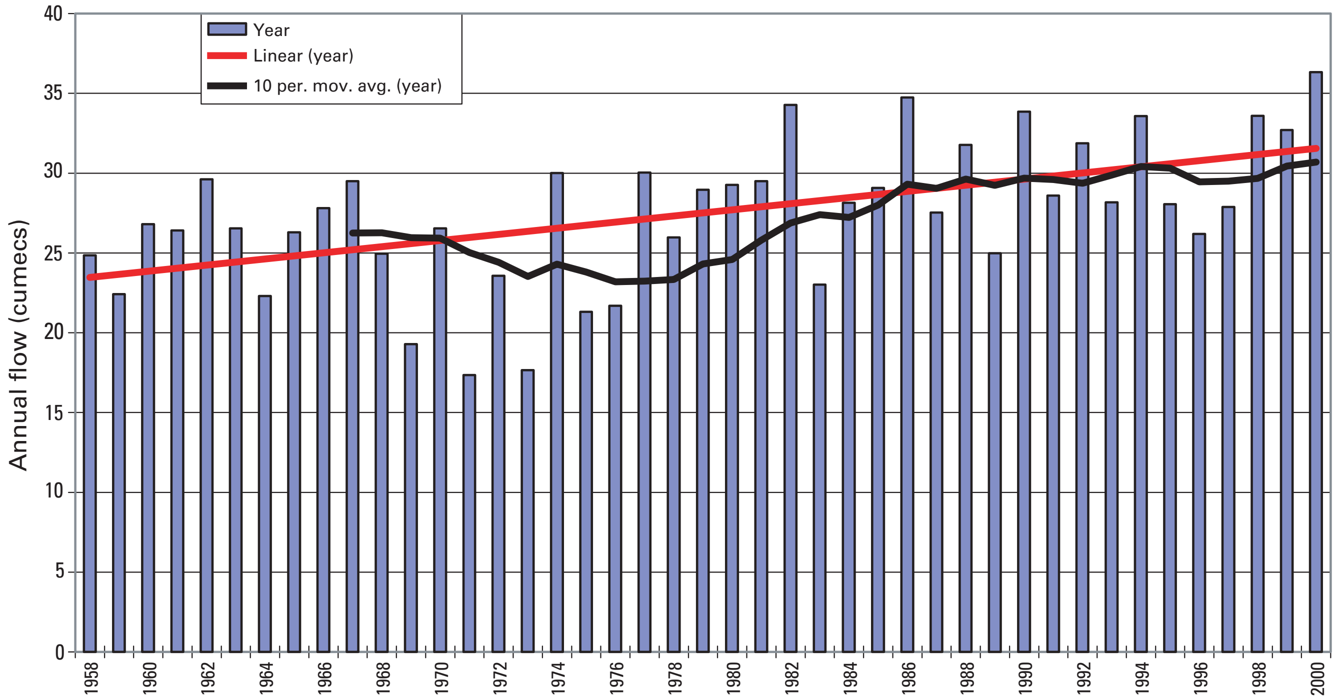


Figure 3.1 Annual flows for the River Nith at Friars Carse, 1958 to 2000.

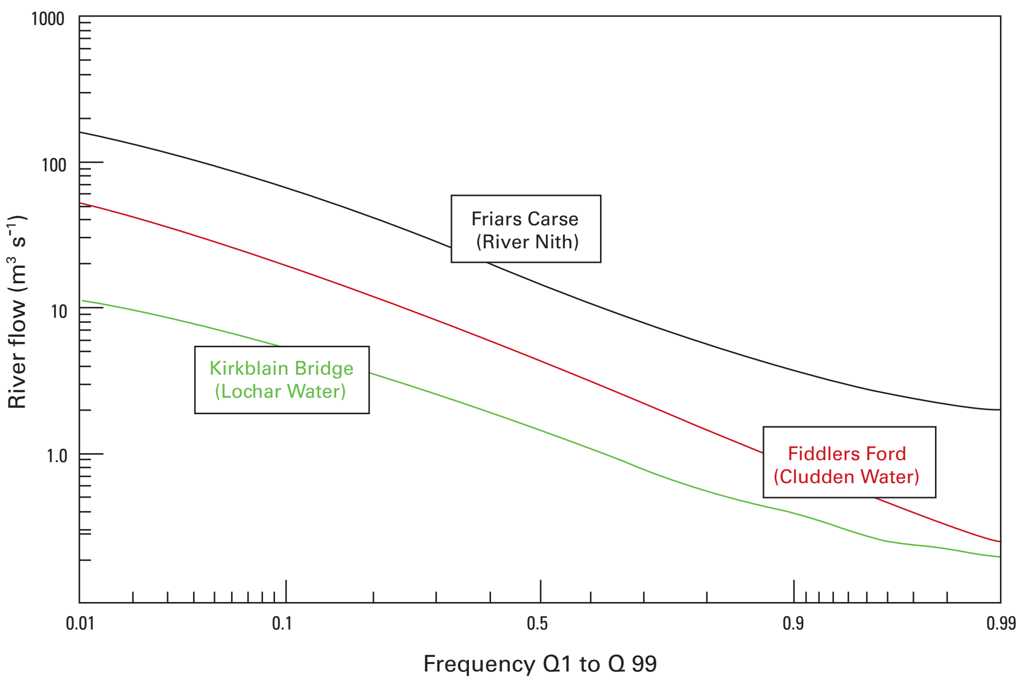


Figure 3.2 Flow duration curves for the rivers Nith, Cluden and Lochar Water.

52 mg l^{-1} alkalinity, which is more representative of the background level for the overall catchment.

Concentrations of TDS in surface water increase from Cluden downstream, suggesting some mixing with groundwater discharge from superficial deposits and bedrock. However, in addition to mixing of groundwater and rainwater, some additional input derives from surface runoff and/or reaction between the surface water and the groundwater baseflow. Simple mixing equations suggest that the chemistry of the River Nith at Dumfries represents, on average, one part groundwater diluted by over three parts rainwater (Jameson, 2001). However, this is a simplistic model as rainfall tends to displace soil and groundwater of varying residence times, rather than flowing overland to the river. It suggests a baseflow index of only 0.23 against the reported average baseflow of 0.38 (CEH/BGS, 2003) although this is for Friars Carse above the Permian basin. Nevertheless, the chemical observations reinforce the concept of groundwater basefow discharge in the catchment to the river.

Table 3.1 Annual BFI estimates for Friars Carse, River Nith (after Jameson, 2001).

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1995
BFI	0.37	0.35	0.43	0.41	0.40	0.38	0.43	0.48	0.48	0.41

4 The Dumfries Basin aquifer

4.1 HISTORY OF DEVELOPMENT

Although groundwater had traditionally been exploited by way of shallow wells, (Plate 4) the first commercial exploitation occurred in the early twentieth century when a number of shallow wells and deep boreholes were commissioned as industrial and agricultural supplies (Robins et al., 2004). Industrial uses included dye and chemical works, an iron foundry, a gas works, rubber manufacturing and two breweries, the latter also producing carbonated soft drinks. The Crichton Royal Hospital also installed its first deep borehole at this time. The borehole had an artesian flow, which from records kept between 1925 and 1930 varied from 1 $m^3\ d^{-1}$ to 0.7 $m^3\ d^{-1}$, with the maximum occurring in January or February and the minimum between July and October. Flow increased in response to a heavy rainfall event with a time lag of ten to fifteen days. The overflow was diverted to a therapeutic treatment pool.

During the 1930s new drilling was carried out to supply a dairy products factory, with additional drilling also carried out at the Crichton Royal. Two boreholes were drilled in the 1950s for a new chemical factory that replaced the former ordnance works at Drungans. These boreholes were the first in the Dumfries Aquifer basin for which detailed core analysis of physical properties, borehole geophysics and pumping tests was carried out (Lovelock, 1968; Tate, 1968; Lovelock, 1969).

Lovelock (1969) showed by laboratory testing that the sandstones were generally of low matrix-permeability (5.3×10^{-2} m d^{-1}) and the breccias were typically of very low matrix-permeability (7.65×10^{-4} m d^{-1}). However, field test pumping of the boreholes indicated bulk permeability values eight to nine times higher than the sandstone value, thus indicating the presence of an important secondary permeability component to account for the groundwater flow to the boreholes.

Local drought in 1977 persuaded the Dumfries and Galloway Regional Council, then responsible for public water supply, to consider groundwater. The first public supply borehole was drilled at Manse Road near Terregles, west of Dumfries, and tested by Harrison (1979) at a yield of 5875 $m^3\ d^{-1}$ for a drawdown of 5.3 m (Plate 5). The borehole had an artesian overflow of 1035 $m^3\ d^{-1}$.

Further major groundwater development, this time for fish farming, took place in the middle and late 1980s with the drilling of six production boreholes at Terregles and in due course the drilling of production boreholes for another fish farm situated at Holywood. Additional public supply sources were also commissioned at Larchfield and Cargen.

4.2 EARLY HYDROGEOLOGICAL INVESTIGATION

The success of the Manse Road pumping station was the beginning of three decades of hydrogeological investigation, albeit piecemeal. An investigation of the groundwater potential of the Dumfries Basin aquifer was begun in 1980 with the drilling of five observation boreholes, ostensibly in

Plate 4 Rabi Burns' well at Bankend [NY 030 684].

Plate 5 An historic picture of the discharge main during testing of the Manse Road production borehole in March 1979.

locations little affected by pumping boreholes, and subsequent monitoring of groundwater levels (Harrison 1983).

The dry summer of 1984 led the Water and Sewerage Department of Dumfries and Galloway Regional Council to initiate a regional appraisal of its groundwater resources. Trial drilling sites were identified at Larchfield and Locharbriggs, and new production boreholes were drilled, tested and geophysically logged. Measurements were also made in a number of existing boreholes. The key findings from this work highlighted the importance of secondary permeability and preferred flow horizons due to structural trends and at the contacts between breccia and sandstone (Robins, 1990). The ratio of pumping test (bulk field) hydraulic conductivity to laboratory-measured intergranular permeability averages 1000: 1 in the Dumfries Basin aquifer (Robins and Buckley, 1988). Borehole flow logging indicated that some boreholes receive water from considerable depth: the main inflow horizon in the Manse Road borehole is situated at 100 m below ground level, and for the Cargen Public Supply Borehole contributions also continue to the same depth (Table 4.1).

A preliminary attempt at bringing together the existing data on the aquifer was made in 1991 using a simple modelling approach. This work concluded that uncertainties existed in a number of areas, particularly recharge processes and aquifer/river interaction (MacDonald and Robins, 1991). A drilling campaign was undertaken in 1992 to address some of these deficiencies,

Table 4.1 Cargen Public Supply Borehole — groundwater inflow horizons.

Depth of inflow (m below ground level)	Percentage of total discharge
<25	15
65	37
72	25
98	13
100	10

including a row of three shallow boreholes perpendicular to the River Nith above Holywood in which river stage and hydraulic gradient to and from the river could be monitored (Cheney and MacDonald, 1993a). During the remainder of the 1990s, drilling and testing was undertaken by Scottish Water at Cargen, Powbridge and Hardthorn Road in the west and at Stragglingwath in the east. The summary results of these drilling and testing programmes are listed in Table 4.2.

Extensive investigations have been carried out by Dames & Moore International acting for ICI and latterly Du Pont regarding pollution beneath the Drungans factory complex (Ball, 1995). Little of the results of this work is available in the public domain.

Available data were reviewed by Gaus and O'Dochartaigh (2000) who concluded that the basic understanding of the groundwater flow regime in the Dumfries Basin aquifer was poor. The only work that had taken place in the eastern part of the basin was a study of the Lochar Moss landfill facility (Ball and O'Dochartaigh, 1999). A preliminary water balance for the basin aquifer had a closure error of 34%, but disregarded the likelihood of significant groundwater discharge to the River Nith from the gravels upstream from Dumfries. The overall estimated rainfall recharge of 100 $Mm^3\ a^{-1}$ was distributed between 11 $Mm^3\ a^{-1}$ to groundwater abstraction and 88 $Mm^3\ a^{-1}$ to discharge, mainly to the sea. The work identified a number of unresolved issues, including the water balance and groundwater flow, and also the need to understand the groundwater flow regime in the eastern part of the basin, and the potential role for groundwater chemistry in assessing groundwater provenance. The paucity of hydrochemical data was underlined in a national review of data undertaken by Robins (2002).

An inception report to the latest project (Robins et al., 2001) identified a list of uncertainties that needed to be addressed. These were:

- the aquifer water balance
- the role of fracture flow and the differences between the eastern sandstone-dominated and western breccia-dominated parts of the aquifer
- the location of preferred flow horizons and the degree of interconnection between boreholes
- the rainfall/runoff relationship
- the location and nature of recharge and discharge zones, including the river/aquifer relationship
- the location of higher transmissivity areas
- the distribution of poor groundwater quality and the role of land use and pollution risk
- hydrochemistry as an indicator of groundwater provenance
- the threat of saline intrusion from the south
- the magnitude of the renewable resource.

Table 4.2 Borehole pumping test results derived in the 1990s (see Figure 1.2 for locations).

Name	Aquifer thickness (m)	Test date	Test yield	Specific capacity ($l\ s^{-1}$)	Transmissivity ($l\ s^{-1}\ m^{-1}$)	Storativity ($m^2\ d^{-1}$)
Crichton Royal		08 1991	15	1.7	210	
Terregles Observation No 1	65.5	06 1992	25.4	23.1	>4000	-
Greenmerse	40	09 1992	7.9	0.3	9	-
Locharbriggs	56.0	09 1992	8.0	4.3	420	-
Holywood	61.0	10 1992	18.5	4.2	270	$1\ 10^{-4}$
ICI Borehole 501	54.1	05 1993	9.0	0.5	62	-
Cargen	110	06 1994	25	3.6	395	-
Cargen Production Borehole	108	03 1995	29.2	3.4	300	-

4.3 THE 3D PICTURE OF THE AQUIFER

The Dumfries Basin is deep, fault-bounded to the west and north-east, and thins northwards and eastwards. The effective depth of the aquifer is variable, but evidence from boreholes in the Terregles area and elsewhere indicates that active fracture flow occurs to depths in excess of 120 m. Slower circulation of older, much deeper and possibly brackish or saline groundwater is likely at depths considerably greater than this, although there is no evidence of upconing of older mineralised waters.

The uppermost 100 m of the aquifer is characterised by the west to east transition from breccia, deposited at the foot of the former scarp face of the western boundary fault, to aeolian and lacustrine sandstone, laid down in a desert environment, in the east (Figure 4.1a). The two depositional environments advanced and receded as the basin developed and subsided under the weight of the sediments. In this way the two lithologies are interdigitated and contemporaneously fractured. The region of most interfingering is also the region where the highest borehole yields are available (Figure 4.1b).

Dilated voids occur at the subhorizontal junction of sandstone and breccia units, as well as less well developed sub-vertical fractures, many reflecting the orientation of the boundary faults.

4.4 ROLE OF SUPERFICIAL STRATA

Much of the Dumfries Basin is covered by a wide variety of superficial deposits that require characterisation to enable their impact on the local groundwater system to be determined. The majority of the superficial deposits in the Dumfries Basin are permeable (see Chapter 2, Figure 2.4 and Table 2.1), including the till, which is sufficiently coarse in nature for percolating water to be readily transported to the water table.

The only significant low permeability deposits are the laminated marine clays (which are up to 20 m thick) in the south of the basin and the peats in the east. Both these deposits inhibit vertical recharge and enhance runoff. Wherever the peat cover is coincident with areas of commercial forestry, drainage channels have been cut and these divert potential recharge from the soil to the Lochar Water and its tributaries. The marine clays have low hydraulic conductivity and limit the interaction between the bedrock aquifer and surface waters, resulting, in places, in the presence of confined groundwater in the Permain aquifer. Therefore, groundwater heads in the vicinity of the River Nith may not be controlled directly by river levels.

The till, being mostly sandy and gravelly, can act as a local aquifer system. Whilst in the south of the basin the water table is close to ground surface and the superficial deposits are saturated, in much of the north-west of the basin groundwater heads are below the base of the superficial deposits. Owing to their relatively high conductivity, the superficial deposits receive significant volumes of rainfall recharge and provide baseflow to the rivers.

4.5 RAINFALL RECHARGE AND RIVER INTERACTION

The water balance for the Dumfries Basin is dominated by flow in the rivers. The key components of the water balance include:

Inflows to the basin:

- rainfall recharge and runoff within the basin
- the River Nith and its tributaries
- Lochar Water and its tributaries
- leakage from water supply mains and sewers
- cross-catchment transfer – water supply and from sewage treatment works.

The main inflows to the basin are the flow in the River Nith and the Lochar Water, and rainfall recharge, with the River Nith dominating all other inflows. Leakage from mains and sewers partly derives from local groundwater as does return water from local fish farms.

Outflows from the basin:

- river flows
- marshes
- springs and seeps
- abstraction
- public water supply abstraction (Scottish Water) – the Cargen borehole supplies the south coast area outwith the basin, whereas other sources are used locally for public supply

Figure 4.1a Location of major abstraction sites.

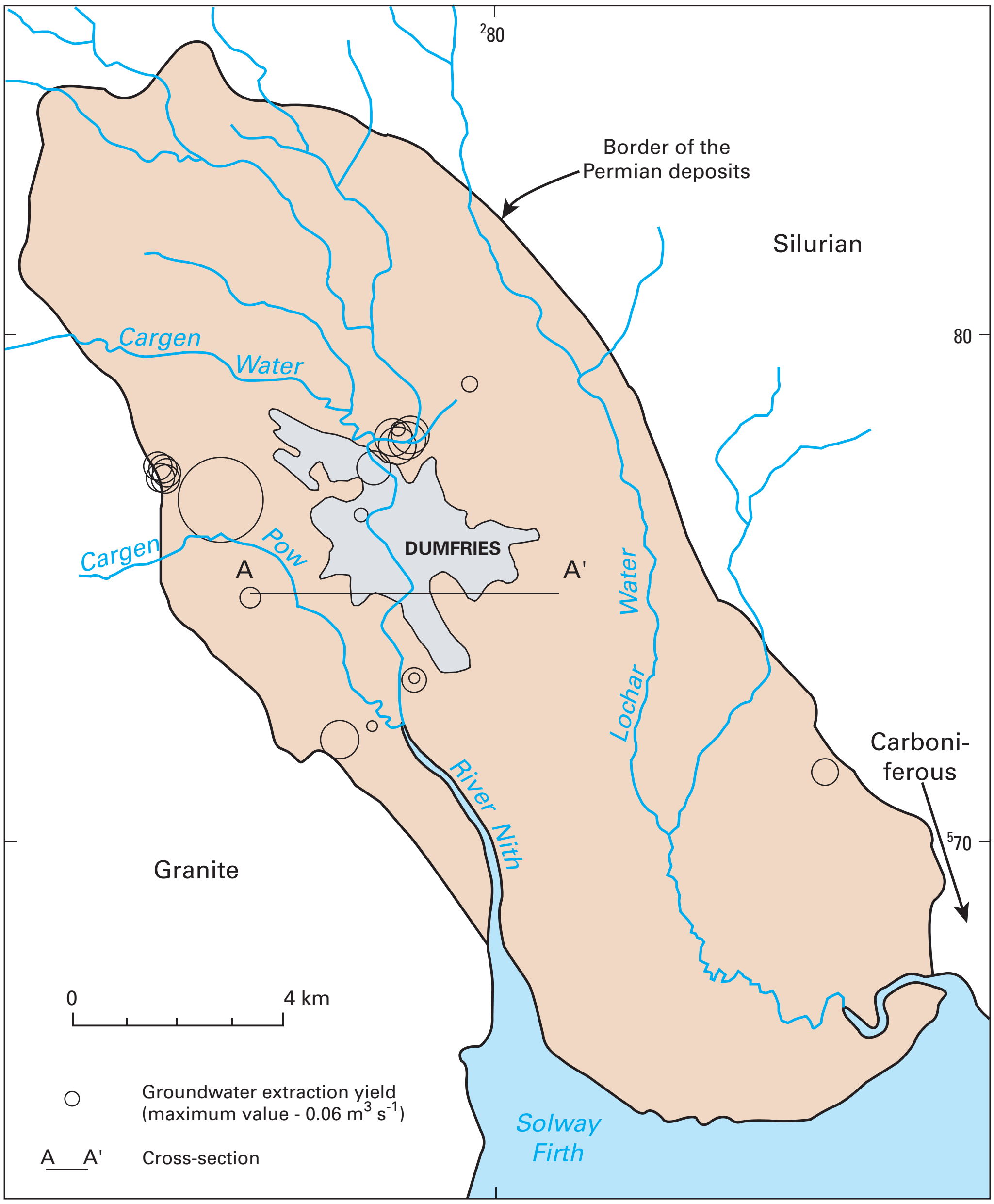
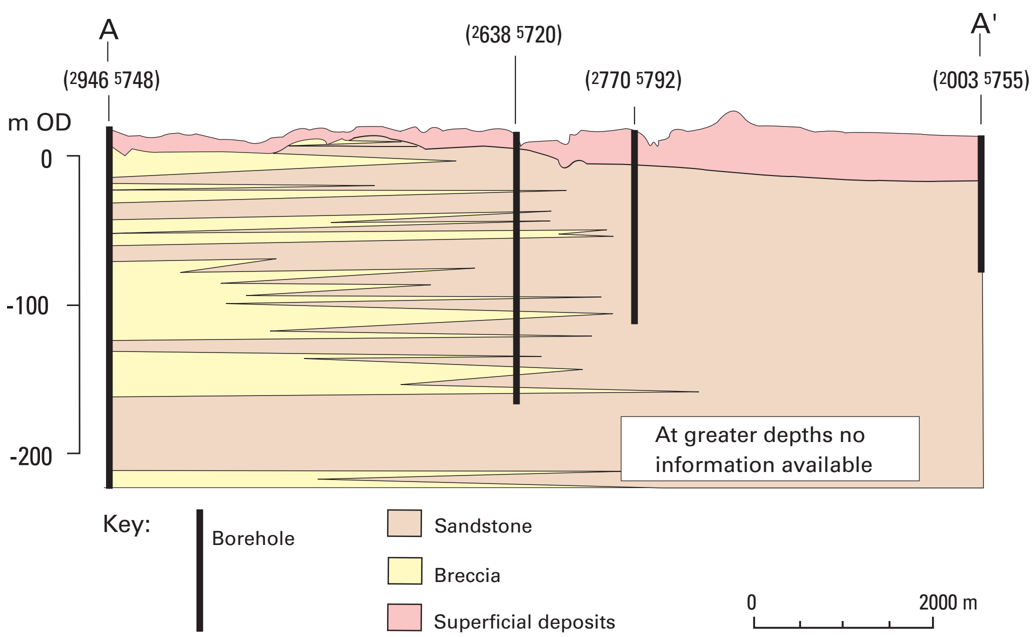


Figure 4.1b West to east cross-section.



- fish farms: Terregles and Holywood
- industrial, agricultural and private supply
- infiltration to sewers from shallow groundwater
- leakage to the sea.

The flows in both the River Nith and the Lochar Water increase downstream across the basin due to both runoff generated in the catchment and groundwater baseflow. This suggests that much of the rainfall recharge leaves the system as baseflow to the two rivers.

Other than baseflow to the rivers, the main outflows from the groundwater system are abstraction, currently at over 30 Ml d^{-1}, springs issuing from the Larchfield-Caerlaverock ridge and elsewhere, and discharge to the sea via leakage.

As a consequence of the high rainfall in the Dumfries Basin, run-off processes are important. Rainfall can reach surface water-courses which have the potential to provide recharge to the system. Whilst it is likely that the main water-courses such as the River Nith and the Lochar Water are receiving baseflow from the groundwater system, leakage from the smaller tributaries, for example as they pass over terraces, could form a source of recharge. Indeed, the Park Burn and Duncow Burn have been known to dry up completely (Plate 6).

Characterising urban recharge processes is important where large towns or cities overlie aquifer outcrops. When water and waste water are moved through the urban environment, a small but significant proportion can be lost. Leakage from pressurised water mains and from breaks in sewers can be a potential recharge source, although roughly 50% of this water derives from groundwater sources in the basin.

Additionally, the construction of impermeable surfaces such as roads, paved areas, and roofs in the urban environment enhances runoff. The runoff resulting from these structures is collected and routed via storm drains to surface water courses. Foul sewers also empty into rivers and streams, either directly or via sewage treatment works and these sources collectively offer a source of recharge. Open spaces, such as parks and gardens, allow direct recharge via the soil to occur, and recharge from this part of the urban environment must also be considered.

4.6 THE BEDROCK AQUIFER

4.6.1 Behaviour with time

Annual variations in potentiometric level in both the western and eastern parts of the Permian aquifer are less than 2 m (Figure 4.2). Potentiometric heads tend to peak in February, with a steady natural decline through spring. Water levels in the Permian are above the rock/superficial strata interface across much of the basin. Higher ridges of bedrock occur in some places, such as around Larchfield south of Dumfries, and there may be up to 15 m of unsaturated rock beneath some of these. In general, surface topography is reflected by the depth to the potentiometric surface. Confined conditions occur under low-lying areas south of Dumfries across the floodplain of the River Nith. Artesian flow occurs wherever the surface level is at or below 10 m OD and laminated silty clay overlies the main aquifer. Elsewhere, individual fractures, and sandstone horizons separated by breccia, may be at different potentiometric heads, as observed in a number of geophysical flow logs that have been measured in boreholes in the western part of the basin (Buckley, 2000).

4.6.2 Borehole geophysics

A considerable amount of data have been gathered from borehole geophysics over the years, and a summary of this information provides useful insight into the flow mechanisms and processes occurring within the Dumfries Basin aquifer.

Plate 6 The dry stream bed of the Park Burn [John Burns].

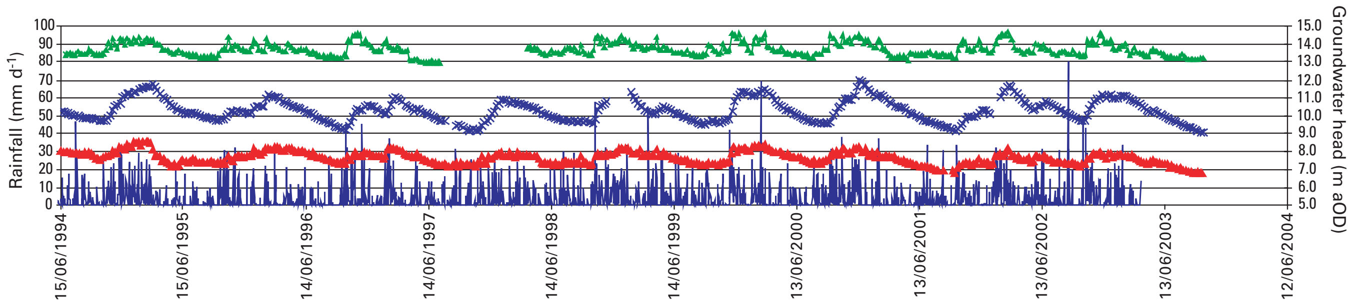


Figure 4.2 Groundwater hydrographs at Newbridge, Redbank and Holywood.

The earliest record of geophysical logging measurements in boreholes within the Dumfries Basin, by BGS, is for the Drungans Factory Borehole 1, which was logged in July 1968 (Tate, 1968). The borehole was later known as ICI Bh1 at Cargenbridge Works and is now known as Dupont 1. Dupont 1 was relogged in May 1998 using a wider range of techniques (Buckley, 1998).

The original borehole was drilled to 215 m depth in 1953. In 1967 a second, fully cored, borehole was drilled 60 m to the east of Borehole 1. This proved alternating thin layers of dark red sandstone and thicker, lighter coloured breccias.

BOX 2 THE BGS LOGGING PROGRAMME

Since 1985, the BGS has logged 18 boreholes geophysically within the Dumfries Basin, initially using analogue equipment (prior to May 1992) and then with digital acquisition. Details of the boreholes logged are listed in Table 4.3. For each borehole a suite of formation logs (caliper, gamma ray (NGAM), electrical resistivity (16, 64-in normals, focused resistivity, point resistance, induction resistivity) and magnetic susceptibility was recorded. At the same time a suite of fluid log measurements (fluid temperature, fluid electrical conductivity and borehole flowmeter measurements) were recorded both before and during pumping in order to pinpoint the positions of water inflow and their relative magnitude. For the pumped fluid logging a pump was installed in the boreholes, and specific capacity measurements were also recorded, and where necessary water samples were collected from the discharge and also from selected depths for later chemical analysis.

Geophysical logs of the Dupont Borehole 1 which is the deepest borehole logged to date in the basin, are shown in Figure 4.3. Also shown is the lithology indicated by the drilling description and examination of the core of adjacent Borehole 2. The 1968 logging consisted of fluid electrical conductivity and fluid temperature (EC/TEMP) logs recorded whilst adjacent Borehole 2 was pumping. The caliper, natural gamma and resistivity logs showed consistent profiles against the breccias and sandstone layers and these logs could be used to identify these main lithologies without reference to a lithological description. The logging-based lithology column is shown alongside in Figure 4.3 and is based on the gamma ray (NGAM), electrical resistivity and caliper measurements. The positions of the lithological units shown by the logging are considered to be more accurate than those indicated by the drilling and core description.

The logging showed that in Dupont Borehole 1 the breccias can generally be identified by high gamma ray and electrical resistivity, whilst the sandstone layers are recognised by low gamma ray and low resistivity. At the same time it is evident the sandstone layers are softer than the breccias because they coincide with zones of enlarged diameter seen by the caliper log.

Geophysical logging of the boreholes across the basin revealed that the gamma ray and resistivity log profiles were of two types. For boreholes at Terregles, Hardthorn Road, Little Fenwick, Dupont Borehole 1 and Powbridge, the gamma ray and resistivity log profiles were generally parallel to each other and the mean gamma ray value was less than 70 API. For boreholes at Cargen, Gibbonhill, Ironhirst Moss, Racks Moss, Longbridgemuir, Locharbriggs and Larchfield however, the relationship was a mirror-image (see Figure 4.4) and the mean gamma ray of the sandstones was greater than 70 API. It was also recognised that the latter boreholes (except for Cargen) were all east of gridline easting 297 whilst the first group with parallel logs were west of easting 297. One explanation is that there are different sources for the sediments of these areas. The sandstones and breccias in the west are cleaner sediments from a source having lower gamma ray and higher resistivities, whilst those in the east are derived from source rocks containing a higher proportion of mudstones and are thus higher gamma ray and lower resistivity.

Figure 4.5 summarises the mean gamma ray and resistivity values for the sandstones and breccias logged in the Dumfries Basin boreholes. Plots to the left of the arbitrary vertical line (70 API) have low gamma ray values and show the parallel relationship. Values plotting to the right of the line have higher gamma ray and their resistivity and gamma ray logs show the mirror-image relationship. Table 4.4 lists the logging parameters used for the plot.

It is noted that the boreholes display the parallel profiles west of easting 297 also have higher specific capacities as recorded during pumped fluid logging (Table 4.5). This reflects the cleaner aquifer source material which, in turn, has permitted the development of a greater groundwater circulation through the rock mass.

Geophysical logging of Terregles Boreholes 1–3 in 1992 (see Table 4.3 for details) showed that the gamma and resistivity profiles could be used to identify the clean sandstones and the breccia layers, and also demonstrated that it is possible to correlate these horizons laterally over distances of up to 2 km.

The Hardthorn Road boreholes at Terregles are up to 148 m deep, and they can be correlated with those of the Terregles Boreholes 1–3 to the north. The geophysical logs

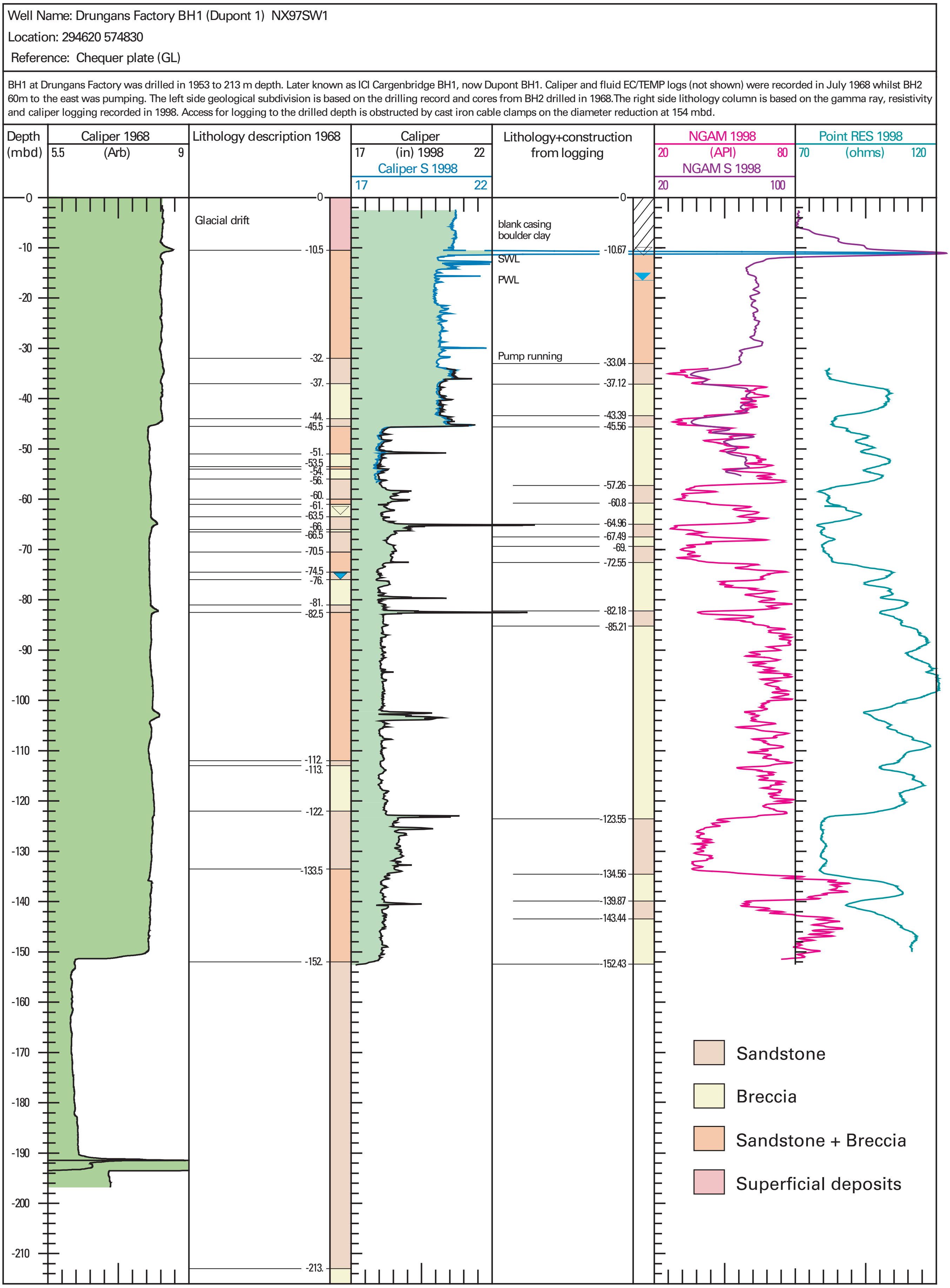


Figure 4.3 Geophysical logs recorded in Drungans Factory Borehole 1 (Dupont 1), Cargenbridge, Dumfries.

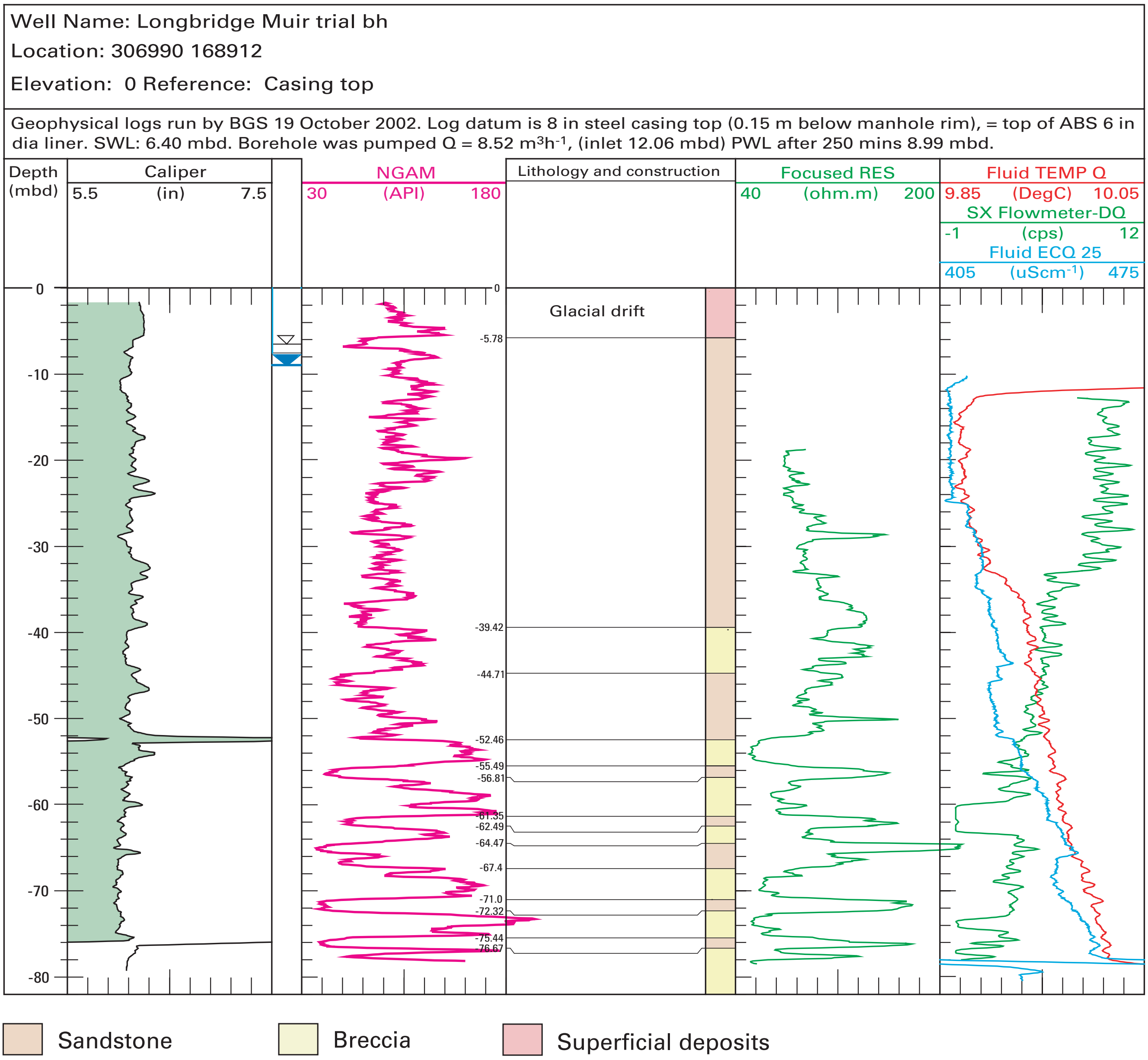
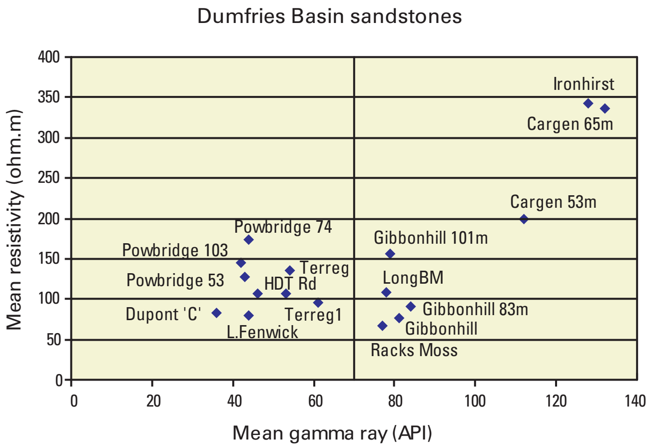


Figure 4.4 Geographical logs showing mirror-image relationship of gamma ray (NGAM) and focused resistivity measurements, Longbridgemuir Borehole, Dumfries Basin.



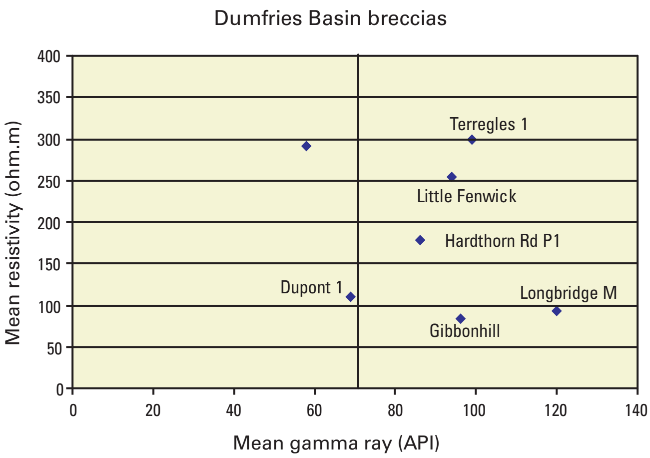


Figure 4.5 Comparison of mean gamma ray and electrical resistivity log measurements of Permian sandstone and breccias, selected boreholes, Dumfries Basin.

of the three Hardthorn Road boreholes, which are only 30 m apart, are shown in Figure 4.6. It shows they each penetrate three main sandstone units and two breccia layers, whilst Borehole P1, which is the deepest, penetrates a third breccia and a fourth sandstone. In Figure 4.6 the sandstones are numbered 1 to 4 from the base upwards. The youngest sandstone, Unit 4, which extends from the static water level (SWL) to the surface, is largely unsaturated, and thus is likely to permit direct recharge via gravelly superficial cover, unlike the Terregles Borehole 1 and Little Fenwick sites where the logging indicates less permeable breccia present at the surface. At Terregles 2 the logging identified a layer of breccia at 12 m depth above which water was cascading into the borehole from a perched aquifer, down to a SWL at about 20 m below surface, which judging by its elevation, may itself be a perched level.

Figure 4.6 shows the interpreted water inflows into the Hardthorn Road boreholes as horizontal blue lines drawn where there are changes on the pumped fluid and flowmeter log profiles. They are at consistent positions in all three boreholes and demonstrate water inflow from Sandstone Unit 3 and its junction with the underlying breccia at -20 to -24 m OD, from near the base of the breccia unit at -58 to -66 m OD, and from the middle of Sandstone Unit 2 at -82 and -86 m OD. In borehole P1, which is deeper, there was a strong upflow from Sandstone Unit 1 below -106 m OD which flowed up the borehole at a rate of 7 l s^{-1}, invading Sandstone Unit 2, the overlying breccia, and Sandstone Unit 3. The invading water from Sandstone Unit 1 was warmer than that entering from the shallower layers, and fluid temperature logging in production Boreholes 2 and 3 identified the return of this invading warmer water when they were pumped. The upward wellbore flow is present either because of a higher natural potentiometric level in Sandstone Unit 4, or due to local abstraction (Manse Road or fish farm boreholes) lowering the hydraulic potential in Sandstone Unit 3.

Whilst Hardthorn Road P1 Borehole illustrated natural or induced upflow from depth to Sandstone Unit 3, Boreholes P2 and P1 also exhibited induced downflow from the water table at 31.6 m depth to Sandstone Unit 3 at 59–65 m depth. This was observed during the pre-pumping fluid logging in these boreholes. Figure 4.6 shows logs of borehole P1 prior to pumping, which illustrates groundwater with relatively low temperature (9.0–10.2 °C) and high electrical conductivity (EC) (430 S cm^{-1}) moving down from 36 m to 59 m depth. Water of this temperature and fluid EC is not seen in the borehole when it is pumped and represents shallow circulating groundwater which is drawn down to the fissured horizon (caliper enlargement) of Sandstone Unit 3 at 59 m depth. It also has a relatively high nitrate concentration.

The wellbore flow effect is not restricted to the Terregles area. Wellbore downflow was recorded in the Cargen trial borehole prior to pumping in September 1994. In this example, cool groundwater of relatively high EC (~550 µS cm^{-1}), is flowing down from 21 m depth to exit into sandstone horizons at 53–54 m, and possibly deeper. On pumping, warmer water and lower EC (~280 µS cm^{-1}) groundwater replaces it from inflows at 72 m and 66 m. The fluid EC increases in steps at shallower depths corresponding to caliper enlargements opposite both breccias and sandstones at 54 m, 32 m and 21 m depth, and may represent some return of formerly invaded relatively high conductivity groundwater from shallower levels. It is not known which abstractions are responsible for lowering the hydraulic head in the sandstones layers between 54 and 72 m depth. They may be due to pumping several kilometres away because the sandstone layers are thin and are relatively highly permeable compared to the breccia layers between. Furthermore, there are only a few inflow horizons in each borehole.

A summary of the depths and elevations of the water flow horizons identified by fluid logging in the boreholes in the Dumfries Basin is presented in Table 4.6. A histogram of the inflows relative to OD is shown in Figure 4.7. The histogram shows that roughly 75% of the inflows are shallower than -68 m OD. The relationship between the various flow horizons and river flow has not been investigated.

Figure 4.8 presents a scaled geological and hydrogeological cross-section of the Dumfries Basin along a north-west to south-east line. It shows a suggested correlation of the main sandstone and breccia units, which although they may change thickness and lithology along the line of section, appear to dip down the basin from Terregles 2 in the north-west to Dupont 1 Borehole. It is not clear how the units match to the south-east of the Dupont site and different source material may be represented. It is also not clear if faulting disrupts the layering along the section.

The static water level measured at the time of logging is shown on the cross-section. It suggests that the Terregles 2

Table 4.3 List of boreholes in the Dumfries Basin that have been geophysically logged.

Borehole	National grid reference	Date logged	Logged depth (m)	SWL (m)	Comments
Locharbriggs	NX 9998 8030	Sept 1985	60.5	0.4	Pumped at 2 $m^3 h^{-1}$, PWL 1.98 m bgl.
Larchfield Trial	NX 9800 7510	Sept 1985	59	25.1	
Terregles	NY 9300 7700	June 1987	22		Infilled from 22 m observation onwards
Terregles 1	NX 9360 7903	June 1992		37	Pump installed
Terregles 2	NX 9280 7905	June 1992	76.7	20	Cascading from 9 to 10 m
Terregles 3	NX 9339 7820	June 1992	73.6	37	Water cascading, pump installed
Gibbon Hill	NX 9780 5600	Sept 1994	116.3	1.7	Pump installed
Cargen Trial	NX 9630 7260	Sept 1994	115.6	16.0	Pump installed at 14 $m^3 h^{-1}$, PWL 16.6 m bgl
Powbridge	NX 9615 7145	Feb 1995	126	Over-flows	Pump installed at 18 $m^3 h^{-1}$, PWL 4.6 m bgl
Hardthorn Road P1	NX 9356 7810	Dec 1997	127.4	30.9	Pump installed at 80 $m^3 h^{-1}$ PWL 34.4 m bgl
Hardthorn Road P2	NX 9358 7808	Dec 1997	127.5	30.9	Pump installed at 80 $m^3 h^{-1}$ water cascading from base of casing
Hardthorn Road P3	NX 9355 7805	Dec 1997	123.7	31.0	
Dupont 1	NX 9462 7483	May 1998	154.6	11.6	Pump installed at 112 $m^3 h^{-1}$ 16.4 m bgl PWL
Racks Moss	NY 0297 7273	Oct 2002	100.0	1.6	Pump installed at 8.6 $m^3 h^{-1}$ PWL 10.0 m bgl
Ironhirst Moss	NY 0490 7071	Oct 2002	97.0	0.3	Pump installed at 4.6 $m^3 h^{-1}$ PWL 14.0 m bgl
Longbridgemuir	NY 0699 6891	Oct 2002	79.7	6.4	Pump installed at 8.5 $m^3 h^{-1}$ PWL 31.9 m bgl
Little Fenwick	NX 9490 7599	Oct 2003	80.5	4.5	Strong downflow between 31 and 38 m bgl

measurements may represent a perched level, or that the Terregles1 and Hardthorn Road P1 levels are depressed because of local abstraction at the Manse Road Pumping Station and the Terregles Fish Farm boreholes. The downward wellbore flow observed in the Little Fenwick and Hardthorn Road boreholes might also be a response to these abstractions. Powbridge Borehole is artesian.

4.7 GROUNDWATER QUALITY

The groundwater chemistry is the product of maritime rainfall modified by the dissolution of carbonate material in the breccia, sandstone and superficial deposits. CFC and SF_6 age-indicator concentrations are interpreted on the basis of mixing between older (>50 years) and recent (1990s) components. There is generally a higher proportion of older water within the Locharbriggs Sandstone than the Doweel Breccia.

Concentrations of nitrate across the aquifer can be directly related to the relative amount of recent recharge. Modern groundwater contains approximately 9 mg l^{-1} NO_3-N and pre-1950s groundwater has approximately 2 mg l^{-1} NO_3-N. Nitrate concentrations measured at individual boreholes are explained by the proportions of modern and pre-1950s groundwater. If current practices continue, the concentrations of nitrate measured across the Dumfries Basin will rise as the proportion of pre-1950s groundwater diminishes.

4.7.1 Distribution of groundwater quality

The Permo-Triassic waters of south-west Scotland are typically hard, moderately mineralised and have bicarbonate concentrations greater than 100 mg l^{-1} (Robins, 2002). Groundwater generally has a near-neutral pH and is of the Ca-HCO_3 or Ca-Mg-HCO_3 type.

The Dumfries Basin aquifer is no exception, and analyses confirm that groundwater is not highly mineralised and its chemistry is predominantly of a Ca-Mg-HCO_3 type. The pH is in the range 7.1 to 7.6 with a median of 7.2 (see Table 4.7, after MacDonald et al., 2003). The major ion chemistry of groundwater in Dumfries is summarised on a Piper diagram, Figure 4.9. The likely source of mineralisation is carbonate

Table 4.4 Summary of gamma ray and electrical resistivity log measurements recorded in selected boreholes penetrating Permian sandstones and breccias.

Borehole	Depth interval (m bgl)	Lithology	Gamma ray (API) Range	Mean	Resistivity (ohm m) Range	Mean
Terregles No 1	57–62	Sandstone C	50–73	61	86–114	96
	66–88	Breccia	87–110	99	155–395	300
Terregles No 2	50–55	Sandstone C	48–59	54	125–150	135
Hardthorn Road P1	54–65	Sandstone C	46–64	53	100–118	106
	71–97	Breccia	73–97	86	161–212	178
	107–137	Sandstone B	38–66	46	96–120	107
Little Fenwick	59–72	Sandstone C	29–73	44	75–87	80
	73–78+	Breccia	77–108	94	226–286	255
Dupont No 1	57–72	Sandstone C	26–49	36	77–93	83
	84–122	Breccia	49–84	69	94–121	110
	123–134	Sandstone B	33–55	42	79–81	80
Cargen Trial Bh.	53–54	Sandstone	102–130	112	185–225	199
	54–61	Breccia	144–174	157	310–377	344
	65–68	Sandstone	113–147	132	267–398	336
	68–71	Breccia	127–158	148	354–452	416
Powbridge	29–53	Breccia	31–88	66	152–380	265
	53–56	Sandstone	22–72	43	101–175	127
	56–71	Breccia	42–63	54	212–386	265
	74–85	Sandstone	29–60	44	120–337	173
	86–93	Breccia	44–66	54	261–460	344
	103–116	Sandstone	27–55	42	114–211	145
Gibbon Hill	57–61	Breccia	73–107	85	72–76	74
	61–68	Sandstone	71–90	81	75–77	76
	68–72	Breccia	91–120	103	73–76	74
	77–82	Breccia	88–113	98	77–81	79
	83–98	Sandstone	73–96	84	85–103	91
	98–101	Breccia	91–111	100	99–109	105
	101–112	Sandstone	67–95	79	140–180	156
Racks Moss	45–96	Sandstone	47–105	77	60–76	67
Longbridgemuir	18–39	Sandstone	61–150	93	77–157	101
	39–45	Breccia	77–128	102	93–146	120
	45–49	Sandstone	53–95	74	85–124	100
	49–55	Breccia	70–164	121	50–167	81
	55–57	Sandstone	47–118	68	74–160	127
	57–61	Breccia	97–174	137	68–95	79
Ironhirst Moss	30–94	Mudstone*	86–168	128	122–623	342

*Lower Palaeozoic

material within the breccia and sandstone and the overlying superficial deposits (which are generally similar in composition to the bedrock). The high Mg/Ca ratios in the water samples suggest the presence of dolomite, though groundwater is undersaturated with respect to both calcite and dolomite.

The distributions of Ca, Mg and HCO_3 throughout the basin is broadly similar (Figure 4.10). Highest concentrations are found in the north-west in the Doweel Breccia Formation and lowest concentrations within the Locharbriggs Sandstone Formation reflecting the aeolian origin of the sediments and the presence of silica cement. Mineralisation of the groundwater also occurs in the superficial deposits. Recent work in southern Scotland (Stone et al., 1999), has shown a good match between stream sediment geochemistry and underlying geology, indicating that superficial deposits generally derive from bedrock less than 1 km distant. Local differences in geochemistry may arise between bedrock and superficial deposits, giving rise to small variations in groundwater chemistry, such as in the south-east of the Locharbriggs Formation.

Concentrations of SO_4 are highest in the southern part of the basin beneath the raised beach marine deposits (Figure 4.11). Other sources of SO_4 may be thin gypsum lenses or oxidation of sulphides in occasional mudstone horizons. Potassium concentrations are low and show little change across the basin, and probably derive from K-feldspar in the sediments (McKeever, 1992).

The main source of NO_3 in the groundwater is farming, notably the application of nitrogenous fertiliser and animal slurry. The median value is 6.1 mg l^{-1} NO_3-N.

Groundwater is saturated with respect to Si and the median concentration is 5.1 mg l^{-1}. Fe and Mn concentrations are low throughout the aquifer, despite the presence of haematite within the sediments (which gives the rocks their characteristic red colour). Iron is generally below the detection limit of 0.02 mg l^{-1}, with Mn less than 0.04 mg l^{-1}. The solubility of these two minerals is strongly

Table 4.5 Summary of specific capacity measurements determined whilst pumping during fluid logging.

Borehole	Specific capacity ($l\ s^{-1}\ m^{-1}$)	GR/RES log response
Terregles No. 3	120	Parallel
Hardthorn Road P1	27	Parallel
Hardthorn Road P2	26	Parallel
Hardthorn Road P3	20	Parallel
Cargen Trial Bh	11	Parallel
Dupont No 1	5	Parallel
Powbridge	1	Parallel
Gibbon Hill	0	Mirror image
Ironhirst Moss	0	Mirror image
Locharbriggs	4	Mirror image
Longbridgemuir	1	Mirror image
Racks Moss	0	Mirror image

redox-controlled, particularly at near neutral pH, and the low Fe and Mn concentrations reflect oxidising conditions throughout the aquifer. Fe and Mn concentrations are elevated in superficial sands and gravels in some areas.

4.7.2 Age and provenance

Fifteen samples were analysed for CFCs and SF_6; data are shown in Table 4.8. Samples from four boreholes had concentrations above present-day atmospheric equilibrium CFC concentrations: samples 6 (Gates Rubber), 8 (Manse Road), 17 (Terregles Fish Farm) and 22 (Dupont). Samples 6 and 22 are from industrial sites where artificially high concentrations of CFC may occur, but samples 8 and 17 are in a rural setting, with no obvious source of CFC nearby.

The CFC and SF_6 data shown in Table 4.9 are expressed in terms of the percentage of modern water present in the pumped water for each borehole. The calculations assume a recharge temperature of 10°C, i.e. the annual average air temperature for the area. SF_6 and CFC concentrations for the modern water component (from Busenberg and Plummer, 2000) are included in the table.

Questionable percentages are italicised to distinguish them from what are considered to be the more reliable data. For example, some CFC-derived modern water percentages are well in excess of 100% and are likely to be due to industrially-derived contamination. While such high values may have a tracing function, they cannot be used in a residence-time/mixing calculation role. In other cases, such as boreholes 9 and 21, one or more of the CFCs may give an elevated percentage compared to the others, but remain below 100%. This may also represent contamination, but at a lower level. In the absence of evidence for reducing conditions in the aquifer, the lower percentages are considered to be most representative. Often these are in relatively good agreement with the SF_6 based values, adding confidence to the interpretation. However, two samples, 4 and 19, show substantial discrepancies, where SF_6 suggests the water is almost or wholly modern while CFCs indicate a much lower percentage. There appears to be no reason why the CFC values should be affected in these two boreholes, and it is assumed that the SF_6 is in error. Since SF_6 is significantly less soluble than the CFCs, SF_6 concentrations are less well buffered against changes due to the inadvertent ingress of air during sampling, which may occasionally occur due to well-head contamination or long lengths of sampling hose.

The CFC and SF_6 data suggest that groundwater within the Dumfries Basin aquifer ranges from 'old' (greater than 50 years) to modern. The distribution of the modern water percentage in the Dumfries Basin is shown in Figure 4.12. Correlation between the depth of the boreholes and the age of the groundwater is poor, whereas that between lithology and age is generally good. Groundwater in the west of the basin, within the Doweel Breccia Formation, has a large component of modern water. This contratsts with the centre of the basin where groundwater is generally older, and the east where it is older still, with generally less than

Table 4.6 Summary of water inflows horizon depth below datum.

Borehole	Depth (m)	SWL (m bgl)	Interpreted flows (m bgl)	Borehole yield ($l\ s^{-1}$)
Cargen Trial Bh	115.6	16.1	54, 65, 72, 95	11.4
Dupont No 1	154.6	11.6	22, 80, 95, 123, c140, c152, c164	5.4
Gibbon Hill	116.3	1.7	58, 78, 92	0.4
Hardthorn Road P1	147.7	31.6	39, 59, 65, 96, 101, 104, 127	26.7
Hardthorn Road P2	127.5	30.9	39, 54, 60, 65, 70, 96, 102–104, 122	25.8
Hardthorn Road P3	132.7	31.0	60, 67, 98, 103, 105, 120	20.3
Ironhirst Moss	97.0	0.3	17, 42, 66, 82	0.1
Larchfield	58.0	25.1	30, 37, 56	
Little Fenwick	80.5	4.5	14, 34, 60, 72	
Locharbriggs	60.0	0.4	28, 39, c.54	3.7
Longbridgemuir	79.7	6.4	24, 32, 52	0.9
Powbridge	126.0	Overflows	54, 78, 83, 106	0.9
Racks Moss	100.0	1.6	34, 52, 70, 80, 88	0.3
Terregles No 1	102	37	46, 66, 89	
Terregles No 2	76.7	C20	39, 50, 66	
Terregles No 3	73.6	37.2	57, 63	12.1

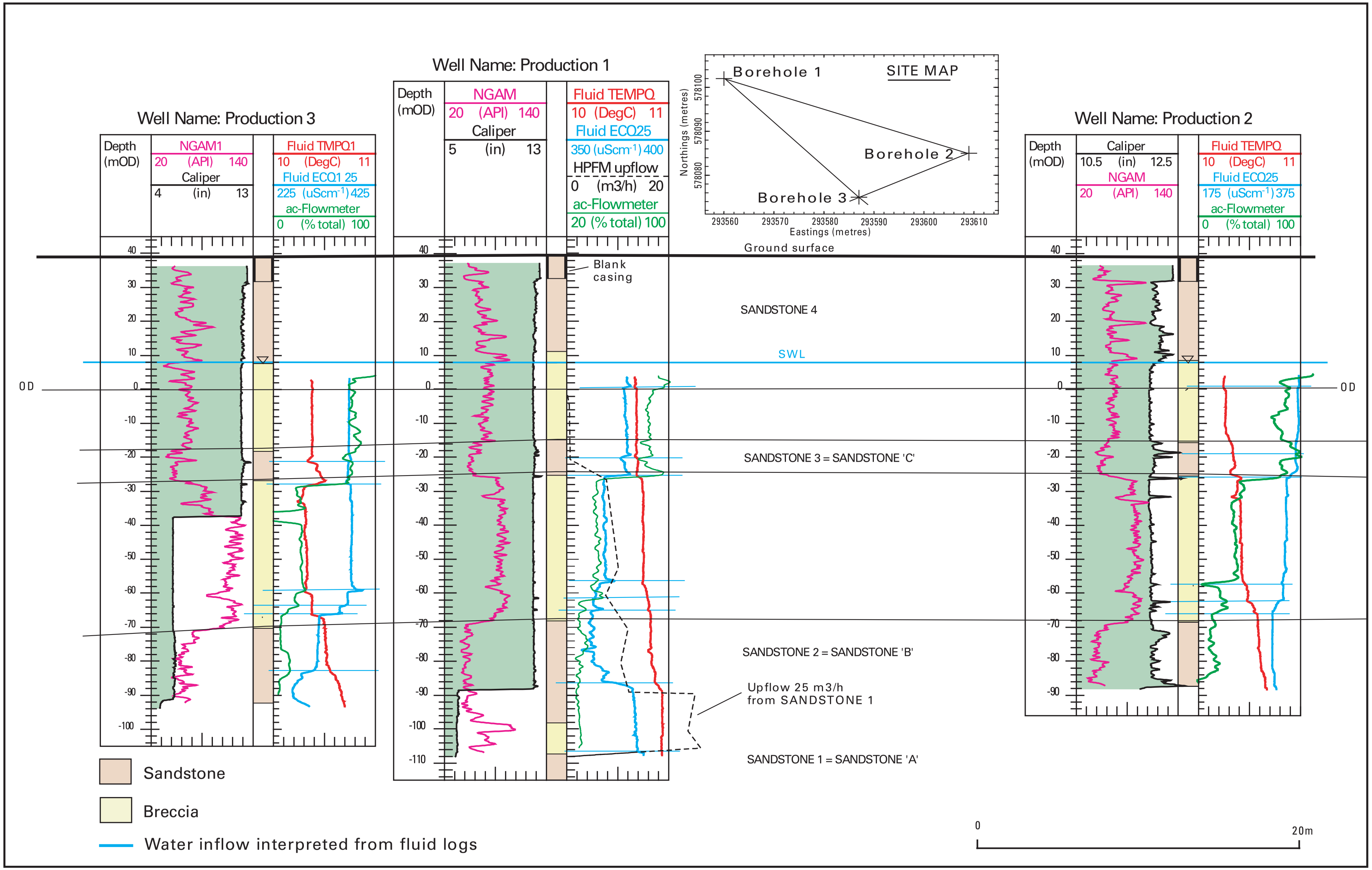


Figure 4.6 Scale cross-section showing geology and water inflows, Hardthorn Road site boreholes,Terregles, Dumfries, based on geophysical logging data.

BOX 3 CFC AND SF_6 AS RESIDENCE TIME INDICATORS

Concentrations of CFCs (chlorofluorocarbons) have been increasing in the atmosphere at known rates since they began to be used industrially (CFC-12 in the 1930s, CFC-11 in the 1950s and CFC-113 in the 1970s (Plummer and Busenberg, 1999). Recharging rainfall contains CFCs dissolved in proportion to the atmospheric concentrations at the time of the event. They have the potential to act as indicators of the time elapsed since recharge, or groundwater 'age'. Gas tracers move diffusively through the unsaturated zone, therefore the actual time elapsed is from when recharge reaches the saturated aquifer (Zoellmann et al., 2001). This produces a negligible error in shallow water tables (Cook and Solomon, 1995), but may introduce an error of several years where the unsaturated zone is greater than 10 m (Johnston et al., 1998). In general CFCs behave in a conservative way during travel in the saturated subsurface. Their use is compromised only in more extreme circumstances such as contaminated and/or highly reducing waters. In such circumstances SF_6 (sulphur hexafluoride), another industrial gas that has been building up since the 1950s, can substitute for the CFCs (Busenberg and Plummer, 2000).

As with all groundwater 'dating' methods, certain assumptions are necessary before the CFC or SF_6 techniques can be applied. In the case of the sandstones and breccias of the Dumfries Basin, where flow within fractures dominates, it is less appropriate to consider groundwater in terms of simple piston flow than as a mixture between younger and older components. In its simplest form this can be reduced to mixing between two end members: a 'modern' water with maximum CFC or SF_6 content (recharged within the past 10 years) and an 'old' water with no detectable CFC or SF_6 content, with an age greater than 50 years. Thus CFC and SF_6 results can be expressed in terms of the percentage of modern water present.

10% modern groundwater. In the far south-east of the basin a more modern groundwater is found near the basin boundary.

The greatest proportion of modern water is found in the northern portion of the breccia close to the edge of the basin. Here the bedrock is covered by highly permeable fluvioglacial sands and gravels. These sands and gravels may allow rapid recharge to the breccia. To the south, however, low permeability raised marine deposits and glacial till cover the aquifer. Recharge in this area is limited and as a consequence the proportion of modern water is much less (Figure 4.12).

Stable isotope and major ion chemistry data allow further interpretation of the older groundwater component in both the Locharbriggs Formation and the Doweel Breccia Formation. Slight depletion in the stable isotopes suggests that traces of late glacial recharge remain. Major ion chemistry for the two sites with depth samples, Manse Road (samples 8, 15) and Hardthorn Road (samples 13, 14) indicate lower HCO_3, Ca and Mg concentrations from deeper fractures which contain a higher proportion of older water. In fact, the concentrations of HCO_3, Ca and Mg in the older water in the Doweel Breccia Formation are similar to those found within the Locharbriggs Formation (see Table 4.7), suggesting that the former is derived from the interbedded aeolian sandstones in the sequence, which have a similar origin to the Locharbriggs Formation.

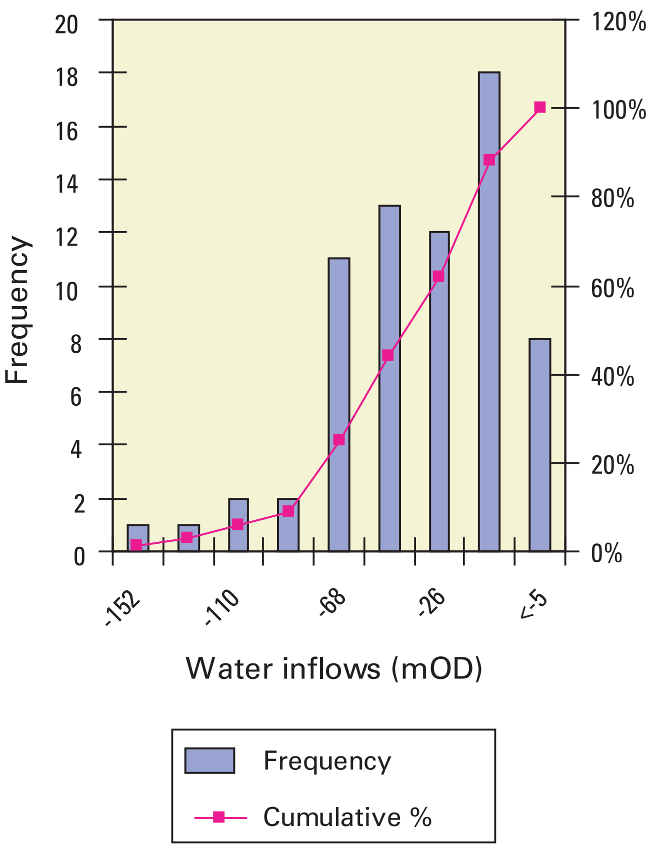


Figure 4.7 Frequency histogram of water inflow horizons, all lithologies, Dumfries Basin boreholes.

4.7.3 Diffuse pollution

Diffuse pollution from nitrogenous fertiliser and animal slurry is a problem in the aquifer. The highest potential for recharge is in those areas where the pathway between the surface and the aquifer is most accessible. These same areas are subject to intensive grassland cultivation for grazing, and disposal of animal slurry. In addition, ploughing and resowing of pasture on a five- to eight-year cycle releases nitrogen from the soil into the underlying sand and bedrock aquifer. Increasing concentrations of nitrate recorded in a number of boreholes (including Terregles Fish Farm, Manse Road, Crichton Royal and Larchfield Pumping Station) indicate that present trends of rising nitrate concentrations in modern groundwater will continue or could accelerate (Ball, 2002).

Historical data are available for a number of sites, the longest record being that for the Manse Road Pumping Station where the earliest measurement of nitrate was in 1983 when it was 5.9 mg NO_3-N l^{-1}. Recent analyses show that on occasion it has been as high as 26 mg NO_3-N l^{-1} (Robins and Ball, 1998).

Figure 4.13 shows the concentration of nitrate plotted against the percentage of modern water in each sample. Excluding one sample (where local contamination from a dairy farm was suspected) the concentration of nitrate shows a significant positive correlation with the proportion of modern water in the sample ($r^2 = 0.70$ from 14 samples). The linear relation between nitrate and the age of the groundwater implies that modern recharge water currently contains approximately 9 mg l^{-1} NO_3-N. Since the average nitrate concentration of groundwater within the basin is

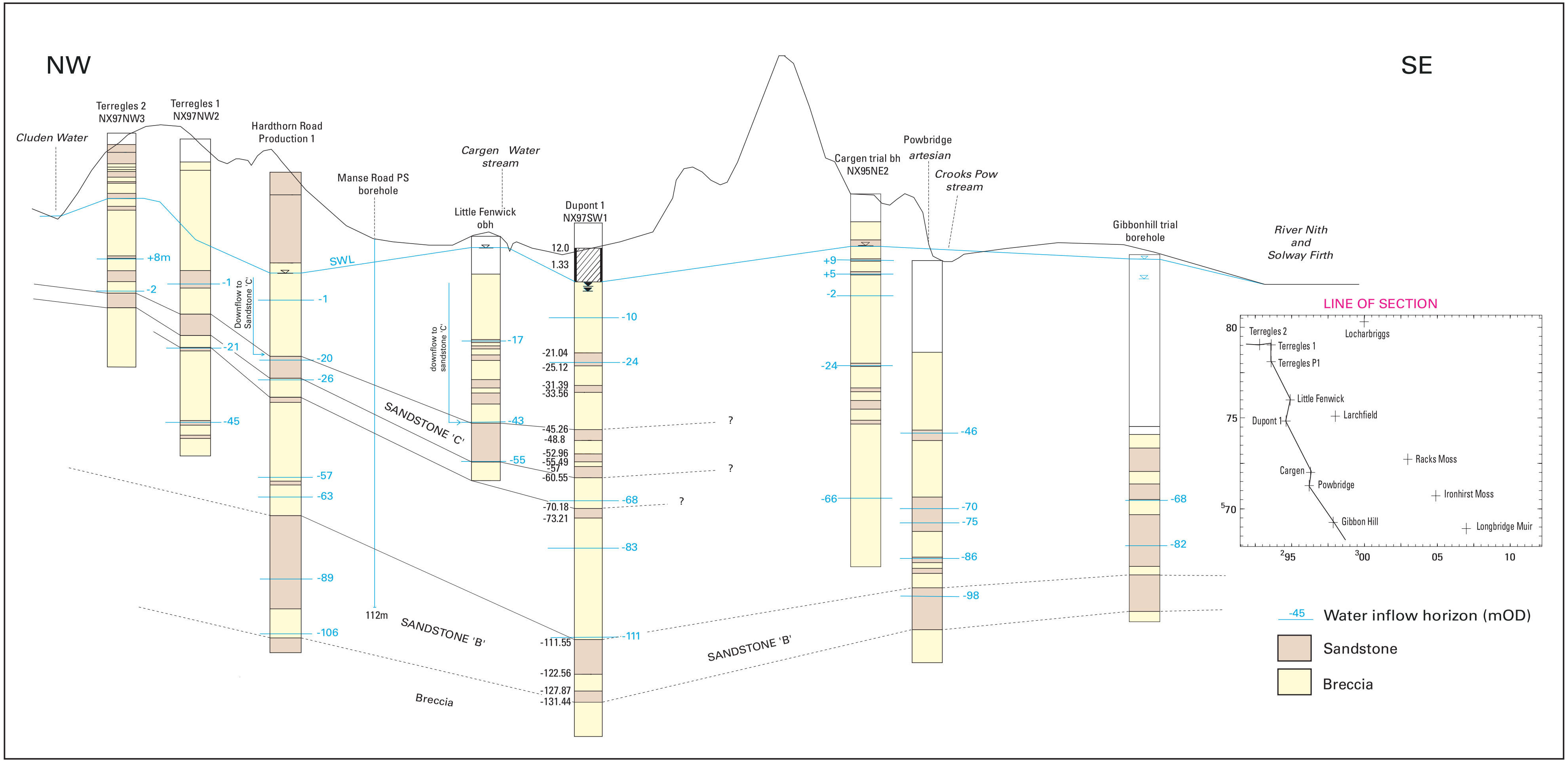


Figure 4.8 Scale geological and hydrogeological cross-section north-west to south-east of the Dumfries Basin showing a suggested correlation of main sandstone and breccia units, and illustrating water inflow horizons.

Table 4.7 Hydrochemical data from groundwater samples from the Dumfries Basin (after MacDonald et al., 2003).

Site	1	2	3	4	5	6	7	8	9	10	12	13	14	15	16	17	18	19	20	21	22	Mean
PH	7.2	7.1	7.4	7.3	7.4	7.3	7.1	7.1	7.0	7.4	7.1	7.0	7.4	7.2	7.2	7.3	7.6	7.1	7.2	7.5	7.0	7.2
TDS	314	493	273	296	136	209	267	311	257	293	255	397	301	464	319	385	303	263	94.3	263	575	293
Mg (mg l^{-1})	20.6	19.2	15.5	19.7	7.84	12.7	18.1	21.7	17.6	15.7	17.3	29.2	21.4	29.9	19.8	23.1	19.8	12.9	3.93	16.8	41	19.2
Ca (mg l^{-1})	41.2	86.1	40.2	42	19.4	26.3	38	45.2	35.5	33.8	37	58.5	41.7	70.9	46.6	58.7	41.5	32.4	10.4	36.8	83.3	41.2
Na (mg l^{-1})	14.1	18.4	11.3	12.9	7.3	11.6	11.1	8.9	10.8	23.3	9.4	7.6	9.3	9.6	9.6	10.1	12.9	25.9	8.9	9.6	23.4	10.8
K (mg l^{-1})	3.4	3.3	1.7	1.3	1.2	1.5	1.6	1.5	1.4	3.9	1.2	1.5	1.2	2.7	1.8	1.7	1.9	2.3	1.4	2	2.3	1.7
Cl (mg l^{-1})	24.2	33.1	18.9	20.1	11.5	17	17.8	15.4	17	14.3	16.4	13.7	14.8	14.6	14.3	16.1	22.6	23.4	9.3	14.2	96	16.4
HCO_3 (mg l^{-1})	147	162	108	159	73.1	112	127	172	117	195	133	232	168	274	188	226	150	122	29.3	157	267	157
NO_3-N (mg l^{-1})	10	28.5	10.7	3.33	1.54	1.98	6.27	5.81	6.13	<0.25	4.19	9.91	6.24	10	5.48	7.15	6.18	2.04	3.51	1.57	6.65	6.13
SO_4 (mg l^{-1})	12.8	40.1	26.6	20.3	3.4	14.8	21	16.8	25	2.1	17.8	7.7	12.4	13.9	10.2	13.4	21.2	29.4	9.3	14.6	26.6	14.8
Si (mg l^{-1})	6.6	5.06	3.67	5.5	5.09	4.83	5.13	4.27	5.33	4.71	4.78	3.47	4.86	4.65	4.67	4.07	5.81	5.37	6.3	5.22	6.01	5.06
SI calcite	-0.68	-0.49	-0.62	-0.5	-1.1	-0.89	-0.89	-0.72	-1.1	-0.42	-0.85	-0.55	-0.44	-0.28	-0.53	-0.3	-0.24	-0.92	-1.9	-0.4	-0.34	
SI dolomite	-1.5	-1.5	-1.5	-1.1	-2.5	-1.9	-2	-1.7	-2	-1.1	-1.9	-1.3	-1.1	-0.85	-1.3	-0.88	-0.67	-2.1	-4.2	-1	-0.84	
Br (µg l^{-1})	110	140	70	80	90	80	70	70	80	50	70	60	60	70	60	60	80	110	60	50	220	70
F (µg l^{-1})	80	80	70	70	70	100	80	60	80	100	70	60	50	60	60	60	80	80	10	50	40	70
I (µg l^{-1})	10	7.3	3.4	3.7	2.8	3.4	2.7	3.4	2.6	5.1	3.8	3.9	3.1	4.3	3	3.2	2.7	2.4	2	2.7	7.5	3.4
Fe (µg l^{-1})	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	70	120	20	30	<20	<20	<20	<20	<20	<20	20	20
Mn (µg l^{-1})	0.16	10	0.05	0.05	0.51	0.53	<0.04	0.05	0.06	0.04	0.79	20	5.38	0.41	0.12	<0.04	0.04	0.04	0.15	40	10	0.15
NO_2-N (µg l^{-1})	6 5.	8 6.	76	3.38	5.8	5.8	8.06	5.8	4.05	5.8	4.05	9.39	5.36	6.7	4.02	5.8	5.8	5.8	5.8	5.3	7.95	19.1
NH_4-N (µg l^{-1})	20	<10	80	20	90	<10	100	<10	<10	<10	<10	170	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
P (µg l^{-1})	<20	40	20	<20	50	<20	50	20	70	80	20	30	<20	30	<20	<20	40	<20	<20	30	20	20
Li (µg l^{-1})	10	10	4.5	5.4	2.6	2.1	2.9	2.1	2.2	3.5	2.8	1.0	3.4	1.5	3.8	1.6	3.9	9.8	2.3	3.0	4.1	3.0
B (µg l^{-1})	20	60	20	10	6.6	20	8.7	10	10	30	9.3	10	9.8	10	10	10	10	10	6.4	7.6	10	10
Al (µg l^{-1})	1.2	0.4	1.4	0.4	0.8	1.2	0.6	4.8	0.7	1.6	2.9	2.6	1.2	7.0	2.4	0.8	1.0	1.4	1.8	0.7	9.9	1.2
Cr (µg l^{-1})	0.2	0.1	0.3	0.5	0.7	0.2	0.4	0.8	0.3	1.9	0.5	1.8	0.6	0.4	0.4	0.3	0.3	0.4	0.5	0.3	1.7	0.4
Co (µg l^{-1})	0.09	0.18	0.07	0.09	0.04	0.06	0.08	0.11	0.06	0.05	0.08	0.17	0.08	0.14	0.09	0.13	0.07	0.07	0.02	0.09	0.24	0.08
Ni (µg l^{-1})	1.5	2.9	1.2	1.4	0.6	1.3	1.2	1.8	1.3	1.0	1.0	2.7	1.3	2.0	1.4	1.9	1.7	0.9	1.3	1.3	3.8	1.3
Cu (µg l^{-1})	4.2	10	1.5	0.2	0.1	0.2	0.7	5.4	3.4	<0.05	4.8	10	0.8	0.7	0.6	0.7	7.6	2.9	1.1	0.6	0.8	0.8
Zn (µg l^{-1})	5.4	3.1	2.4	4.5	0.5	2.5	1.9	10	4.9	<0.45	7.8	10	2.0	1.8	1.7	1.1	8.6	4.1	7.6	3.8	40	3.8
As (µg l^{-1})	10	4.7	2.2	0.9	0.7	0.4	0.7	1.9	0.7	0.6	1.9	0.7	2.2	0.8	5.8	1.1	1.7	1.7	0.3	0.9	3.1	1.1
Se (µg l^{-1})	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3	<1.3
Rb (µg l^{-1})	2.2	2.1	1.3	1.0	0.7	2.8	0.7	0.8	0.8	0.6	0.9	0.8	0.9	1.0	1.2	0.9	1.0	0.6	2.2	1.1	1.6	1.0
Ba (µg l^{-1})	180	120	180	30	10	160	50	50	20	40	30	40	50	70	110	180	20	10	30	30	80	50
Pb (µg l^{-1})	0.3	0.24	0.09	0.06	<0.04	0.05	0.09	0.44	0.58	0.05	0.59	0.75	0.18	0.17	0.2	0.2	0.44	0.22	0.55	0.17	0.49	0.2
U (µg l^{-1})	2.17	1.17	0.28	1.56	0.10	1.14	0.37	0.69	0.23	1.44	1.38	0.16	0.92	0.13	1.04	0.51	1.36	1.91	0.11	1.00	0.60	0.92

Table 4.7 (cont).

Sample number	Borehole	Grid reference	Borehole depth (m)
1	Townfoot Farm	NY 0625 7200	60
2	Holmhead Farm	NY 0590 7133	30
3	South Bowerhouse Farm	NY 0719 7034	62
4	Nestlé Borehole 1	NX 9691 7733	183
5	Dundas Chemical	NY 0002 7756	90
6	Gates Rubber	NX 9893 7906	103
7	Galloway Mineral	NX 9782 7321	150
8	Manse Road Pumping Station	NX 9402 7677	112
9	Larchfield Pumping Station	NX 9809 7506	95
10	Locharmoss Borehole 1.3	NY 0119 7682	43
12	Shortridge Laundry	NX 9679 7646	48
13	Hardthorne Road No 1	NX 9356 7810	128
14	Hardthorne Road No 3	NX 9355 7805	128
15	Manse Road Observation	NX 9392 7659	27
16	Terregles Fish Farm	NX 9295 7717	122
17	Terregles Fish Farm	NX 9289 7737	122
18	Cargen Production	NX 9638 7203	112
19	Greenmerse	NX 97767048	75
20	Galloberry Farm	NX 9680 8270	90
21	Hollywood Fish Farm	NX 9754 7817	122
22	Dupont No 1	NX 9450 7450	30

only 6.1 mg l^{-1}, the NO_3-N concentrations will inevitably increase over the next few decades.

Allowing for uncertainties, the regression equation for the data implies that the older water contains on average 1.7 mg l^{-1} (± 1.4) NO_3-N. This estimate suggests that some nitrate was leached to groundwater prior to the use of fertiliser in intensive agriculture and the recent increases in NO_x atmospheric emissions. This small concentration of nitrate may reflect ploughing of established grasslands or the use of unlined slurry pits.

4.7.4 Point source pollution

There are two significant hazards with regard to point source pollution in the basin. These are the Dupont factory at Drungans, beneath which the bedrock aquifer is contaminated with formaldehyde, largely concentrated along discrete horizontal zones (Ball, 1995), and the large sanitary landfill site at Lochar Moss. Risk posed by the urban and industrial centre of Dumfries is reduced by there being a positive external pressure from groundwater on part of the sewer system in the town, although the normal risks from handling and processing hazardous chemicals at various factory sites, as well as that from transport spillages, remain important.

A great deal of investigation has been carried out at Drungans by a variety of consultants (principally Dames & Moore International) and research organisations, but few of the findings have yet found their way into the public domain. In the interim, scavenger pumping and treatment at rates up to nearly 1000 m^3 d^{-1} has been taking place in order to contain the spread of the pollutant.

At Lochar Moss, the bedrock aquifer is protected by up to 35 m of weakly permeable superficial cover, including peat, and as yet there has been little evidence of leachate reaching the sandstone aquifer (Ball and Ó Dochartaigh, 1999). The Lochar Moss waste disposal site, operated by Dumfries and Galloway Council, has been used for the disposal of mainly domestic waste from the Dumfries area. A lack of knowledge of the hydrogeology and geology of the area around the site combined with the requirement to apply for a waste disposal licence recently led the Council to carry out investigations into the extent, if any, of leachate infiltration to the underlying aquifers.

Drilling and surface geophysical work (Raines et al., 1998) has shown the presence of thick silty clay deposits under the central and western parts of the site. Along the eastern margins, a sandier sequence is present (Table 4.10). The depth to the main Permian sandstone aquifer has been established as varying from 26.5 m to 33 m below surface. Measurements of the depth to the water table has shown that a south-easterly gradient is present. Three aquifer units have been identified. An upper thin sand underlies the landfill and surface peat. This unit is separated from a lower sandy unit in

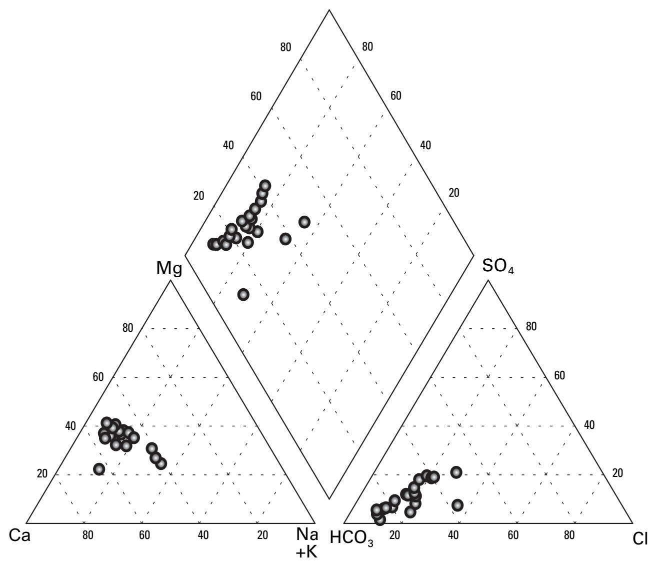


Figure 4.9 Piper diagram of Dumfries Basin aquifer groundwaters.

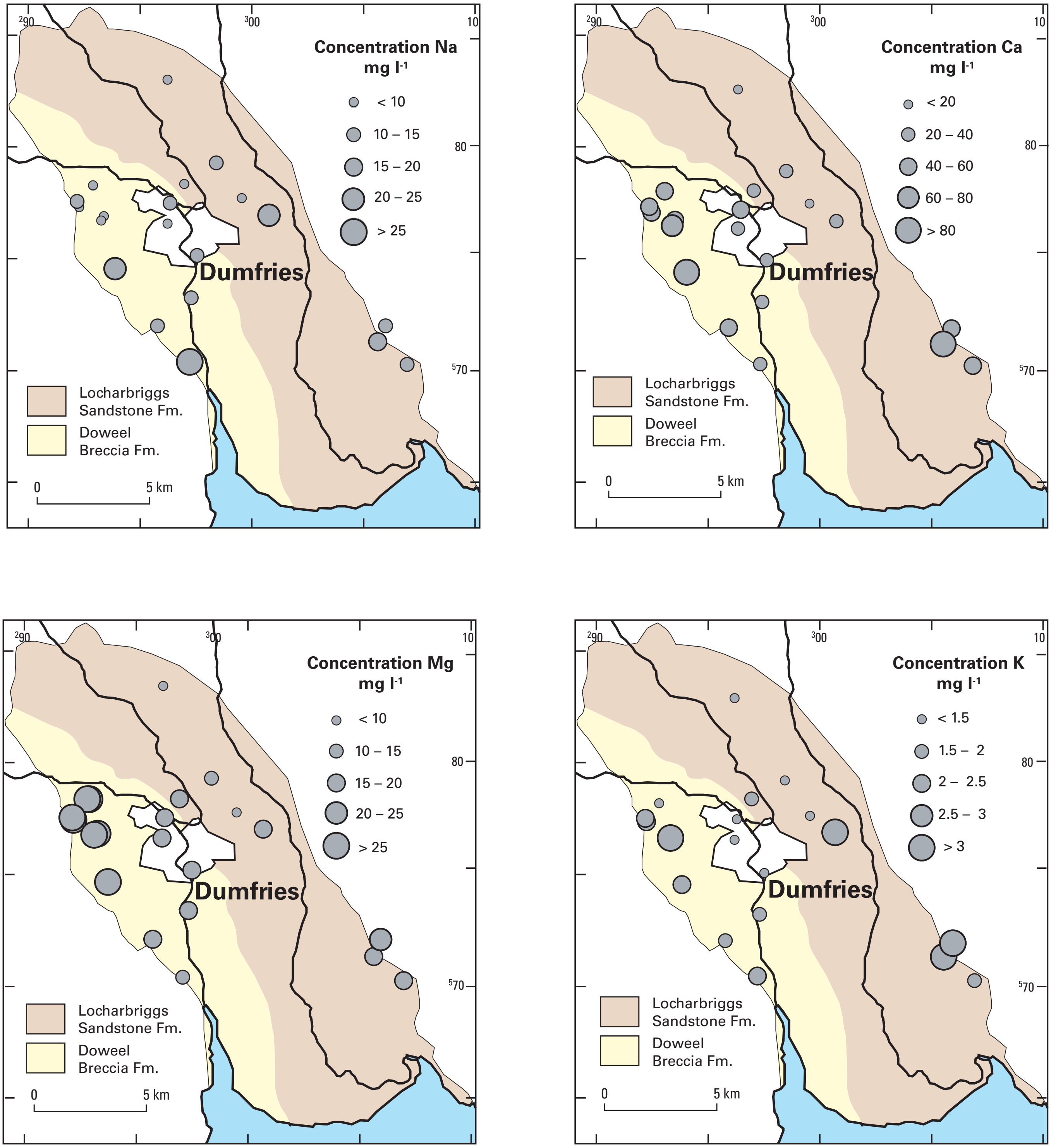


Figure 4.10 Distribution of major anions (showing breccia to the west of the basin and sandstone to the east).

the western and central parts of the site by a thick laminated silty clay deposit. The lowest unit is the Permian sandstone aquifer that occupies the whole of the Dumfries Basin.

Groundwater sampling has shown that minor amounts of pollution are present in the upper sand aquifer, thought to be due to infiltration of dilute leachate from overspill at the site. Other evidence of polluted groundwater in the boreholes, particularly significant levels of ammonium in Bh 4.1, drilled into the Permian sandstone, are thought to be due to the effects of leakage around the borehole casing and not to indicate the presence of a pollution plume in the main aquifer.

Measurements of water quality in the surface drainage ditches that surround the landfill show that significant inflows of dilute leachate are entering the watercourses. These eventually join the Lochar Water which flows to the sea near Caerlaverock. It is concluded that the majority of leachate escaping from the Lochar Moss waste disposal site is entering the drainage ditches and not infiltrating to the Permian aquifer at depth. Water samples from boreholes penetrating the sandstone aquifer show groundwater to be relatively old, indicating a recharge source some distance away from the landfill area.

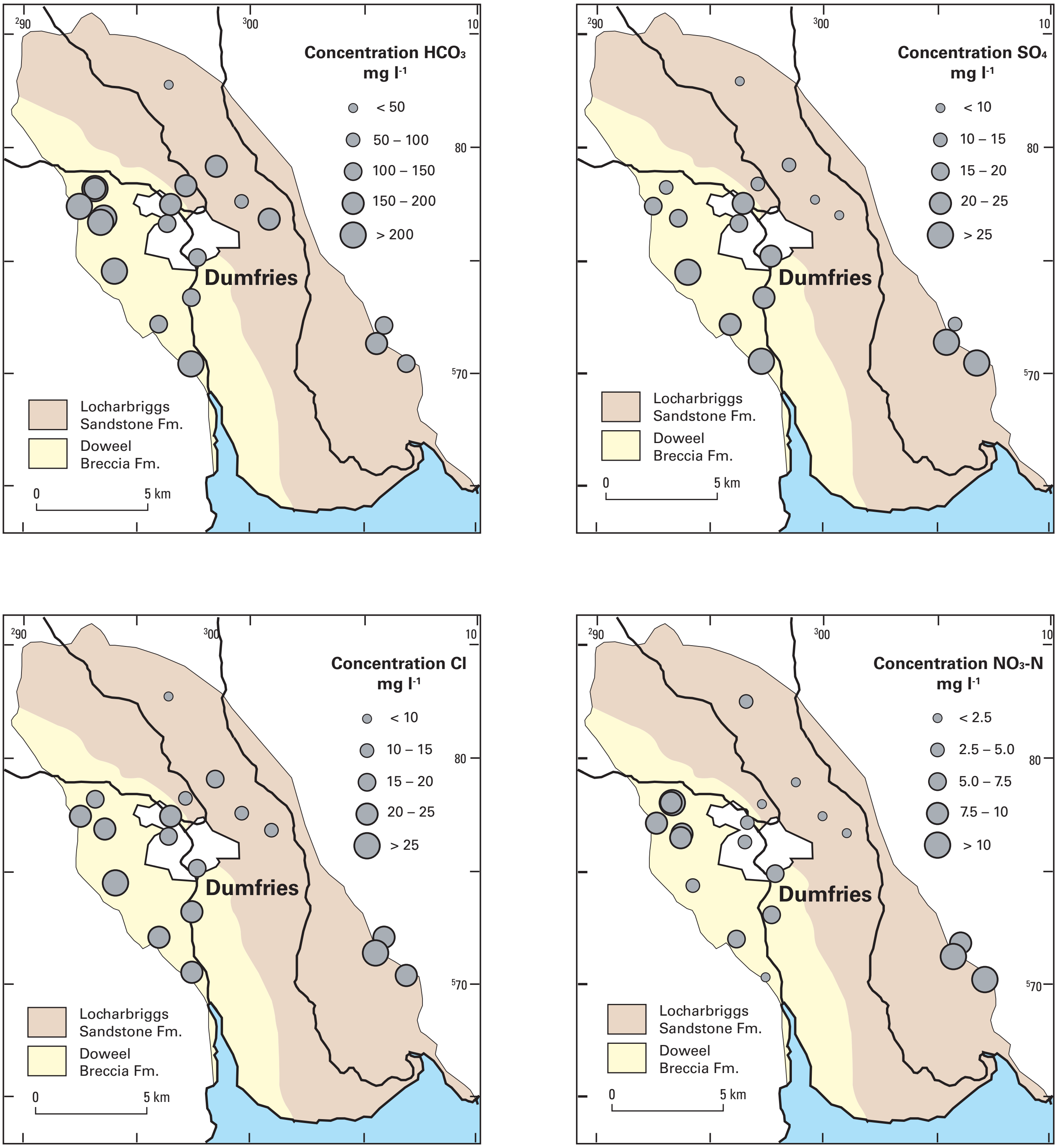


Figure 4.11 Distribution of major cations.

Table 4.8 CFC and SF_6 data for Dumfries Basin sites (after MacDonald et al., 2003).

Site No	SF_6 Conc (pmol l^{-1})	±	CFC-11 Conc (pmol l^{-1})	±	CFC-12 Conc (pmol l^{-1})	±	CFC-113 Conc (pmol l^{-1})	±
2	1.5	0.3	4.3	0.3	2.2	0.2	0.73	0.05
4	2.1	0.42	8.2	0.5	1.2	0.1	0.22	0.05
5	<0.1	-	0.07	0.05	0.01	0.05	0.03	0.05
6	0.3	0.06	11	2	7.9	0.4	2.6	0.6
8	1.0	0.2	>70	-	17	2	2.1	0.6
9	0.5	0.1	4	0.2	1	0.1	0.32	0.05
10	0.4	0.08	0.51	0.05	0.02	0.05	5.6	1.2
15	1.4	0.28	7	0.4	2.9	0.2	3.7	0.8
16	1.3	0.26	6.2	0.4	2.1	0.2	0.62	0.05
17	1.9	0.38	9.6	0.5	3	0.1	1	0.1
18	-	-	2.8	0.2	1.2	0.1	3.8	0.8
19	1.8	0.36	0.31	0.05	0.68	0.05	0.03	0.05
20	<0.1	-	0.35	0.05	0.02	0.05	<0.01	-
21	0.5	0.1	0.16	0.05	0.78	0.05	0.01	0.05
22	1.5	0.3	>200	-	20	4	1.5	0.2

Table 4.9 Summary of age determinations of groundwater in Dumfries expressed as percentage of 1990 water mixed with pre 1950 water (after MacDonald et al., 2003).

Site ID	SF_6	Percentage of modern water in sample CFC-11	CFC-12	CFC-113	Best estimate
2	79	78	73	*133*	77
4	*111*	*149*	40	40	40
5	<5	1	0	5	2
6	16	*200*	*263*	*473*	16
8	53	*1273*	*567*	*382*	53
9	26	*73*	33	*58*	30
10	21	9	1	*1018*	9
15	74	*127*	*97*	*673*	74
16	68	*113*	70	*113*	69
17	100	*175*	100	*182*	100
18		51	40	*691*	46
19	*95*	6	*23*	5	6
20	<5	6	1	<2	3
21	*26*	3	*26*	2	3
22	79	*3636*	*667*	*273*	79

Modern water composition used:
SF_6 = 1.9 pmol l^{-1}; CFC-11 = 5.5 pmol l^{-1};
CFC-12 = 3.0 pmol l^{-1}; CFC-113 = 0.55 pmol l^{-1}
Less reliable data are italicised.

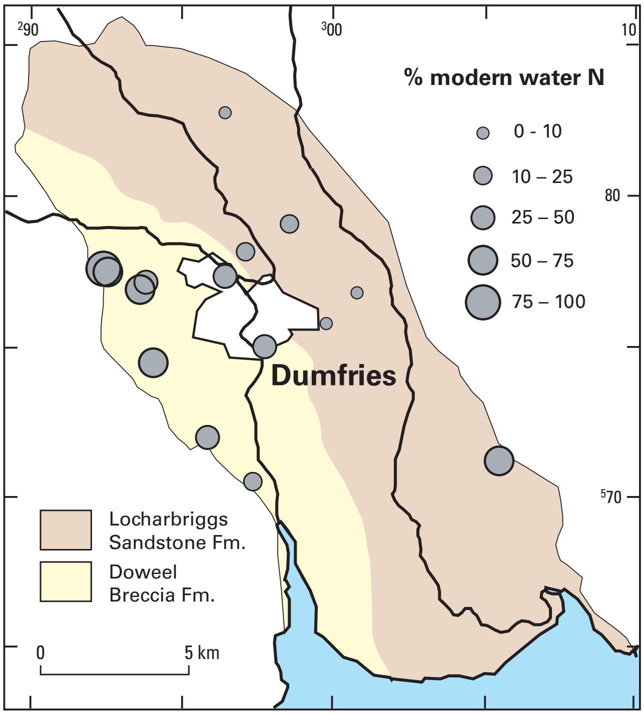


Figure 4.12 The age of groundwater as the proportion of modern groundwater with respect to older groundwater (pre-1950).

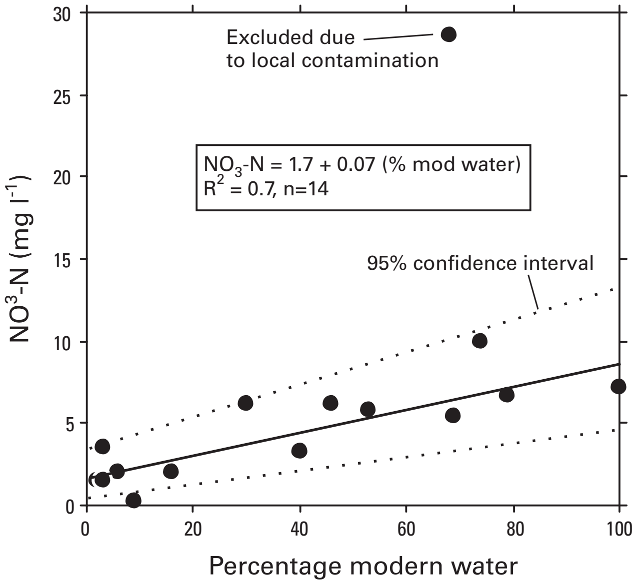


Figure 4.13 Relation of nitrate to the proportion of modern water.

Table 4.10 Summary of geology at Lochar Moss.

Eastern Sites 2, 3, 4	Western Site 1
Peaty soil: 0.5 m	Sandy soil: 1.0 m
Silty sand: 1.70–6.0	Peat: 0.80 m
Laminated silty clay with sand layers: 16.0–23.6 m	Silty sand with bands of silty clay: 6.2 m
Clayey gravel: 1.0–2.0 m	Sand, with silt and clay bands: 22.0 m
Permian sandstone (26 to 28 m bgl)	Clayey sand and gravel: 3.0 m
	Permian sandstone (33 m bgl)

5 Flow model and water balance

5.1 CALCULATION OF RAINFALL RECHARGE

Recharge was calculated with a distributed recharge model using the soil moisture deficit (SMD) method (Penman, 1948; Grindley, 1967). The technique calculates the change in soil moisture on a daily time-step based on a relationship between actual evaporation (AE) and potential evaporation (PE). The relationship between AE and PE is derived from the SMD in relation to the root constant (C) and wilting point (D). For the case when the PE is greater than rainfall so that water is being taken out of the soil, the following is true:

- if the SMD is between zero and the root constant then AE is equal to PE
- when the SMD is between the root constant and the wilting point then the AE is a fraction of the PE. This fraction is usually 0.1 and this is the value used for the Dumfries recharge model.

The distributed recharge model carries out the recharge calculation across a regular grid within the study area. A daily time-step is used for the recharge calculation, with the output supplied as monthly averages (Jackson et al., 2004).

The nodal values of long-term average recharge produced by the model are presented in Figure 5.1. Recharge is zoned, based on the Quaternary domains for the Nith and Lochar Water catchments (described in Chapter 2), and the results for each hydrogeological domain (Figure 2.3) are summarised in Table 5.1.

Figure 5.1 shows that recharge is highest in the north-west of the study area. This is due to a combination of greater rainfall over the topographic high in this part of the

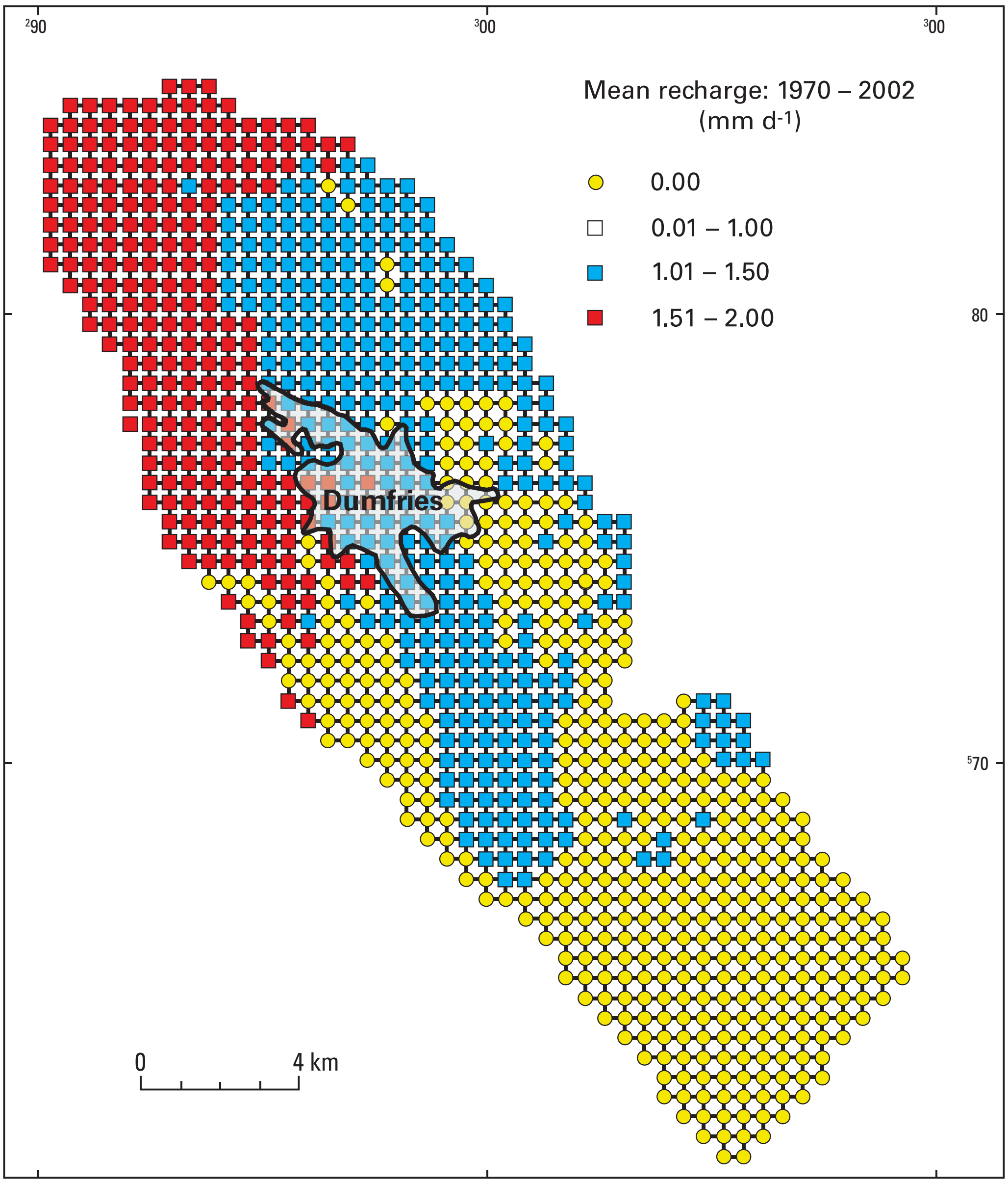


Figure 5.1 Long term average recharge results for modelled grid 1970–2003 (non detected in the range 0.01 to 1.00 mm d^{-1}).

Table 5.1 Summary of output from recharge model by zone (Ml d^{-1}).

Zone	Rainfall	Run-off	PE	Recharge	Quaternary domains	
1	47.03	4.70	21.85	23.08	1	Nith
2	21.63	20.55	10.31	0.00	2	
3	16.79	15.95	7.58	0.00	3	
4	15.31	1.53	7.05	7.63	4	
5	3.13	0.31	1.41	1.55	5	
6	66.40	6.64	30.49	32.80	6	
7	43.71	4.37	20.18	21.51	7	
8	103.66	10.37	46.52	51.88	8	
9	17.22	1.72	7.75	8.59	9	
10	0.00	0.00	0.00	0.00	10 to 11	
11	0.73	0.07	0.35	0.35	12	
12	2.63	0.26	1.41	1.17	13 to 14	
13	7.01	0.70	3.44	3.32	1	Lochar Water
14	32.00	30.40	16.56	0.00	2	
15	78.44	74.52	38.59	0.00	3	
16	9.00	0.90	4.32	4.30	4 to 6	
17	30.28	3.03	14.71	14.32	7	
18	29.61	2.96	14.45	14.22	8	
19	1.45	0.14	0.70	0.68	9	
20	0.74	0.07	0.35	0.35	10 to 12	
21	11.56	1.16	5.64	5.22	13	
22	4.74	0.47	2.47	2.15	14	
Total	**543.09**	**180.85**	**256.14**	**193.12**		
Nith	338.25	66.49	154.90	148.57		
Lochar	204.84	114.36	101.24	44.55		

basin, and the widespread occurrence of grassland which together provide the optimum conditions for recharge. The zero values of recharge are associated with marine clay and peat, which are assigned a high run-off coefficient and which reduce the rainfall supplied to the recharge calculation.

Rainfall is greatest in the Nith catchment because it is generally at a higher elevation than the Lochar Water catchment within the Dumfries Basin (Table 5.1). However, runoff is higher in the Lochar Water catchment because the Quaternary deposits restrict vertical recharge and drain water to the Lochar Water and its tributaries. The resulting long-term average (1970–2003) recharge for the Nith is nearly three times that for the Lochar Water catchment. The long-term average recharge for the Nith catchment in the Dumfries Basin is 434 mm a^{-1} and for the Lochar Water catchment is 200 mm a^{-1}. This is based on an area of 125 km^2 for the Nith and 81.25 km^2 for the Lochar Water catchment in the recharge model.

To examine the validity of the time-variant nature of the recharge, a time series of recharge is compared with normalised borehole hydrographs. Three long-term borehole hydrographs are available at Holywood, Newbridge and Redbank (Figure 4.2, Plate 7). The recharge time series for Newbridge and Redbank are similar, but the maxima of the recharge series calculated at Holywood are greater and occur at different times. In all cases, peaks in the recharge time series occur before peaks in the groundwater hydrographs. This is noticeable for the 'double peaks' observed in the winters of 1993/4, 1996/7 and 2000/1. It is also possible to identify recharge events in the summer months, e.g. June 1998 and May 2001. The recharge model predicts that recharge should occur during these months and is confirmed by the groundwater levels responding accordingly. It is difficult to identify any consistent time lag between recharge calculated by the model and a response by the groundwater level hydrographs, although it is possible to identify delays of up to one month at various times. The model results provide the current best estimates of rainfall recharge to the basin.

5.2 CLIMATE AND RIVER INTERACTION

Considering that the last twenty years have been the wettest since the 1850s it is notable that borehole hydrographs indicate a decline in groundwater level at Redbank [NX 9670 7420], in the west of the Dumfries Basin, since 1981

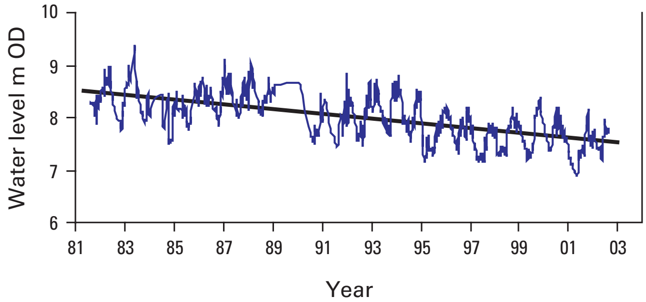


Figure 5.2 Redback Borehole hydrograph showing linear regression.

BOX 4 RECHARGE MODEL DATA REQUIREMENTS

The model requires extensive datasets to calculate recharge on a distributed basis using a daily time step. A single calculation grid is specified for the recharge model with a 500 m spacing. The data used for the model includes:

- rainfall — daily rainfall and Theissen polygons for the selected rain gauges (6 stations) and gridded long-term average (LTA) rainfall
- land use — gridded land-use distribution and coefficients required by the SMD method; root constant and wilting point
- potential evaporation (PE) — monthly PE from the UK Meteorological Office (1 station) and the distribution of PE over the study area
- run-off — gridded sub-catchments and monthly run-off coefficients for the 22 sub-catchments.

The recharge model requires a distribution of daily rainfall over the model area. This is achieved using gridded LTA rainfall and daily rainfall sequences at selected rain gauges. The distribution of LTA rainfall was obtained from CEH Wallingford and is the 1 km^2 gridded long-term average rainfall for 1961 to 1990. The LTA rainfall increases from 954 mm a^{-1} at the coast to 1263 mm a^{-1} between Burnhead and Newtonairds, in the north of the basin. The difference in LTA rainfall in the area (approximately 300 mm a^{-1}) is mainly due to the combination of rise in topography coupled with the prevailing westerly winds.

The use of the SMD method requires that the distribution of the root constant (C) and wilting point (D) to be specified. The C and D coefficients are related to crop type and, therefore, land use. By determining the spatial distribution of land use, the corresponding spatial distribution of C and D values can be determined. The ITE © NERC 25 m data were used. The 26 land use categories are amalgamated into the ten master categories:

1. broad-leaved / mixed woodland
2. coniferous woodland
3. arable and horticulture
4. improved grassland
5. semi-natural grass
6. mountain, heath, bog
7. built up areas and gardens
8. standing open water
9. coastal
10. oceanic seas

Recharge is calculated for each of the main land-use types at each node. The land-use data are, therefore, processed to produce arrays of percentage land use for each land-use type.

Monthly potential evaporation (PE) data were provided by MORECS. The recharge model area is divided up into two surface catchments, the River Nith and the Lochar Water, and a number of sub-catchments for each drift domain were specified. The use of sub-catchments enables run-off coefficients to be varied across the model area according to the nature of the drift deposit. A run-off coefficient of 10 % is applied to the majority of the sub-catchments and 95 % is applied to areas of relatively impermeable cover such as the marine clay and peat.

(Figure 5.2) and that some other sites in the west of the basin also reflect this trend. The decline tends to be stepped as new groups of boreholes have been commissioned. However, at Newbridge [NX 9510 7870], to the north-west of the centre of the basin, the groundwater level is relatively stable. The implications are that the decline in the west is a result of intensive abstraction in this area, which commenced in the late 1970s and gathered pace in the early 1980s.

The relationship between surface water and groundwater, as indicated by river gauging and recession analysis, suggests that the Cluden Water does not gain significantly from groundwater whereas the Lochar Water does show some small gain. This is probably from shallow gravel deposits rather than the Permian aquifer. Comparison of relative river stage and groundwater level in the gravels and underlying sandstone at Holywood indicates that groundwater discharges to the river at all stages of river flow, save for brief periods of flood when the river level is greater than the potentiometric level (Figure 5.3). Using the data from test pumping and river stage measurement conducted at this site and reported by Cheney and MacDonald (1993b), simple Darcian calculation suggests that under normal flow conditions some 5000 m^3 d^{-1} could discharge from the gravel aquifer into the river along a 1 km length of river (given a transmissivity of 250 m^2 d^1; hydraulic gradient of 0.01, and width of flow of two 1000 m river banks).

5.3 THE WATER BALANCE

The water balance is based on a catchment scale for both the rivers Nith and Lochar Water. The surface water divide is used to determine the boundary between the two catchments for the basin. The water balances for each catchment are expressed as:

Nith rainfall recharge + total river flow from tributaries joining the basin + return from fish farms + leakage from water mains ± leakage to or from sewers	= =	abstraction + total river flow at bottom of the catchment + spring flow + leakage to the sea
Lochar Water rainfall recharge + run-off + total river flow from tributaries joining the basin + leakage from sewers	=	abstraction + total river flow at bottom of the catchment + springs + leakage to the sea

An assessment of abstraction changes enables a time series of abstraction rate for January 1970 to October 2003 to be developed (Figure 5.4). This shows that abstraction increased markedly during the late 1980s/early 1990s because of the commissioning of the Terregles and Holywood fish farm boreholes (Plate 8), and increased steadily over the last decade. Aside from the fish farms, another major industrial abstractor is the Dupont plant just outside Dumfries. It is now estimated that groundwater abstraction has reduced to approximately 0.25 Ml d^{-1}, compared to the 0.8 Ml d^{-1} estimated by Akhurst et al. (2006).

The components in the time-variant water balance are summarised as long-term averages for the Nith and Lochar Water catchments, and presented in Table 5.2. A combined surface water and groundwater balance has been developed due to the importance of surface water flows in the

BOX 5 SOURCES OF DATA

Rainfall recharge derives from the distributed recharge model (Chapter 4).

Run-off is derived from the recharge model and calculated as a percentage of rainfall. A run-off coefficient of 10% is used for the recharge model. Where there are impermeable deposits such as peat overlying clays and the marine clays, a run-off coefficient of 95% is used. The application of this high run-off coefficient results in little or no recharge being calculated for these deposits. The validation of the run-off coefficients requires more data in the River Nith catchment and a better understanding of the peat deposits in the Lochar Water catchment.

Daily river flow data are available for various gauging stations on the Nith and the Lochar Water. These daily data have been averaged to monthly values and the monthly river flow values used in the water balance. The main issue for the water balance is that the flow at the tidal limit of the River Nith, at Greensands in Dumfries, has had to be estimated. The flow is assumed to be 200 Ml d^{-1} greater than the combined inflows for the River Nith and its tributaries. This assumption is based on the limited spot flow gaugings for the River Nith.

Returns to the river from sewage treatment works and fish farms are also included in the water balance. However, the returns from sewage treatments works are estimated. The flows from the fish farms at Terregles and Holywood are estimated based on the assumptions that all the groundwater abstraction is returned to the water course.

An estimated value of 10 Ml d^{-1} of leakage from pressurised water mains is assumed to recharge the aquifer under Dumfries.

Abstraction data are derived from Akhurst et al. (2006). Areas containing springs have been identified. These areas are the Larchfield ridge, running from Crichton to Bankend, and Lochhead Muir. The volume of discharge is estimated at about 20 Ml d^{-1} for the Larchfield ridge and 5 Ml d^{-1} for the area around Lochhead Muir.

In the south of the basin, the sandstone aquifer dips beneath the sea and is overlain by confining marine clays. The current understanding is that the marine clays only allow a limited connection with the sea. Therefore, a small amount of leakage may occur from the sandstone aquifer to the sea and is estimated to be about 5 Ml d^{-1}.

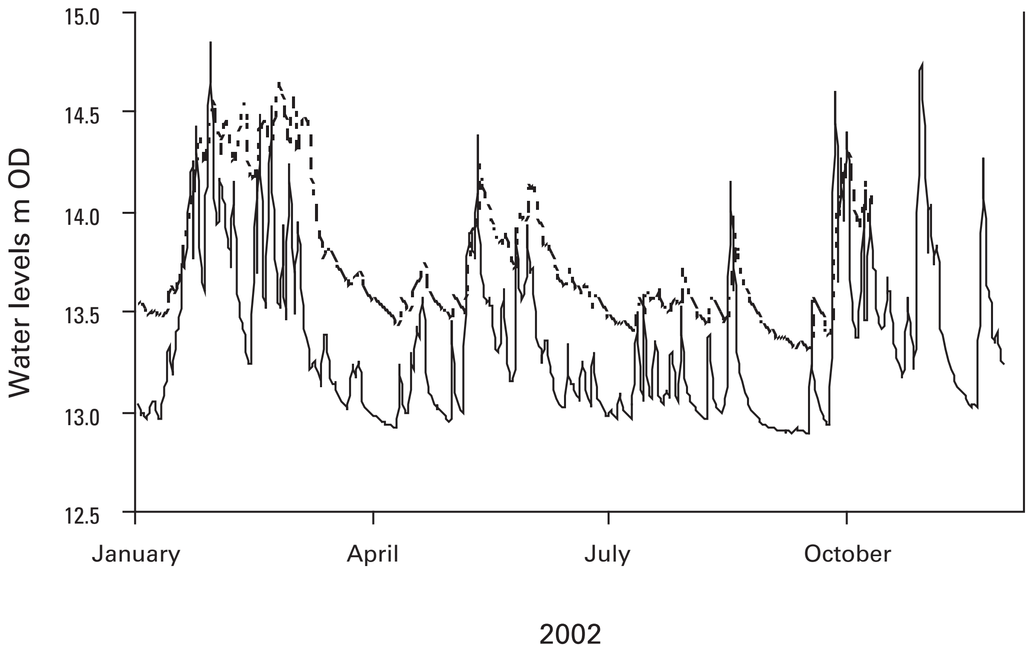
Dumfries Basin. The predominance of surface water flows is illustrated by the magnitude of the inflow to the River Nith catchment which is greater than 3200 Ml d^{-1}. Recharge to the basin aquifer is calculated at nearly 200 Ml d^{-1}. Therefore, surface water flows are approximately sixteen times that of rainfall recharge, which means that river-aquifer interaction is difficult to quantify. The problems associated with quantifying river-aquifer interaction in the River Nith catchment are further compounded by the lack of a continuous flow measurement at the White Sands weir in Dumfries (Plate 9).

The water balance for the Lochar Water is less complicated and can be summarised as rainfall recharge supplying baseflow to the Lochar Water with few other minor components. Runoff is a significant component of the water balance because of the impact of the peat mosses which cover a significant area of the Lochar Water catchment, and which overly clayey material. The mosses have been drained for a number of decades and numerous channels have been cut into the peat to direct water to the Lochar Water and its tributaries. This mechanism is included in the water balance as runoff.

Table 5.2 also includes estimates of percentage errors in each of the components of the water balance. The most significant absolute error is contained in the estimate of the flow of the Nith at the lower end of the basin. River

Plate 7 Data logger over the Holywood monitoring borehole.

Figure 5.3 Holywood Borehole hydrograph (dotted line) versus stage in the River Nith at Friars Carse, the elevation at Friars carse normalised to Holywood rivers levels (±0.1 m).



flow at this point is estimated to be accurate to only ± 10% which is equivalent to 350 Ml d^{-1}. The lack of gauging data at the bottom of the River Nith also affects the accuracy of the runoff calculation. The run-off calculated by the recharge model cannot be validated. For the water balance for the Lochar Water, the largest absolute error is contained in the estimate of run-off. This is related to the role of the mosses in reducing vertical recharge and increasing surface flows to the Lochar Water.

5.4 CONCEPTUAL MODEL

There are two basic aquifer types in the basin. In the west, thin sandstone units are interbedded with lower permeability breccias. The porosity of the sandstones ranges from 13% to over 20%. Fracturing associated with sandstone/breccia boundaries appears to form the principal pathway for groundwater movement. It is these near-horizontal fractures that provide a broad interconnection between many of the main abstraction boreholes in the west, and coupled with the less well developed near-vertical fracture system, point to a dynamic groundwater system of young water moving relatively rapidly through the western part of the aquifer. The system is recharged via near-vertical fractures principally in the north-west and other areas of higher ground where granular superficial deposits prevail. This contrasts with the eastern part of the basin where breccia is largely absent and sandstone predominates. Here, a combination of higher specific yield, low groundwater abstraction and a covering of silty marine clay over part of the area has resulted in the presence of older groundwater that has a significantly lower nitrate content.

Lack of extension of the main fracture system to the east of the River Nith isolates the eastern part of the aquifer from that to the west of the river. Groundwater flow does not cross the line of the river, which, for the most part acts as a constant head boundary and a groundwater sink wherever groundwater is in hydraulic connection with the river, except possibly in the Cargen/Crichton area.

Groundwater occurs in both the Permian bedrock and the overlying granular superficial deposits. The transmissivity of the Permian aquifer ranges up to 10^3 m^2 d^{-1} in the west,

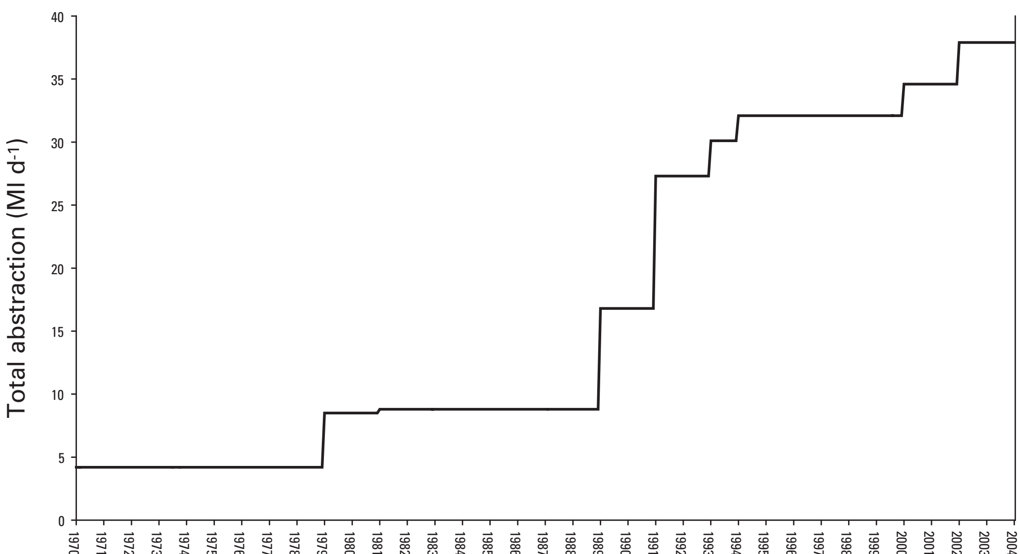


Figure 5.4 Time series abstraction in the basin.

Plate 8 Outflow from the Terregles Fish Farm.

although it is not uniformly permeable with depth. Storage of groundwater, particularly west of the River Nith, is restricted to sandstone horizons which account for only 20% of the thickness in the upper 100 m of the aquifer. In general the hydraulic response is confined except where the aquifer is in contact with permeable superficial deposits beneath which unconfined or delayed yield responses will occur.

Annual variations in potentiometric level in both the western and eastern parts of the Permian aquifer are less than 2 m. Potentiometric heads tend to peak in February, with a steady natural decline through spring. Water levels in the bedrock aquifer are above the rock/superficial strata interface across much of the basin. Higher ridges of bedrock occur in some places, such as around Larchfield south of Dumfries, where there may be up to 15 m of unsaturated rock. Confined conditions occur under low-lying areas south of Dumfries across the floodplain of the River Nith. Artesian flow occurs wherever the surface level is at or below 10 m OD and laminated silty clay overlies the main aquifer. Elsewhere, individual fractures, and sandstone horizons separated by breccia, may be at different potentiometric heads, as observed in a number of flow logs measured in boreholes in the western part of the basin (Buckley, 2000).

The Permian basin receives direct rainfall recharge through alluvial and glaciofluvial sands and gravels and also receives some indirect recharge from losing rivers and streams. In the main, however, the rivers are gaining from groundwater. The basin is traversed by the River Nith, but the eastern part of the basin is hydrologically separate and is part of the Lochar Water catchment. The effective surface catchment of the basin is much greater than the outcrop area of the aquifer, and encompasses the high hills surrounding the basin and throughout the Nith catchment. Direct recharge from rainfall occurs across the higher ground within the basin to the north and west of Dumfries. In these areas, sand and gravel deposits promote infiltration to the water table. In addition to these main areas of recharge, a small amount of indirect recharge is thought to be provided from streams running off the high Silurian and granite hills, particularly from the west.

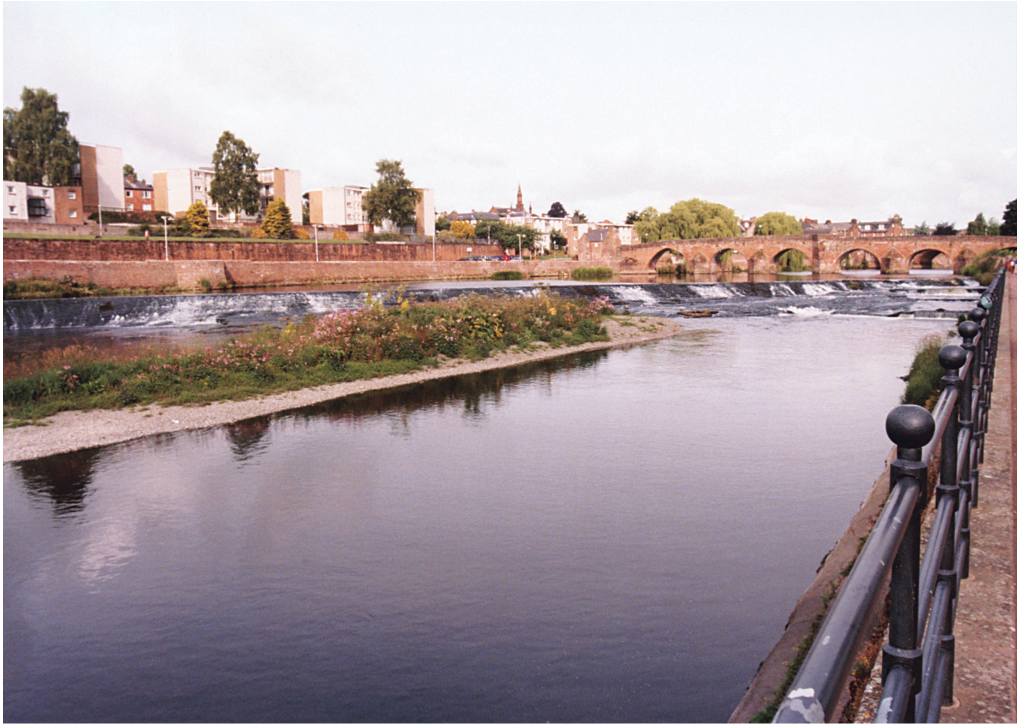
Discharge from the Permian aquifer is principally via superficial gravels to the River Nith north of Dumfries with some also to the Lochar Water and the sea.

The current conceptual model for the Dumfries Basin Aquifer is shown schematically in Figure 5.5. It is based on the work carried out during the 1980s and 1990s as well as the recent two year study, which was targeted at infilling

Table 5.2 Summary of water balance.

		Nith (Ml d^{-1})	Error (%)	Error (Ml d^{-1})	Lochar Water	Error (%)	Error (Ml d^{-1})	Total (Ml d^{-1})
IN	Recharge	148.57	15%	22.29	44.90	15%	6.74	193.47
	Run-off	66.49	50%	33.24	114.43	50%	57.22	180.92
	River inflow	3264.92	10%	326.49	61.50	10%	6.15	3326.42
	Urban leakage	10.00	100%	10.00	0.00			10.00
	Irrigation return	0.00			0.00			0.00
	Fish farm return	8.41	10%	0.84				8.41
	Sewage return	15.00	100%	15.00	5.00	100%	5.00	20.00
	TOTAL	3513.39		407.86	225.83		75.10	3739.22
OUT	River flow	3470.00	10%	347.00	192.61	10%	19.26	3662.61
	GW outflow	5.00	200%	10.00	2.00	200%	4.00	7.00
	Abstraction	16.94	25%	4.23	1.00	25%	0.25	17.94
	Springs	10.00	100%	10.00	10.00	100%	10.00	20.00
	TOTAL	3501.94			205.61		113.61	3707.55
IN-OUT			11.45			20.22		31.67

Plate 9 White Sands Weir, Dumfries, the uppermost tidal reach of the River Nith.



gaps in knowledge. Although the conceptual groundwater flow model for the aquifer has grown in complexity as investigation has progressed, confidence in the model has remained low and even now the water balance cannot be closed satisfactorily. The current model has the following features (Akhurst et al., 2004):

- The basin edge is effectively a no-flow boundary given the comparatively low hydraulic conductivity of the surrounding Palaeozoic rocks.
- Rainfall recharge occurs to the bedrock aquifer via superficial sands and gravels which principally occur in the north-western and central part of the basin. Rainfall recharge is greatly inhibited in areas underlain by clay or silt grade superficial material and peat.
- The superficial deposits and bedrock aquifer are not always in hydraulic contact.
- Some surface water indirectly recharges the aquifer, probably in the upper or northernmost part of the basin.
- Potentiometric heads indicate both lateral flow towards the River Nith and a groundwater sink in the western-central part of the basin which is intensively pumped.
- Marine and alluvial silts inhibit discharge from the basin directly to the sea.

5.5 GROUNDWATER FLOW SIMULATION

The Dumfries aquifer was modelled using the regional groundwater flow code ZOOMQ3D, which simplifies the process of representing multiple rivers (Jackson, 2001). The model boundaries are defined by the edge of the Permo-Triassic Dumfries Basin, and the seaward boundary is the Waterbeck Fault, 9 km offshore, which represents the physical limit of the sandstone (Jackson et al., 2005). The model area is enclosed by the rectangle defined by the co-ordinates (NX 9000 5850) in the south-west and (NY 1150 8550) in the north-east.

The model cells are 500 m by 500 m. The model contains two layers. The upper layer (Layer 1) represents the superficial Quaternary deposits and the lower layer (Layer 2) represents the bedrock aquifer. The bedrock aquifer is specified to be 200 m thick, reflecting the likely depths of flowing fractures. Parts of four river catchments are included in the model: the Crooks Pow, the Cargen Water, the River Nith and the Lochar Water (Figure 1.2). These comprise a series of interconnected reaches, or river nodes, each of which interacts with the aquifer and along which simple flow accounting is performed.

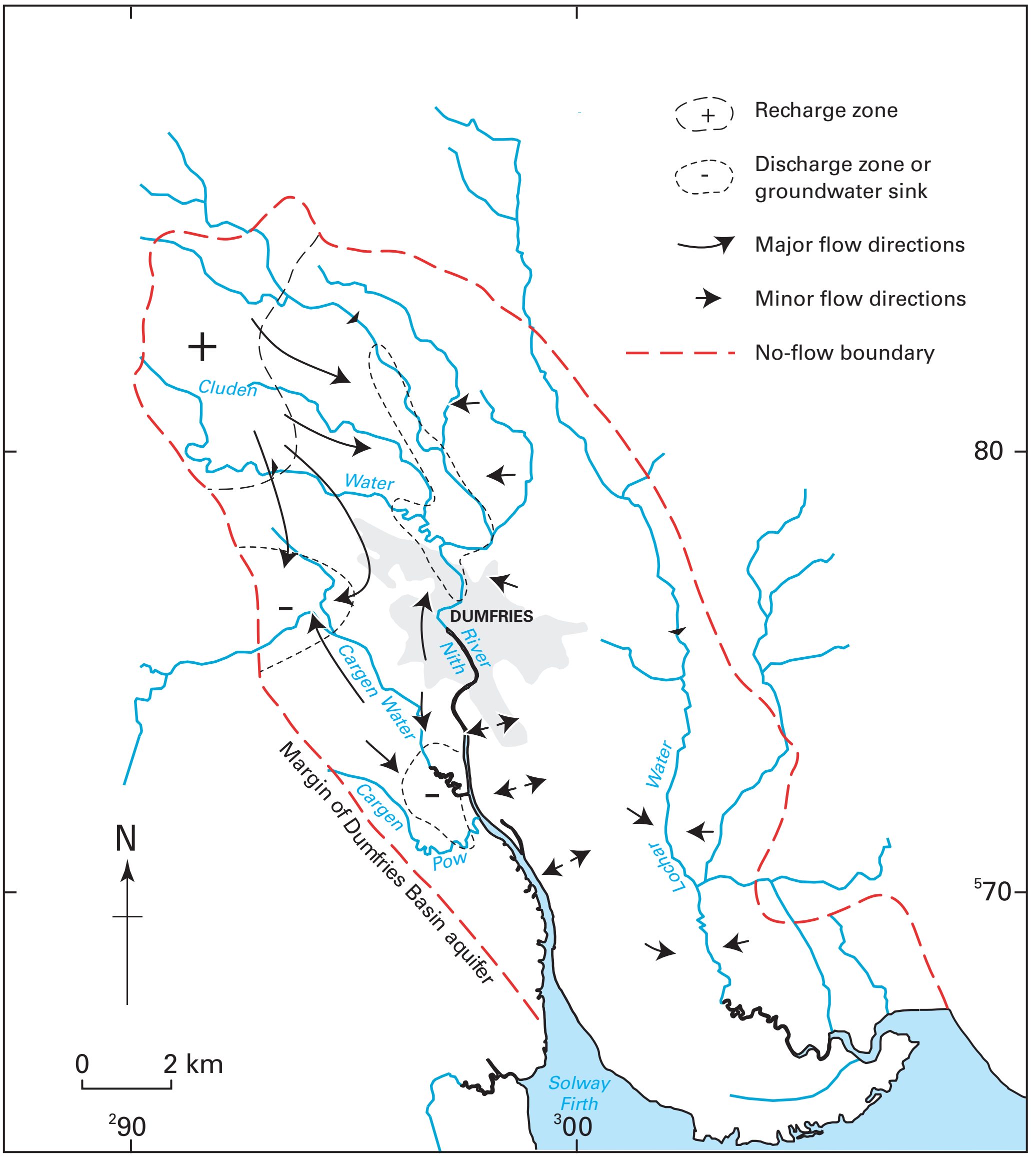
The hydraulic properties of the superficial deposits (Layer 1) have been assigned according to the Quaternary hydrogeolgical domains listed in Table 2.1. The values range from 10^{-6} to 10^{3} m d^{-1} for marine clay to 10^{1} to 10^{3} m d^{-1} for a well-sorted gravel.

There are six zones of transmissivity specified for bedrock (Layer 2):

1. higher transmissivity in the Terregles area specified as part of a sensitivity analysis
2. the area in the north over the Locharbriggs Sandstone
3. low transmissivity in the Dupont area specified as part of a sensitivity analysis
4. the Doweel Breccia
5. the Locharbriggs Sandstone
6. lower transmissivity in the lower Lochar Water catchment and beneath marine clay deposits — this also covers the aquifer offshore

Whilst there is certainly significant variability in the transmissivity values estimated from pumping tests, it is difficult to convert these discrete data points into regional zones of transmissivity. For example, there are transmissivity values in the area of Terregles of up to 4000 m^{2} d^{-1}, but it is difficult to construe this as being indicative of the bulk aquifer transmissivity. Consequently, a simple distribution of transmissivity is adopted based on the division of the aquifer into the Locharbriggs Sandstone (Zones 2 & 5: 150 m^{2}d^{-1}), the Doweel Breccia (Zones 1, 3 & 4: 600 m^{2}d^{-1}) and the southern part of the basin under the marine clays (Zone 6: 50 m^{2}d^{-1}).

Figure 5.5 Schematic conceptual flow model of the Dumfries Basin aquifer.



5.6 STEADY-STATE SIMULATIONS

The simulated steady-state groundwater head contours for the sandstone and breccia layer (Layer 2 or the bottom layer) of the model are shown in Figure 5.6. In general the shape of the simulated contours is compatible with the conceptualisation (Figure 5.5), the latter has few control points away from the central western part of the basin. However, there are areas of the model where the modelled groundwater heads are not quite as expected:

- The influence of the River Nith, Cluden Water, Lochar Water and Cargen Water is apparent though the impact of the rivers is more pronounced in the model.
- Simulated groundwater heads are significantly higher in the north of the model.
- Simulated heads are approximately 15 m too high at Longbridgemuir.

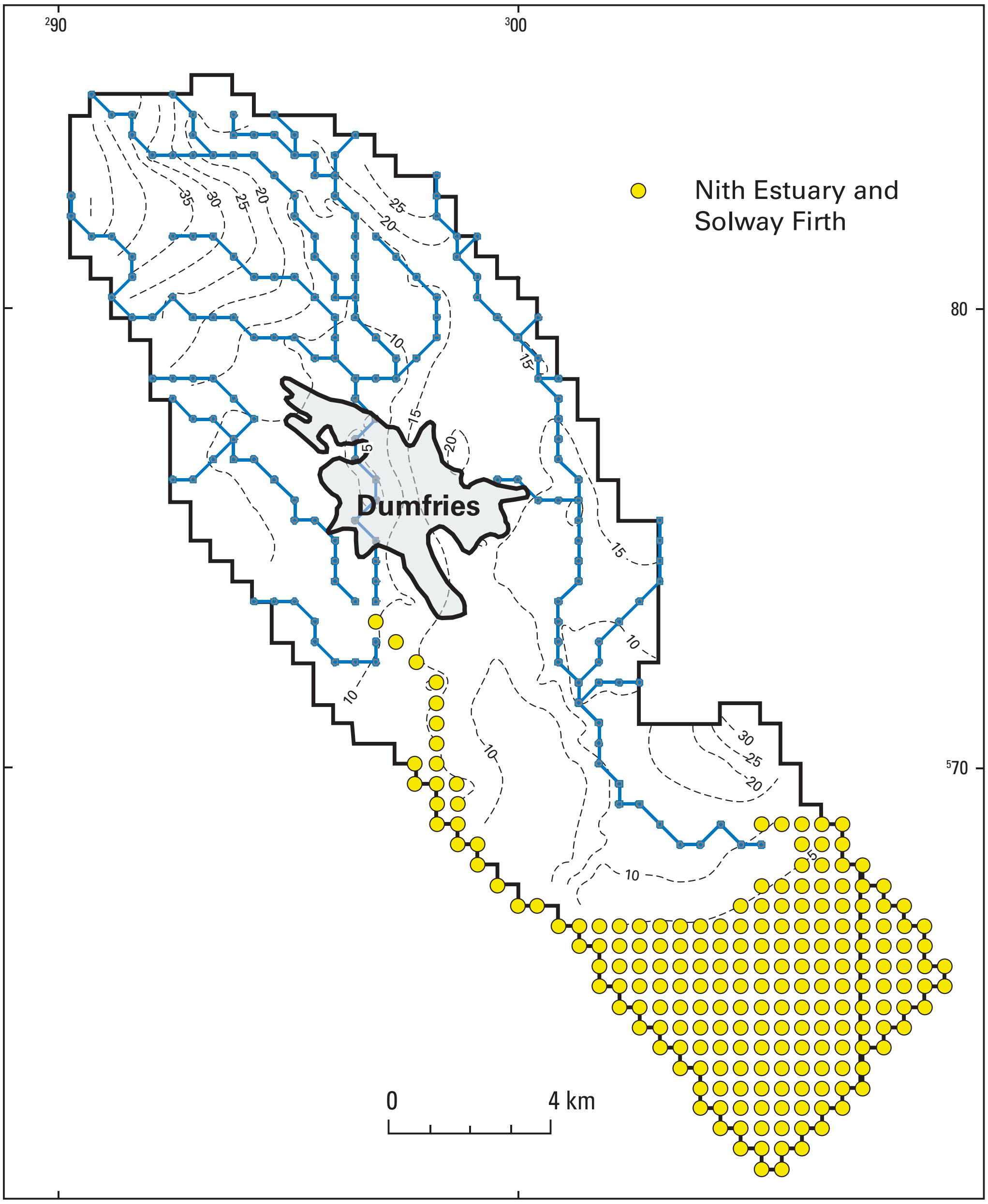
Groundwater head contours are not plotted in the Quaternary deposits (Layer 1) because a significant proportion of this layer dewaters. The nodes which the model simulates as being dry are shown in Figure 5.7. These are located on the high ground around the edge of the basin, in the north-west of the model and along the north-north-west trending ridge between the Nith and the Lochar Water.

Jackson et al. (2004) provide a detailed analysis of the results of the simulation against observed data. Reasonable agreement is found for the most part (Table 5.3) but there are areas where the agreement is poor, notably around Terregles and in some of the boreholes around the Dupont factory where pumping has depressed water levels, and the simulated head at Longbridgemuir is high.

Simulated steady-state river accretion profiles are plotted for the major rivers in the model in Figure 5.8. These graphs show the groundwater head and river stage plotted against the right-hand axis, and the simulated and estimated (or observed) river baseflow plotted against the left-hand axis. The following points summarise the simulated behaviour of the rivers as shown in these figures:

- The River Nith gains baseflow along its full length except at one model node.
- The Nith gains 80 Ml d^{-1} above the Cluden Water and 18 Ml d^{-1} below this tributary.
- The simulated mean baseflow at the downstream end of the modelled Nith is 1305 Ml d^{-1}.
- The reduction of the river-bed permeability from 1 m d^{-1} to 10^{-3} m d^{-1} results in a rise in groundwater head of approximately 7 m at its downstream end.

Figure 5.6 Simulated steady-state groundwater contours.



- The Cluden Water gains approximately 29 Ml d^{-1} along its length.
- The model does not provide enough baseflow to the Lochar Water.

The estimated rate of increase in baseflow along the Lochar Water is approximately four times greater than the simulated results. The model could be improved by transferring the spring flow from the high ground to the west into the Lochar. However, this would still not produce a close match. The difference between the accretion profiles is attributed to the role of the peat deposits and their representation in both the recharge and groundwater flow models. Further development of the conceptual model and numerical representation of this area is required to improve the model.

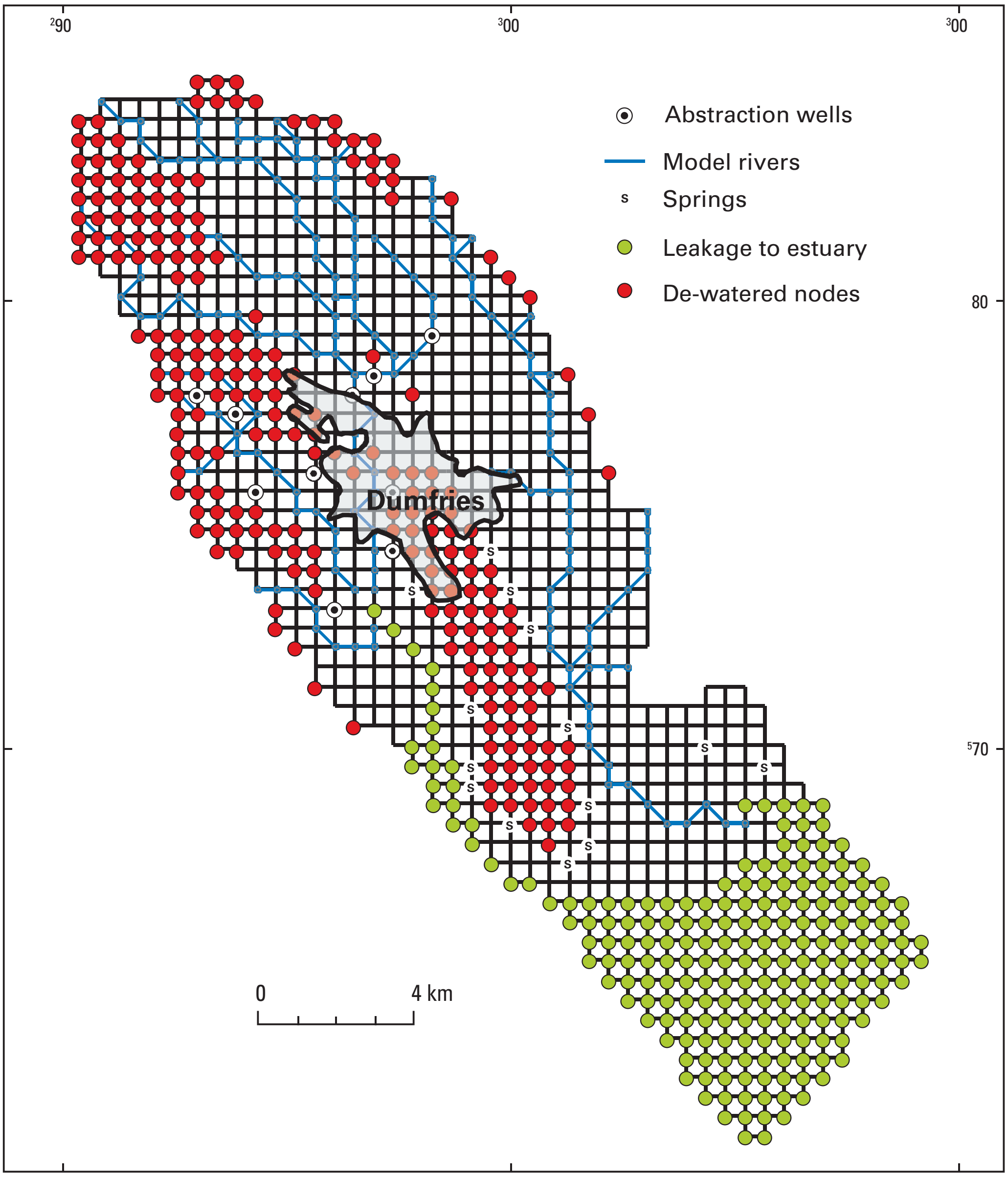
Similar profiles for the smaller rivers, the Cargen Water, Crooks Pow and Wath Burn show that they all gain water from the aquifer along their course.

The global groundwater flow balance for the steady-state simulation is shown in Table 5.4. The discharge into the rivers of 21 Ml d^{-1} at the two major fish farms is split between 8 Ml d^{-1} into the Cargen Water and 13 Ml d^{-1} into the Nith. If these amounts are subtracted from the gain in baseflow along these rivers then the groundwater flow balance can be expressed in percentage terms as the following:

- 17% of the recharge is abstracted from boreholes
- 1% of the recharge becomes baseflow in the Crooks Pow
- 10% of the recharge becomes baseflow in the Cargen Water
- 46% of the recharge becomes baseflow in the River Nith
- 11% of the recharge becomes baseflow in the Lochar Water
- 3% of the recharge discharges into the Solway Firth as groundwater flow
- 12% of the recharge becomes spring flow.

The sensitivity of the model to input parameters was examined by modifying a single parameter set for each of seven additional runs and comparing the results with observed data. These show that the modelled heads in the valleys and particularly the river baseflows are not sensitive to changes in transmissivity. However, they demonstrate that a good estimate of recharge is important.

Figure 5.7 Model nodes in the superficial layer (layer 1).



The modelling (Jackson et al., 2004) confirms that river interaction with groundwater and rainfall recharge are critical to the hydraulics of the Dumfries Basin aquifer. Rivers and streams flowing onto the west of the basin lose water in their initial reaches as they pass onto the basin, but within a very short distance become gaining streams receiving baseflow discharge from the aquifer. The model suggests a groundwater throughflow of 1470 Ml d^{-1}. The modelling has not only confirmed the main features of the conceptual model, but has also improved it and highlighted where understanding is inadequate.

The analysis of the superficial deposits, undertaken in conjunction with the recharge modelling, has shown that they are largely permeable and allow recharge to the groundwater system over much of the basin. Rainfall recharge is greatest in the north-west, where rainfall is highest and grassland predominates, but is limited towards the lower end of the Lochar Water catchment where peat overlies clay. Here, the role of the mosses, or drained peats, in limiting vertical recharge and enhancing flow to the Lochar Water has been identified. The calculated long-term average recharge for the Nith catchment within the basin is approximately two and half times the maximum recharge rate included in the previous modelling work undertaken by Cheney and MacDonald (1993).

Whilst the estimate of recharge to the aquifer has increased, the major inflow and outflow to the groundwater system is via the rivers. Flow in the River Nith dominates the water balance, however, the flow at the tidal limit of this river is only estimated. Towards the downstream end of the Nith, marine clays separate the river from the bedrock aquifer and locally confine the sandstone. These marine clays not only limit vertical recharge and control the outflow of groundwater to the sea, but also restrict the possibility of saline intrusion.

Whilst the modelling process has enhanced the development of the conceptual model it has also highlighted the processes, which are poorly understood. In particular, deficiencies in knowledge have been identified regarding recharge processes in the Lochar Water catchment and surface water–groundwater interaction along this river. The model fails to simulate the gains in baseflow along the Lochar Water adequately, however, springs issuing from the Larchfield ridge are clearly significant. The main deficiencies in the data are groundwater heads in the north of the basin, under the Larchfield ridge and in the east of the basin, and discharge values for the River Nith as it passes over the White Sands Weir to its tidal reaches.

Table 5.3 Comparison between measured and simulated groundwater levels.

Location	Easting	Northing	Observed	Model	Difference
Carnation No 1	296910	577330	7.3	5.9	-1.4
Dundas Chemical	300230	575580	14.2	16.0	1.8
Golf Course	295890	575670	8.2	8.3	0.1
Greenmerse	297760	570480	7.9	12.1	4.3
Holywood Fish Farm	297890	580900	7.0	13.4	6.4
Holywood Pro BH	296000	581600	13.8	13.8	0.0
Dupont BH 401	294900	574900	8.5	9.2	0.7
Dupont BH 403	295000	574800	13.3	9.2	-4.1
Dupont BH 404	294550	574950	3.3	10.9	7.6
Dupont BH 501	294300	574500	1.8	13.0	11.2
Dupont BH No 2	294620	574830	12.8	10.9	-1.9
Kingholm Mill	297580	573570	7.6	10.7	3.1
Larchfield Expl BH	298200	575050	11.1	8.6	-2.5
Larchfield Obs BH	298200	575050	12.2	8.6	-3.6
Larchfield Pro BH	298100	575000	12.6	8.6	-4.0
Locharbriggs	299800	580200	13.1	16.2	3.1
Locharbriggs	299950	580250	13.8	16.2	2.4
Newbridge	294990	578850	10.0	11.0	1.0
Redbank Obs BH	296670	574320	7.5	8.5	1.0
Terregles FF House B	292800	577430	15.0	9.0	-6.0
Terregles No 1	293620	579050	9.1	19.2	10.1
Terregles Obs 1	293620	579050	9.6	19.2	9.6
Terregles Obs 2	293390	578180	7.3	16.1	8.8
Terregles Pro BH	294020	576770	9.9	7.0	-2.9
The Manse	293930	576590	8.5	7.1	-1.4
Well Cottage	297840	573250	12.2	11.0	-1.2
Workington Brewery	297320	575730	4.6	4.1	-0.5
Racks Moss	302970	572730	9.4	11.2	1.8
Longbridgemuir	306990	568910	13.6	30.7	17.1

Dupont boreholes – highly variable, pumped levels estimated at 10 m OD.

Terregles No 1, Terregles Obs 1 and Obs 2 – data are significantly below river levels.

Table 5.4 Steady-state model global flow balance in Ml d^{-1}.

INFLOWS (Ml d^{-1})		**OUTFLOWS (Ml d^{-1})**	
Recharge	193	Abstraction	33
River baseflow into aquifer		River baseflow	
Crooks Pow	5	Crooks Pow	7.8
Cargen Water	24	Cargen Water	50.8
Nith	1204	Nith	1305
Lochar Water	24	Lochar Water	45.4
Discharge from fish farms into rivers	21	Groundwater leakage into Solway Firth	5.7
		Springs flow at edge of Caerlaverock Ridge	22.0
		Spring flows at Longbridgemuir	1.1
Total	**1471**		**1471**

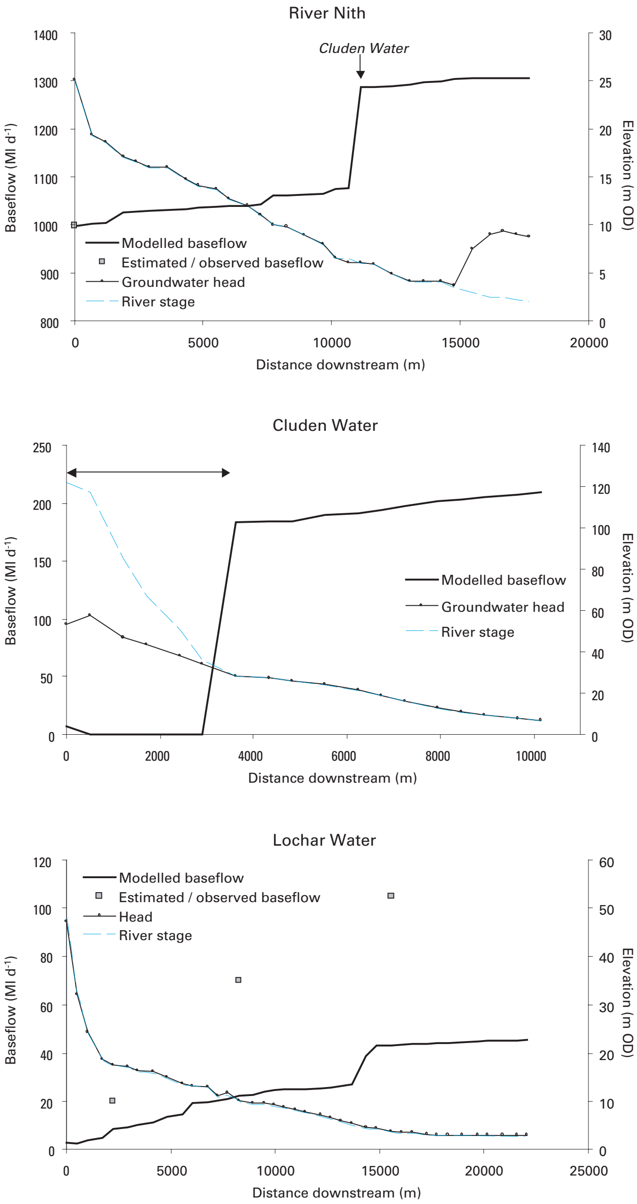


Figure 5.8 Simulated steady-state baseflow accretion profiles along the rivers Nith, Cluden Water and Lochar Water.

6 Groundwater development and management

6.1 WATER RESOURCE POTENTIAL

The groundwater flow balance output from groundwater modelling for the basin suggests that there is considerable surplus groundwater potential available for development in the basin as a whole (Table 5.3). Locally, in the Terregles area, the groundwater is over-developed and there has been a decline in groundwater levels coupled with an issue of worsening water quality. Further groundwater development will, therefore, need to exploit the bedrock aquifer away from the central western part of the basin, but must also be restricted to perceived areas of higher transmissivity. The western half of the basin should remain a target for development for three reasons:

1. This is where interfingered breccia and sandstone formations occur at the junction of which are highly transmissive horizons (see Figure 4.12).
2. The sandstone in the eastern part of the basin, although it has higher storage values, has lower transmissive properties.
3. Much of the rainfall recharge and river-loss recharge is centred in the western part of the basin.

Clearly there are parts of the western basin to avoid, not least the overpumped area around Terregles, but also the polluted aquifer centred on the Dupont factory and other sources of potential pollution such as urbanised and industrial areas in general. Diffuse pollution also puts some of the northern part of the basin at risk from elevated concentrations of nitrate arising beneath grassland cultivation, particularly over superficial deposits of sands and gravels (Plate 10).

There remain two significant areas of unexplored potential, and these are the north-western and north-eastern corners of the basin where the majority of river loss to the aquifer is taking place. Strategically placed boreholes in this area may be able to draw on river water lost to groundwater as it flows southwards to the central part of the aquifer. Natural filtration processes would ensure reasonable quality and the small component of rainfall recharge in this area would lessen the risk of nitrate contamination. Whether the aquifer is capable of providing sufficiently high yields for public supply purposes in this area remains to be seen, but it is certainly worthy of some exploratory investigation.

6.2 POLLUTION PREVENTIOIN AND ABSTRACTION CONTROL

The European framework for groundwater protection is undergoing fundamental change, which is having a significant impact on the way in which groundwater is managed in Scotland. Historically, the main European legislation that has been concerned with groundwater protection is the Groundwater Directive (80/68/EEC), which sought to protect groundwater from polluting discharges of certain listed chemical substances. The Water Framework Directive (2000/60/EC), however, is a major piece of European legislation. Its primary aims are to promote sustainable water use, to protect terrestrial and aquatic ecosystems dependent on groundwater and to ensure the progressive reduction of pollution of groundwater.

The Water Framework Directive (WFD) requires that control regimes for abstraction, and for point and diffuse sources liable to cause pollution, must be introduced. The Water Framework Directive has been transposed into Scottish law through the Water Environment and Water Services (Scotland) Act 2003. The regulations that will specify the control regimes have not yet been introduced, but the control regimes are expected to commence in 2005 for the revised point source and the new abstraction control regime and in 2006/2007 for the diffuse pollution control regime.

The Directive's specific requirements with respect to groundwater include the creation of management units for groundwater known as groundwater bodies and an assessment of the risk of failing to meet the environmental objectives of the Directive must have been made by the end of 2004. The environmental objectives for groundwater are:

- Groundwater bodies must be classified into either good or poor status dependent on quantity and chemical quality by 2009. This objective is designed to ensure a long-term supply of water for people's use while protecting and, where necessary, restoring the water needs of those surface water bodies and terrestrial ecosystems, such as wetlands, that depend on groundwater flows. To meet good status, there must, therefore, be an appropriate balance between abstraction and recharge, the water needs of associated surface ecosystems must be met and saline or other intrusions must not be occurring.
- No deterioration in status must occur.
- Bodies of groundwater at poor status must be restored to good status by 2015 where this is technically feasible and does not entail disproportionate cost.
- Any significant and sustained upward trends of pollutants in groundwater must be identified and reversed.
- Protected area (such as Nitrate Vulnerable Zones and Natura 2000 sites) standards and objectives must be met by 2015.
- Drinking water protected areas must be designated and measures put in place with the aim of avoiding deterioration in their quality in order to progressively reduce the level of purification treatment required.

The Dumfries Basin has been designated identified as a single groundwater body and is likely to be designated as a Drinking Water Protected Area. An initial coarse screening, using the concepts of source pressure, pathway susceptibility and receptor sensitivity, has been undertaken at a national scale to identify the pressures from human activity which may be putting groundwater at risk of failing to meet the objectives specified. It is consistent with

Plate 10 Typical rolling country of the sand and gravel covered upper basin. View at Holywood from the Sanquhar road.

this report, that this screening has identified that the Dumfries groundwater body is at risk of failing to meet both good chemical and good quantitative status objectives because of diffuse pollution and abstraction pressures respectively. Issues relating to point pollution pressures are also under consideration. Further characterisation work, along with a review of the existing monitoring network, will be required to refine the risk assessment and the results of this study will feed into this more detailed appraisal of risk of failing to meet the environmental objectives for the groundwater body.

If, following further characterisation, the Dumfries Basin is still considered to be at risk of failing to meet the objectives and if the monitoring network requires upgrading to reflect the assessment of pressures, then appropriate new monitoring must be put in place by the end of 2006, to validate the risk assessment and to allow the classification of the groundwater body into good or poor status by 2009. Should the Dumfries body be designated classified at as being of poor status, then programmes of measures must be designed to protect, enhance and restore the body to good status. where this is technically feasible and not disproportionately expensive. If it is not technically feasible or is disproportionately expensive to restore the body, then time extensions are available until 2027, but thereafter, lower objectives must may be set for the body.

In addition, the WFD requires Scotland to implement measures to prevent or limit the input of pollutants to groundwater. The characterisation process cannot, and is not intended to, examine specific risks from all potential sources of pollution, such as from potentially leaking petrol stations or from every septic tank, landfill or pesticide application. These require site-specific data and assessments, for example from site-investigation work, and such risks are principally addressed through on-going measures or guidance. Both existing and new regulatory regimes, along with development control and codes of good practice, will form part of the measures to prevent or limit the input of pollutants to groundwater. In light of the new objectives for groundwater, SEPA has reviewed its Groundwater Protection Policy (SEPA, 2003) to ensure that the requirements of the WFD are incorporated into its day to day work of environmental regulation and protection.

The primary mechanism for the implementation of any measures that are required for the protection and restoration of the water resources of the Dumfries aquifer will be the new abstraction control system being created under the Water Environment and Water Services (Scotland) Act 2003. Under these regulations, all existing abstractors are likely to need to apply to SEPA in 2005 but existing abstractors are expected to be able to continue their existing operational practice. Where measures are necessary then these will be identified as part of a review of authorisations from 2006 onwards and will come into force from December 2012.

In order to support the introduction of the abstraction control regime, SEPA will, where necessary, develop Water Resources Management Strategies for groundwater where it is subject to significant environmental pressures arising from abstraction. The high level strategy and the criteria for invoking a local Water Resources Management Strategy, will be developed is being undertaken in conjunction with key stakeholders. Each strategy will then focus on the specific problems in an area with the aim of enabling effective and equitable management of the resource involving the minimum regulatory burden.

7 Issues and uncertainties

The investigations to date have studied the characteristics of the Permian aquifer and overlying superficial deposits using a variety of methodologies including numerical simulation.

The basin aquifer does not have uniform characteristics. The presence of interdigitated breccia and sandstone units in the west and centre of the basin has led to the development of a widespread fissure system that interconnects much of the west-central section of the aquifer. Here, groundwater storage is limited to the sandstone units which occupy only 30% of the total rock mass. The breccias contain almost no groundwater within their matrices. The continued heavy abstraction of groundwater in this area means that sustainability can only occur by rapid groundwater movement through these fissures, with constant recharge not only from storage held in the sandstone, but from sources outside the area. This has resulted in a slight deterioration in groundwater quality, as modern nitrate rich water has penetrated to over 100 m depth due to abstraction of older better quality water. Abstraction boreholes in the west-centre, between Terregles and Cargen, all rely on a small number of major fractures to sustain supply. This means that even small increases in overall abstraction are felt over a wide area. Recharge to the west-centre zone is not understood in detail, but evidence suggests that recharge is occurring through sandy gravels to the north-west of this area.

It is estimated that all land at elevations greater than 30 m OD has the potential to contain an upper, unsaturated zone within the Permian aquifer. This includes the bedrock ridges in the south. These areas allow generally greater access to the aquifer from direct rainfall recharge via fissures, leading to relatively rapid movement of water into the groundwater system. These elevated areas commonly coincide with land that is intensively farmed with excess available nitrate, and hence are subject to pollution.

The western zone contrasts with the east, where a greater proportion of porous sandstone in the sequence means that groundwater storage is more significant. Lower groundwater velocities, combined with largely confined conditions in the Permian aquifer, and with very little abstraction, inhibit rapid movement of water from the surface to the deeper parts of the groundwater system. Exploitation of the eastern part of the basin would lead to a gradual deterioration in water quality, but this would be less marked here than it has already been in the western part of the basin.

The Dumfries Basin aquifer is under increasing stress from a combination of rising demand, pollution risk from both point and diffuse sources, and changing rainfall patterns. Together these conspire to inhibit groundwater potential and to reduce options for further groundwater development. Paradoxically there is considerable untapped development potential, but optimal locations for development are few, and all the options are limited to the western part of the basin which currently sustains the majority of exploitation.

Although the basin has been studied, albeit mostly in a piecemeal fashion, for the last 35 years, there remain some considerable gaps in knowledge. A key piece of missing information is the amount of water flowing out of the Nith over the White Sands Weir in the centre of Dumfries. Another is the hydraulic processes that control cross-flow between the bedrock aquifer, the superficial strata and the river.

The current studies have enabled a far greater insight into the hydraulics of the Dumfries Basin aquifer than was previously possible. However, even though the simulation modelling has provided a robust and defensible interpretation of the groundwater flow system, it is still inadequate for some of the tasks that will be required in the future. One of these is the issuing and maintenance of groundwater abstraction licences, for which a comprehensive understanding of the overall resource and interaction between sources is needed. Another is the need to manage surface activities through planning procedures that minimise risk to the groundwater resource. Yet another is the need for major groundwater users such as Scottish Water and the fish farms to be able to manage their existing assets and to develop further ones as required.

The current investigation erects a milestone in the understanding of the Dumfries Basin aquifer with description of the hydraulics of the aquifer within this report and with the model codes that have been developed to understand the basin. Nevertheless, these products do not draw a line under the investigation of the aquifer, which should continue in order to solve issues that will arise from time to time. Further investigation will, of necessity, be required, as pressures intensify on the available resource.

Groundwater head measurements are currently concentrated in the western central part of the basin, and coverage needs to be widened to the rest of the basin. Improved monitoring of groundwater heads, both spatially and temporally, is required to aid the understanding. Groundwater heads need to be monitored in the north-west of the basin, in the vicinity of the high ground at Caerlaverock in the south of the basin, and in other areas of the basin where there are currently few observation boreholes.

A lack of surface water flow data means that uncertainties exist in both the understanding of river–aquifer interaction and the water balance. The main omission is a flow record as close as possible to the tidal limit of the River Nith. Without these data, the difference in flow along the River Nith within the basin cannot be determined and an accurate water balance for the Nith catchment cannot be created. A priority is to establish the gauging of outflow on the River Nith at its lowest non-tidal point. Additional spot gaugings along the Nith, Cluden Water and Cargen Water will enable losing and gaining stretches of these rivers to be identified at different river stages.

A greater understanding of the water budget could be achieved by studying the role of the peat deposits and their influence on run-off and recharge potential.

A fully time-variant groundwater flow model should be developed once additional data have been collected. Due to the importance of the surface water system, a recharge model with run-off routing should be used. The inclusion of run-off routing will enable the surface–groundwater interaction to be modelled appropriately.

In addition, an assessment of risk to the groundwater resource from the main point sources of the Drungans industrial area and the Lochar Moss Landfill site is recommended. This should be carried out both from a contaminant perspective and, in the case of Drungans, also from the amount of water that is being abstracted and pumped to a sea outlet in order to ameliorate the problems beneath the site.

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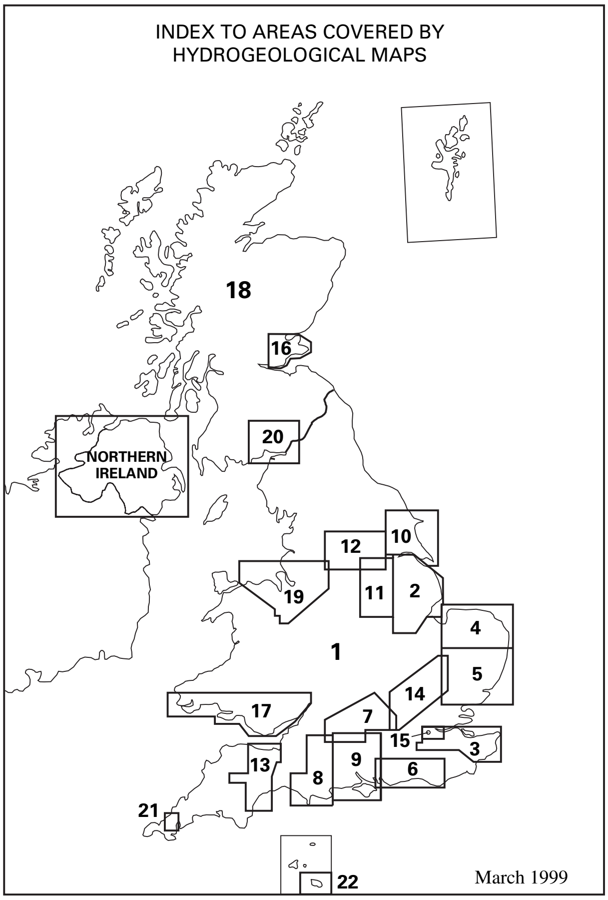

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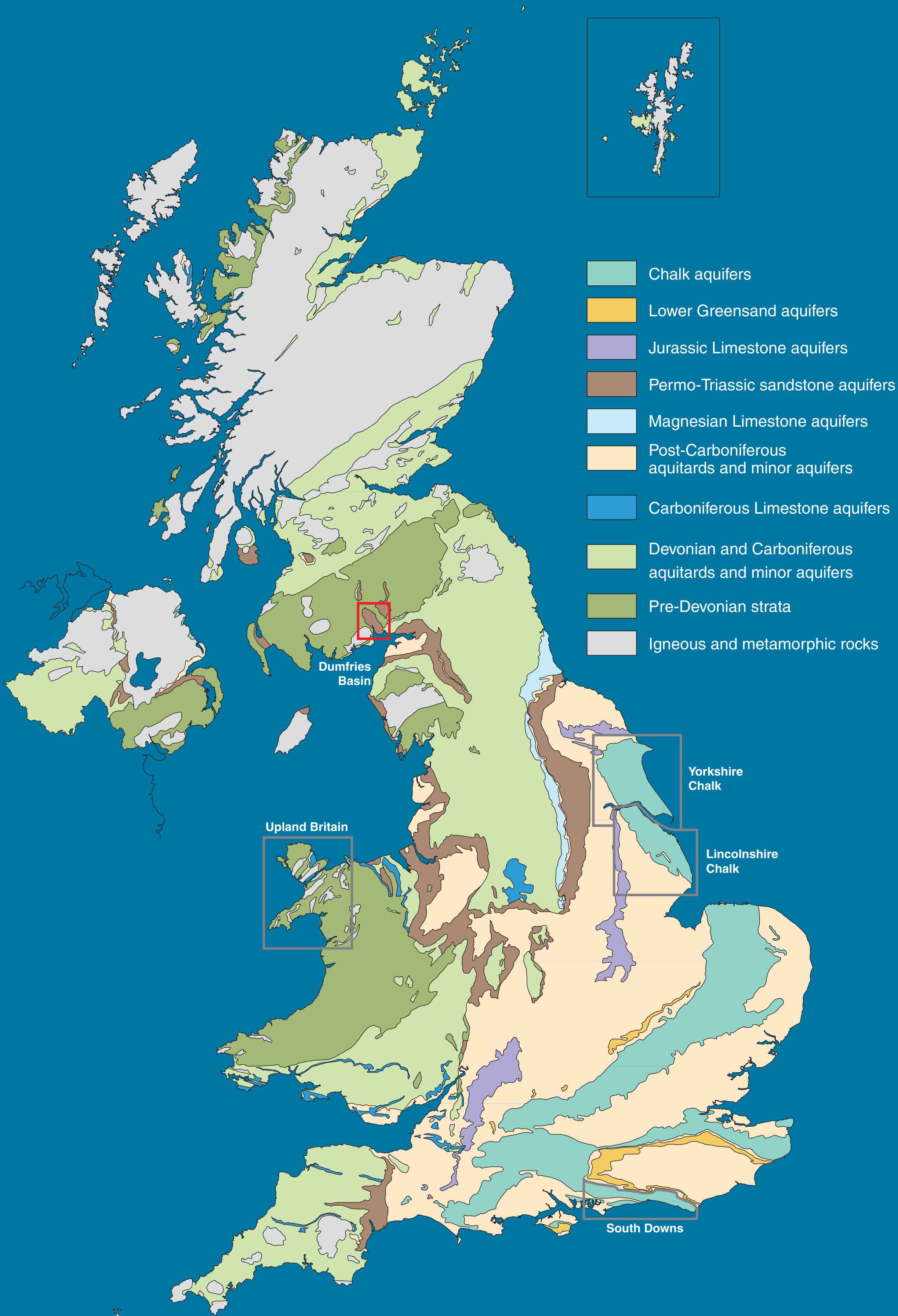

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