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The Upper Devonian Sandstone Aquifer of Fife

Ó Dochartaigh B É, Ball D F, Browne M A E, Shand P,
MacDonald A M, Robins N S and McNeill G W

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East of Scotland Water Authority,
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1. INTRODUCTION

1.1 Background

The Devonian sandstone aquifer of Fife has long been recognised as one of the most important hydrogeological units in Scotland. Its importance was first acknowledged by Earp and Eden (1961), and the aquifer was later described by Foster et al (1976). Data were subsequently gathered together in map form (BGS, 1986) but little analysis of the aquifer was carried out other than a dissertation prepared by Barker (1981), occasional reports on specific issues such as nitrate pollution (e.g. Frost and Sargent, 1993; MacDonald, 1993; Ball, 1994), and the preparation of the 1: 100 000 scale Aquifer Vulnerability Map of Fife (SEPA, 1999).

The aquifer currently supplies some 20 Ml/d during the winter, rising to 40 Ml/d in the summer months, when irrigation boreholes are put into use. Groundwater provides an important back up to public water supplies, particularly during dry years when river abstraction is restricted. Despite this, relatively little is known about the overall renewable resource potential of the aquifer. It is also only in recent years that means of safeguarding groundwater from pollution have been investigated in any detail.

Renewed interest in the aquifer is now being driven on two fronts. The first is that the East of Scotland Water Authority (ESWA) needs to expand its source provision due to increasing demand. The second is that the Scottish Environment Protection Agency (SEPA) needs to look more closely at the aquifer potential if in the future groundwater abstraction licensing is introduced in significant aquifers (Robins and Ball, 1998). In addition, the requirements of the proposed EU Water Framework Directive indicate that a greater understanding of the aquifer and the sources it supplies will be needed in order to implement properly integrated surface and groundwater management on a catchment basis.

With these goals in mind, the East of Scotland Water Authority, Scottish Environment Protection Agency and NERC have jointly commissioned this preliminary study of the Eden valley aquifer.

1.2 Project Objectives

(1) To create a conceptual model of the groundwater flow system and to calculate a generalised water balance for the Devonian sandstone aquifer of Fife.

(2) To bring together and catalogue the available groundwater data for the catchment, and to prepare and review a synopsis of these data in order to provide a statement of understanding.

(3) To identify the issues pertaining to the catchment with particular regard to the sustainable resource potential and groundwater quality management.

(4) To make and prioritise recommendations for future work.

1.3 Scope of the Investigation

The project gathers together data on the Eden valley and Loch Leven basin sandstone aquifer in order to present a synopsis of the hydrogeology of the aquifer. In addition, the project has identified shortcomings in the available data on, and understanding of, the aquifer. A key element has been to create a conceptual groundwater flow model of the aquifer based on a broad catchment-wide water balance.

The conceptualisation incorporates a number of assumptions regarding recharge differentials through drift and runoff to the aquifer boundary from the volcanic rocks that surround the aquifer. The conceptualisation is heavily dependent on meteorological data for the input function, and equally reliant on runoff data for part of the output function. Resort to MORECS effective rainfall data was made as there were inadequate local evapotranspiration data. In addition, a lack of gauged hydrograph separation information placed reliance on estimates of baseflow from low flow studies and derived baseflow indices. However, the resultant conceptualisation and water balance is relatively robust and offers a good foundation for more detailed study and ultimately for the preparation of a numerical groundwater model.

Previous investigations are reviewed and the available data identified and catalogued. Much of the data relate to the former Regional Council drilling programmes and subsequent operational experience. The issue of nitrate contamination is considered in the light of historical data and the geographical distribution of nitrate-rich groundwater; the distribution is compared with the conceptual groundwater flow model. This work is hindered by lack of knowledge regarding the depth of effective shallow groundwater flow; reports of water strikes in excess of 100 m below ground during drilling suggest that the aquifer is actively transmissive to this depth if not more. What happens below 100 m is unknown. It has been suggested that groundwater flows are small and that the degree of salinisation increases markedly (Foster et al, 1976).

Other issues include a lack of drilling data in the northern part of the aquifer, doubt over the effective southern boundary of the aquifer as it dips underneath Carboniferous strata, and the relationship between surface and groundwater in the western part of the catchment and the Leven sub-catchment.

The study concludes with a list of data needs and recommendations for further work. This will enable the proper management of the groundwater resources to be undertaken, and encourage new groundwater development to be undertaken on a rational and justifiable basis. In this way the sustainable resource potential of the aquifer can be optimised and both the quantity and quality of the resource can be protected.

1.4 History of Groundwater Exploration

Shallow wells and springs have provided reliable water supplies to many farms and dwellings in the Fife and Kinross area for centuries. With the advent of mechanisation and the development of drilling rigs, deeper probings were made into bedrock aquifers. One of the earliest attempts at exploiting the Devonian aquifer was at Ladybank in 1905 when the Town Council successfully drilled to 114 m depth to provide a small standby supply for the village. Since that time, boreholes have been constructed throughout the area from time to time, with a slight increase in activity in the ten years leading up to the Second World War. Boreholes for both public supply and industrial use were constructed, but several were abandoned, such as the Council boreholes at Falkland, Milnathort and Springfield, near Cupar. The total number of deep sources remained low throughout the 1960s, with only a few farm boreholes constructed, along with the first of the Todd and Duncan industrial sites at Kinross.

The commencement of more systematic exploration in the early 1970s by the then Fife Regional Council led to the development of the Balmalcolm, Kettlebridge, Falkland and Kinnesswood Nos. 1 and 2 boreholes. Successful commissioning of these sources for public supply led to a further phase of drilling in 1979-81 when the Freuchie, Newton of Lathrisk, Newton Maltings, Kinnesswood No. 3 and Kinneston sources were constructed. However, the later phase boreholes have not, as yet, been put into use although it is planned to commission the Freuchie and Newton sites in 1999.

By mid-1999, seven sources will be on standby for public supply. The Balmalcolm borehole, owing to rising nitrate concentrations, is planned only for use in extreme contingency. The planned usage by ESWA of their public supply boreholes is given in Table 1.1.

Table 1.1 ESWA public supply boreholes with abstraction ranges and current status

Source	Range of abstraction (Ml/d)	Status
Balmalcolm	2.5	Dormant. Only for extreme contingency.
Falkland	0.9	Standby. UV disinfection only.
Freuchie	3.5 – 4	Standby. UV disinfection; hypochlorite.
Kettlebridge	2.5	Standby.
Kinneston	2.0	Dormant.
Kinnesswood 1	2.3 – 2.5	Standby. Hypochlorite.
Kinnesswood 2	2.3 – 2.5	Standby. Hypochlorite.
Kinnesswood 3	2.0 – 2.4	Standby. Hypochlorite.
Newton of Lathrisk	3.5 – 4	Standby. UV disinfection; hypochlorite.
Newton Maltings	3.5	Dormant.

All standby sources are in use on a 24-hour basis when required. The abstraction period is normally from April to September, but can be dependent on other operational work. Apart from Falkland, all the boreholes are operated automatically, with flexible abstraction rates according to demand and trunk main pressure.

The period from 1990 has seen a significant increase in the number of boreholes drilled for farm irrigation, particularly in the Falkland–Kettlebridge area, but also along the northern slopes of the Lomond Hills to Gateside. For those farms without direct access to the River Eden, groundwater has proved to be a valuable source for arable crop irrigation.

Groundwater is also used by a number of industries, including vegetable washing and poultry breeding.

2. THE DEVONIAN AQUIFER

2.1 Geological Setting

2.1.1 Geological history of central Fife

The oldest rocks that crop out in Central Fife form part of a major basaltic andesite volcanic province of early Devonian age. Earth movements folded, faulted and uplifted these rocks which were eroded to produce a subdued landscape that was subsequently buried under late Devonian largely fluvial sedimentary rocks (Stratheden Group), mainly sandstones.

The oldest Carboniferous rocks (Inverclyde Group) were deposited on a low-lying alluvial and coastal plain which was subjected to periodic marine incursions. Above this, the Strathclyde Group is dominated by lacustrine-deltaic and fluvial depositional processes typified by the minor components such as freshwater limestones and algal-rich, poor oil shales. Effusive basaltic volcanism produced lava dominated successions (Bathgate Group) interbedded with and replacing the normal sedimentary succession. Coal-forming swamp conditions were a feature of much of late Carboniferous time especially when the Limestone Coal Formation and Lower and Middle Coal Measures were laid down. Continuing earth movements helped to create the basins in which the sediments accumulated.

A complex pattern of Quaternary events took place characterised by the deposition of glacial till and gravels as well as raised marine deposits.

The next section describes in more detail the hydrolithostratigraphy of the Upper Devonian and immediately overlying Carboniferous rocks. The outcrop pattern of the solid geology in the central Fife region is illustrated in the simplified map in Figure 2.1.

2.1.2 Hydrolithostratigraphy

UPPER DEVONIAN - STRATHEDEN GROUP

The Upper Devonian Stratheden Group aquifer incorporates, in ascending succession, the Burnside, Glenvale and Knox Pulpit formations and consists predominantly of reddish brown, yellow and white sandstones with subordinate siltstones, mudstones and conglomerates. The base is marked by an unconformable contact with the underlying largely impermeable Lower Devonian lavas of the Ochil Volcanic Formation. Many of the Stratheden Group rocks are fluvial in origin but the main aquifer of the Knox Pulpit Formation is aeolian.

Burnside Formation

The Burnside Formation is up to 160 m thick but locally is not always present. The unit consists predominantly of fine- to very coarse-grained sandstones that are dull red or purplish in colour. The sandstones are characterised by the presence of well-rounded, siliceous pebbles up to 15 cm across, mainly of quartzite and vein quartz of "Highland" origin, and of more locally derived pebbles of Ochil Volcanic Formation lavas. The lava pebbles are found predominantly at, or near the base of the formation and form beds of conglomerate up to about 2 m thick. Beds of red siltstone and silty mudstone up to 60 cm thick are rare.

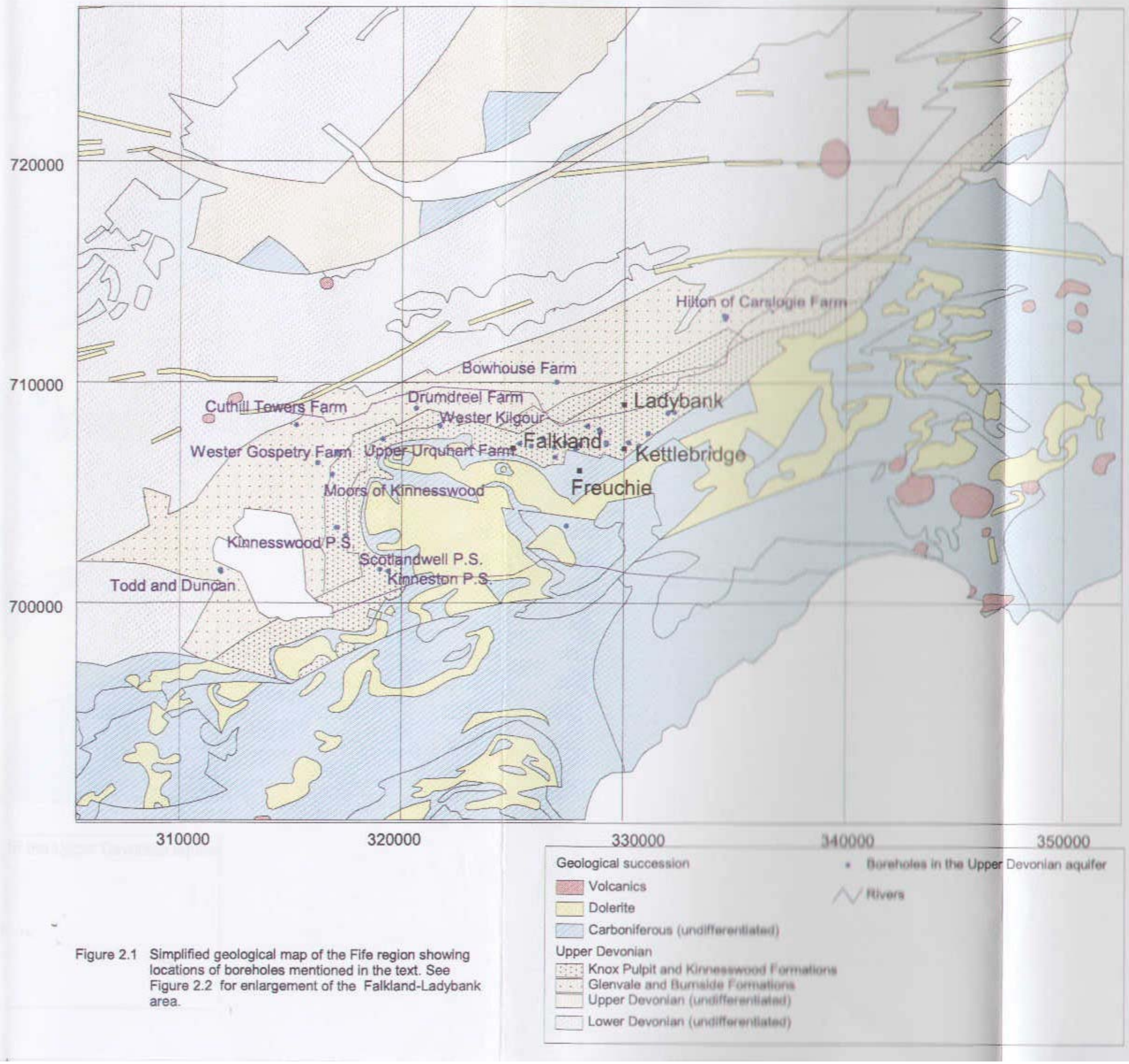

Figure 2.1 Simplified geological map of the Fife region showing locations of boreholes mentioned in the text. See Figure 2.2 for enlargement of the Falkland-Ladybank area.

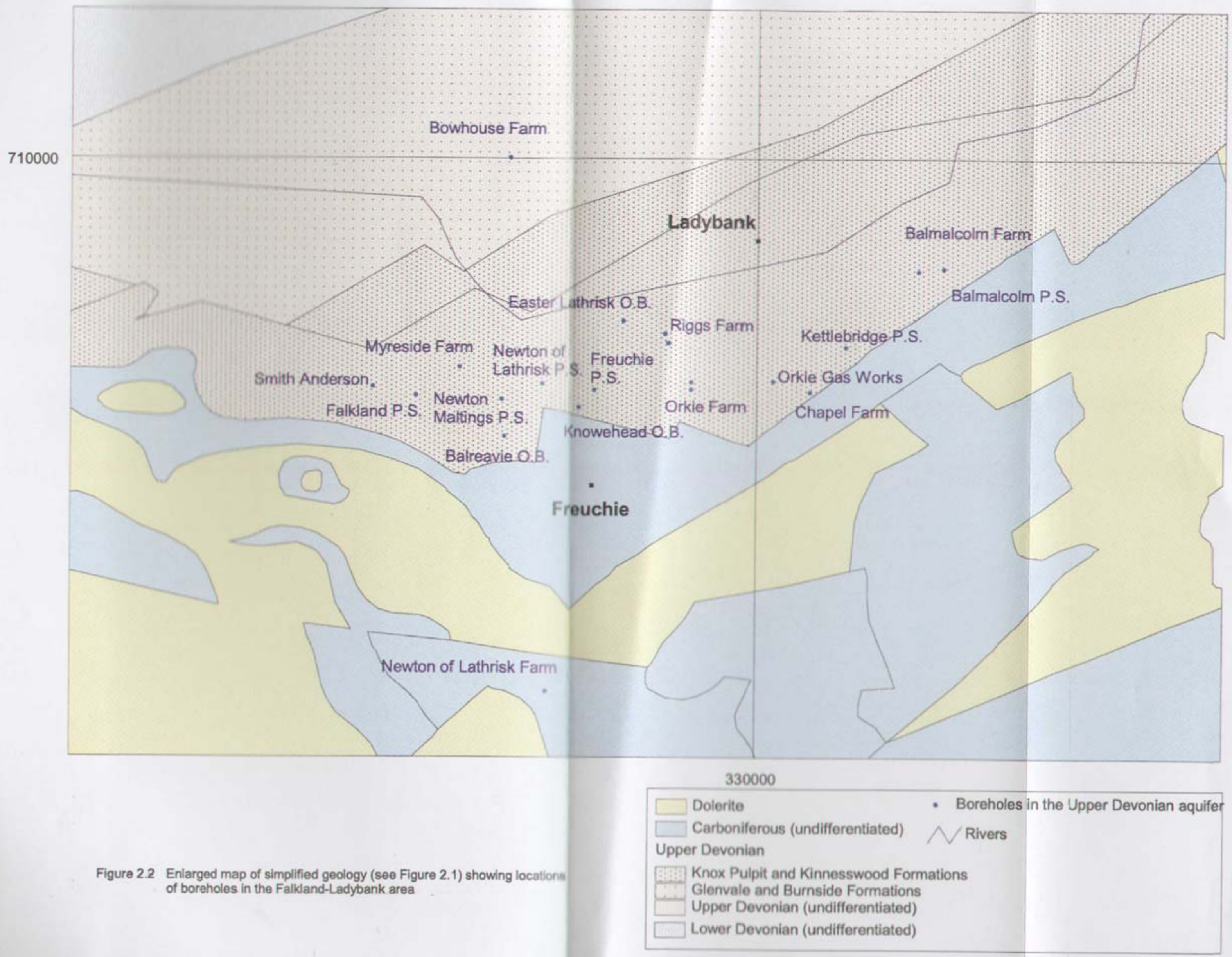

Figure 2.2 Enlarged map of simplified geology (see Figure 2.1) showing locations of boreholes in the Falkland-Ladybank area

The sandstones and conglomerates of this unit are generally moderately- to well-cemented which is usually effected by a clay-mica matrix but also quite commonly by carbonate (calcite). In the shallow outcrop (less than 80 m deep), the formation has a porosity ranging from 10 to 20% and a mean intergranular permeability of 0.2 m/d.

Glenvale Formation

The Glenvale Formation is up to 350 m thick, and consists of fine- to coarse-grained, white, yellow, brown, red and purple, feldspathic sandstones. The sandstones contain few siliceous pebbles, but pebbles of red, cream and green silty mudstone, up to 15 cm across, are common. Beds of greenish grey and red silty claystone and siltstone are also present, but not common, and some form the upper parts of upward-fining cycles.

The sandstones of this unit range from weakly to well cemented which is usually effected by a clay-mica matrix but also by calcite. In the shallow outcrop (less than 80 m deep), the formation porosity ranges from 10 to 20%, and mean intergranular permeability is 0.2 m/d.

Knox Pulpit Formation

The Knox Pulpit Formation is 130 to 180 m thick, and consists of soft, white and cream, very fine- to coarse-grained feldspathic sandstones. The sandstones throughout the formation are characterised by the presence of “pin-stripe” lamination of aeolian origin. The laminae are 1 to 10 mm thick and are defined by marked variations in grain-size. The rarity of pebbles is another distinctive feature along with small masses of ochreous decomposed dolomite (cornstone) near the top of the formation and greenish-grey silty claystone near the base. A range of cross-stratification forms and flat lamination occur. Ripple lamination is rare except near the top of the unit. Well-rounded “millet seed” grains are common in coarser laminae.

The sandstones of this unit are weakly cemented which is usually effected by a clay-mica matrix where present. In the shallow (less than 80 m) outcrop, the sandstones are highly porous (over 20%) and permeable (over 0.5 m/d). These features may be original, reflecting deposition by aeolian processes. However, cored samples from depth (449 m to 567 m) in the Glenrothes Borehole are much less porous (ranging from 4 to 22%, with most values between 11 and 18%) and permeable (most values between 2×10^{-4} m/d and 0.06 m/d), suggesting that shallow aquifer characteristics have been developed through weathering, during which cementing material has been chemically removed.

CARBONIFEROUS – INVERCLYDE GROUP

The Inverclyde Group comprises the Kinnesswood, Ballagan, and Clyde Sandstone formations. These formations are characterised by sandstones with pedogenic carbonate ('cornstones') and by silty mudstones containing thin beds of dolomite and limestone ('cementstone').

Kinnesswood Formation

The Kinnesswood Formation ranges in thickness from 20 m in the northern part of the Lomond Hills, to greater than 130 m. It consists predominantly of yellow, white, purple-red and grey-purple sandstones which are mostly cross bedded and arranged in upward-fining units.

The sandstones range from sometimes weakly to well cemented, usually effected by a clay-mica matrix but also by carbonate (calcite and dolomite). In the shallow outcrop (less than 80 m depth), the formation has a porosity ranging from 10 to 20% and a mean intergranular permeability of 0.2 m/d. At depth in the Glenrothes Borehole (362 m to 449 m) porosity is in the range 8 to 17% and the permeability generally between 8.35×10^{-5} m/d to 0.07 m/d (rarely over 0.3 m/d).

Ballagan Formation

The Ballagan Formation, a major aquiclude, attains a maximum thickness of at least 160 m, but has been removed by intra-Carboniferous erosion in the northern part of the Lomond Hills. The formation is characterised by generally grey mudstones and siltstones, with nodules and beds of ferroan dolomite (cementstones), the beds generally less than 0.3 m thick. Gypsum, and to a much lesser extent anhydrite, and pseudomorphs after halite occur. Desiccation cracks are common and the rocks frequently show evidence of brecciation during diagenesis. Both these features are associated with reddening of the strata. Thin sandstones are present.

CARBONIFEROUS - STRATHCLYDE GROUP

The Strathclyde Group (Viséan) consists of interbedded sandstones, siltstones and mudstones with common seatearths, coals and sideritic ironstones. The group represents a lithological change from the cornstone- and cementstone-bearing strata of the Inverclyde Group to a seatrock- and/or coal-bearing sequence in which volcanic rocks may be common. The range of depositional environments includes fluviatile, deltaic, lacustrine and marine, which commonly alternate in thin cycles.

Pathhead Formation

The Pathhead Formation (Brigantian) is 40 to 130 m thick and consists predominantly of mudstone and siltstone with beds of limestone and dolomite. Pale coloured, fine- to medium-grained sandstone is subordinate to the argillaceous rocks. Thin beds of coal and ironstone also occur. The overall pattern of sedimentation within the formation is of upward-coarsening deltaic cycles, with thinner upward-fining fluvial units erosively capping them.

STRUCTURE

A number of medium and small-scale faults are known in the area. Along much of its length the northern boundary of the Upper Devonian sandstone is formed by the Fernie Fault. This trends south-west to north-east, downthrowing the aquifer relative to the Lower Devonian volcanics to the north. Towards the eastern end of the Eden valley the southern boundary of the aquifer is formed by the similarly-trending Dura Den Fault, which down-throws the formations against the Lower Carboniferous to the south.

A small number of faults strike perpendicularly across the Eden valley, such as near Falkland and Ladybank, where a graben structure exists. The degree of movement on the faults is unknown. In the area surrounding Falkland and Freuchie a group of smaller faults radiates from the cross-valley fault and has created a number of even smaller fault-bounded blocks.

QUATERNARY

The Quaternary Era was a time of extensive glaciation in Scotland. However, all the accessible Quaternary deposits and features in Central Fife are late-glacial and less than 30 000 years old (late-Devensian and Flandrian age). Geological history during Quaternary glacial periods is described in colder and warmer climatic episodes called stades and interstades.

Dimlington Stadial (c.27 000 – 13 500 years ago)

The generally eastwards moving ice sheet of the Dimlington Stadial eroded the landscape producing striated bedrock surfaces, rôche moutonées and crag and tail features. East Lomond Hill is an example of the latter landform. Erosion by the ice removed pre-existing glacial and interglacial sediments. The ice then deposited an incomplete sheet of glacial till, generally a few metres thick, on the bedrock surface. Glacial till consists of pebble to boulder sized particles isolated in a plentiful, stiff to hard, sandy, silty clay matrix. This is generally of low permeability (10^{-8} to 10^{-9} m/s), but the presence of jointing provides conduits for water to pass through. The ice also sculpted the till into streamlined ovoid mounds called drumlins as around Strathmiglo.

When this ice sheet retreated westwards across the district about 14 000 years ago, substantial volumes of glaciofluvial sand and gravel were deposited on top of the glacial till by the meltwaters. Meltwater channnels were also cut. Ice-contact deposits of sand and gravel, forming mounds, eskers (sinuous ridges) and terraces with kettle-holes, are common in Stratheden and also around Loch Leven. They generally rest on the till but locally also on bedrock.

The interplay of the local isostatic recovery with world sea level changes has created raised marine deposits. During deglaciation, local relative sea level was high and it is not unusual to find raised marine sediments at about 40 to 45 m above OD. By about 13 500 years ago, the sea had invaded the valleys of the Forth, Tay, Earn and Eden reaching both Crieff and Aberfoyle. The characteristic marine sediment associated with the deglaciation is a thin and discontinuous sheet of firm to stiff, red clay which occurs at surface around Auchtermuchty. In the Jennystown Borehole [NO 3243 1097] near Ladybank, the clay occurs at 8 m depth below younger deposits. The clay commonly rests on the glacial till but also rests on, and may interfinger with the glaciofluvial sand and gravel.

Windermere Interstadial (13 500 - 11 000 years ago)

Other evidence of falling base levels include the late Devensian glaciofluvial and alluvial sand and gravel terraces in Stratheden and west of Loch Leven. During the Interstadial the local landscape was largely devoid of trees and generally tundra-like with lakes of significant size including Loch Leven and Rossie Loch [NO 26 12] in large kettleholes. Thick deposits of glaciolacustrine clay accumulated in Loch Leven after deglaciation resting either on glacial till or glaciofluvial sand and gravel.

Loch Lomond Stadial (11 000 - 10 000 years ago)

Central Fife lay beyond the ice margins at this time, but there is possible evidence of frozen ground including frost-wedge casts, and materials moved by freeze-thaw action and by rockfall as on the steep slopes in the Lomond Hills.

Flandrian Interstadial (less than 10 000 years ago)

About 10 000 years ago, there was a major change in the climate associated with the disappearance of glacial ice from Scotland and thawing of ground ice. Lake and river alluvium continued to be laid down and peat accumulated widely at surface although much of this has since been removed by Man.

2.2 Hydrogeology

2.2.1 Introduction

The Knox Pulpit Formation, together with the overlying Kinnesswood Formation, which is usually mapped with it, generally has the highest porosity and permeability of the Upper Devonian of Fife. These two formations crop out along the southern edge of the aquifer outcrop (Figure 2.1). The underlying Glenvale and Burnside Formations tend to have lower permeability, but provide significant yields in some cases. Public supply boreholes abstracting from the Knox Pulpit and Kinnesswood Formations, such as Freuchie and Newton of Lathrisk, provide yields of up to 4 Ml/d each, while those constructed in the Glenvale and Burnside Formations, such as Kinneston and the Kinnesswood boreholes, do not generally yield more than 2.4 Ml/d each. The highest permeability in each of the Upper Devonian units tends to be in the uppermost 10 to 15 metres of the saturated zone, where weathering has significantly increased secondary permeability (Foster et al, 1976).

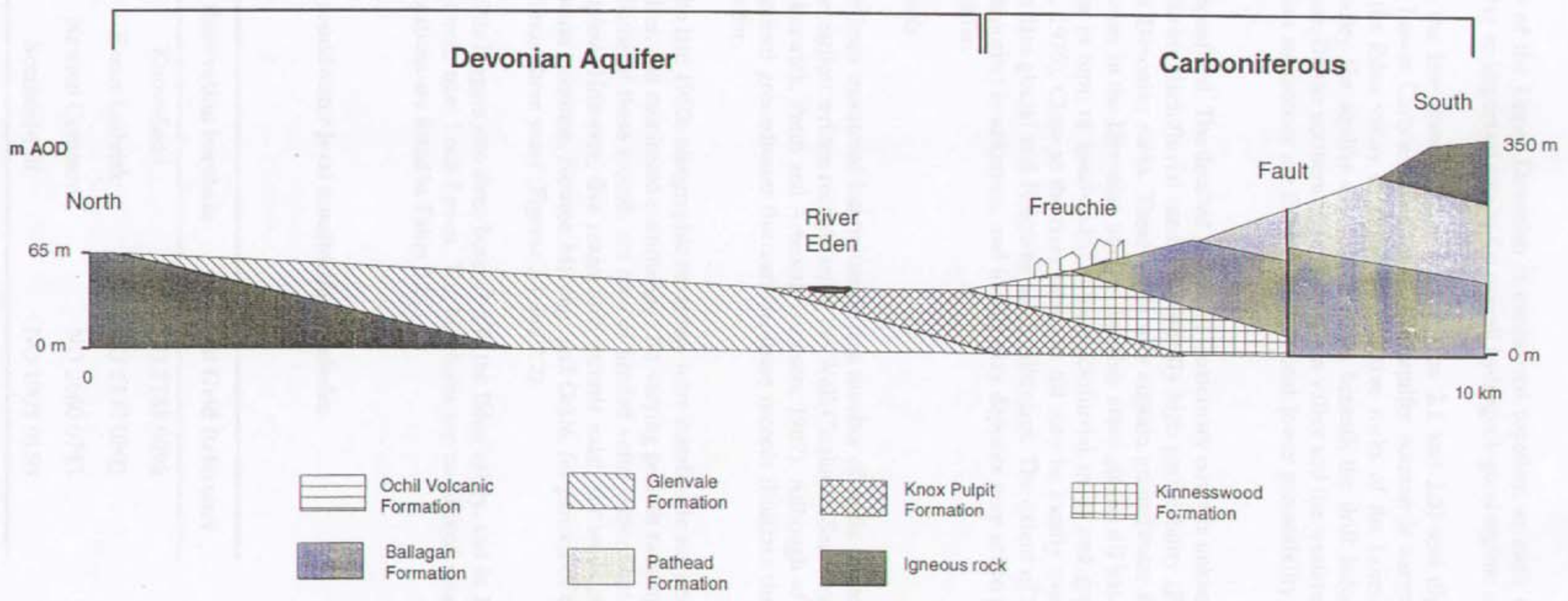

Figure 2.3 Schematic cross-section through the Devonian aquifer at Freuchie

In this study the whole of the Upper Devonian is considered together, as each of the component formations is likely to play an important role in the overall hydrogeological regime of the area.

The aquifer rocks form the low ground of the area (Figure 2.1 and 2.3) and dip south-eastwards beneath less permeable Lower Carboniferous rocks. The aquifer outcrop is narrowest between the Loch Leven basin and the Eden valley north of the intrusive rocks of the Lomond Hills. East of Falkland in the Eden valley the aquifer expands in width beneath the drift before narrowing and disappearing east of Cupar. On the northern edge of the Eden valley and the western edge of the Loch Leven basin the Devonian sandstones are downfaulted against lower permeability Lower Devonian volcanic rocks.

The aquifer is usually unconfined. The detailed pattern of Quaternary cover is unknown, but a number of borehole logs have shown glaciofluvial sands of generally high permeability (Foster et al, 1976) directly overlying Upper Devonian rocks. These sands may contain groundwater in direct hydraulic continuity with deeper water in the Devonian aquifer. In other areas glacial till has been observed to rest on bedrock, overlain in turn, or interbedded with, glaciofluvial sands and gravels (Aitken and Ross, 1982; Foster et al, 1976). Close to the river Eden the till may be locally overlain by clay-rich estuarine deposits and/or late glacial and Holocene sandy alluvium. The extent of clay cover (either glacial till or estuarine deposits) is unknown, and locally clay deposits may act to partly confine the underlying sandstone aquifer.

2.2.2 Groundwater levels

Groundwater levels have been monitored intermittently in a number of wells in the Eden valley and Leven basin. Some of the earliest written records are in the Well Catalogue Series report covering the areas of Kinross, North Berwick, Perth and Arbroath (Jackson, 1967). Although of limited value for assessing seasonal and annual groundwater fluctuations, these records illustrate the general trend of the water table in the aquifer.

From the late 1970s to the late 1980s autographic recorders were installed in ten observation wells in the Upper Devonian aquifer, and monitored continuously for varying periods ranging from less than a year to almost 9 years. Some of these records are now of limited value either because they are very short, or they are incomplete. However, five reasonable records exist, for wells at Easter Lathrisk, Kinnesswood No. 3, Newton Common, Newton Maltings and Orkie, for periods of time ranging from about one and a half to almost three years (Figures 2.1 and 2.2).

In 1997 SEPA installed data loggers into three boreholes in the Eden valley, and in 1998 a logger was also installed at Scotlandwell, near Loch Leven. The boreholes are monitored continuously at two-hourly intervals. Their locations are listed in Table 2.1.

Table 2.1 SEPA groundwater level monitoring boreholes

Observation borehole	National Grid Reference
Knowehead	NO 2783 0696
Easter Lathrisk	NO 2837 0802
Newton Common	NO 2660 0743
Scotlandwell	NO 1903 0150

Figure 2.4 shows the available groundwater level series for Easter Lathrisk for the periods June 1979 to February 1982 and April 1997 to May 1999.

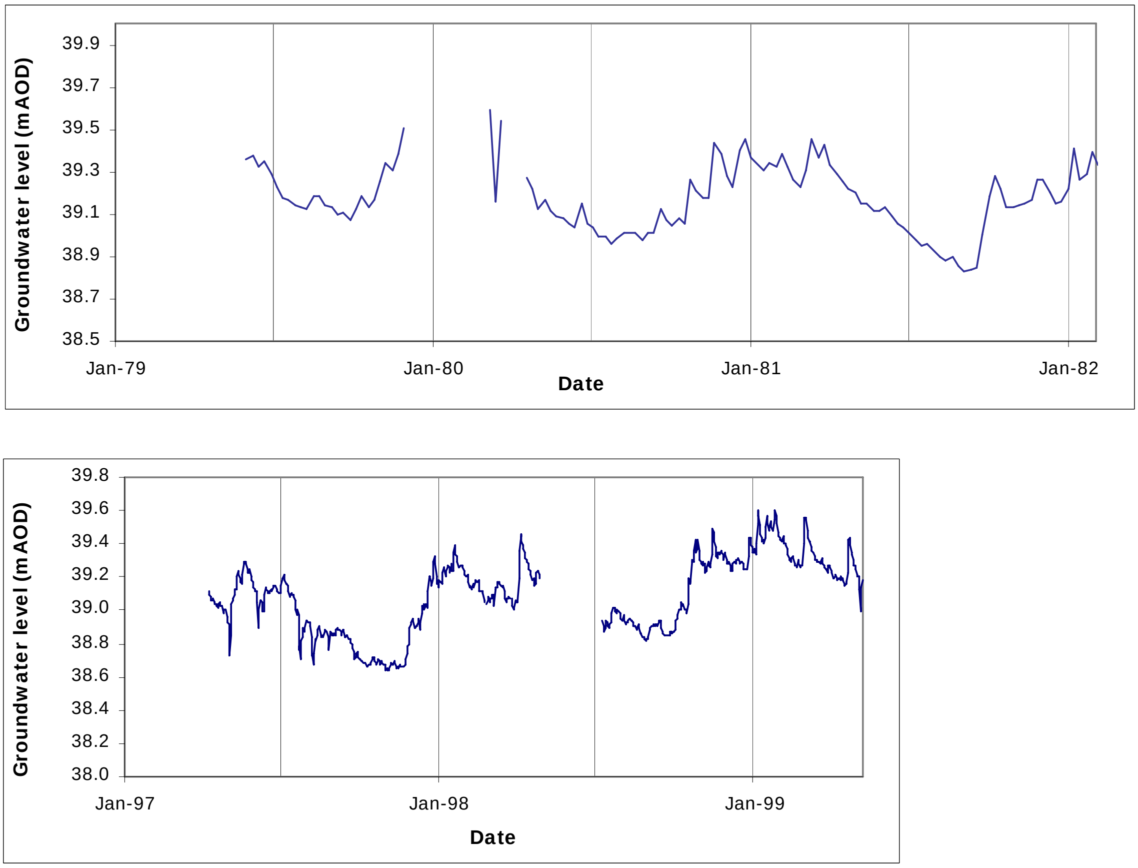

Figure 2.4 Available groundwater level series for the Easter Lathrisk observation borehole

The borehole hydrographs show that annual fluctuation of natural groundwater levels is small, between 1 to 4 m. Boreholes at higher elevations, such as Kinnesswood, often show annual fluctuations of more than 4 m. The record for 1997 and 1998 shows lower overall groundwater levels than in the early 1980s, but 1999 appears to show a recovery to very similar levels as seen in the earlier record. Much of 1997 and 1998 saw groundwater levels depressed across the UK, and it is probable that the situation in Fife reflected this.

On shorter time scales, the monitoring boreholes in the Freuchie area all show a rapid response to rainfall. Groundwater level rises occur within hours of a rainfall event, possibly due to a thin drift cover and the shallow water table.

The water table lies close to the ground surface across most of the aquifer outcrop, particularly under the river Eden flood plain, where the unsaturated zone is generally less than 5 m thick. Figure 2.5 shows the probable distribution of groundwater contours across the aquifer based on spot measurements taken in September 1985. The contour pattern within the Eden valley implies that there are two components to groundwater flow: one parallel to the length of the valley and one perpendicular from the valley sides towards the river Eden. Within the Leven basin the contours suggest that Loch Leven acts as a groundwater discharge point, but that there is also a component to flow out of the basin to the Eden valley. However, the contours in the Leven basin are based on very few data points, with a great degree of extrapolation. The true situation in the basin may be very different.

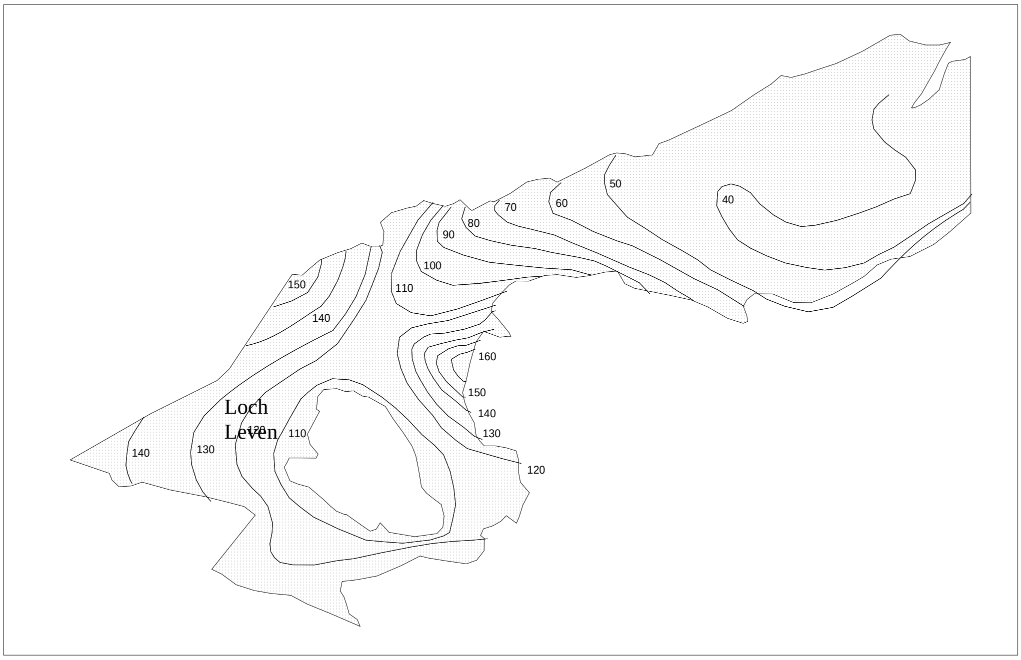

Figure 2.5 Sketch map of the Upper Devonian aquifer outcrop showing the probable groundwater surface in m above OD

2.2.3 Physical aquifer properties

Aquifer property data are derived from field and laboratory tests. Field investigations include pumping tests and down-hole geophysical logging. Laboratory experiments done to analyse core samples for porosity and hydraulic conductivity include standard permeameter and liquid saturation tests. The results of tests on core samples from ten boreholes in the Upper Devonian aquifer of Fife are available. The boreholes are listed in Appendix 1 and the results are illustrated in Figures 2.6, 2.7 and 2.8.

Intergranular porosity

The distribution of intergranular porosity in cored samples from the boreholes referred to above is shown in Figure 2.6. Porosity in the aquifer is generally relatively high. The sampled values range from 4 to 30%, with a geometric mean of 19%. Laboratory measurements of pore-size distribution and centrifuge specific yield for the same core samples show that the specific yields of sandstones with porosities exceeding 20% are likely to reach 12 to 15%. Sandstones with porosities of less than 20% tend to have more variable pore size distributions and may have specific yields of less than 5% (Foster et al, 1976).

The distribution of porosity with depth in the aquifer is illustrated in Figure 2.7. No overall trend in porosity is visible with depth. One or two of the shallower boreholes (less than 100 m deep) show porosity to decrease slightly with increasing depth (e.g. Figure 2.7c and 2.7d), but in other boreholes this is not obvious (e.g. Figure 2.7a and 2.7b). At much greater depths porosity is generally lower, as seen in the Glenrothes borehole where the Upper Devonian was penetrated at over 400 mbgl (Figure 2.7e).

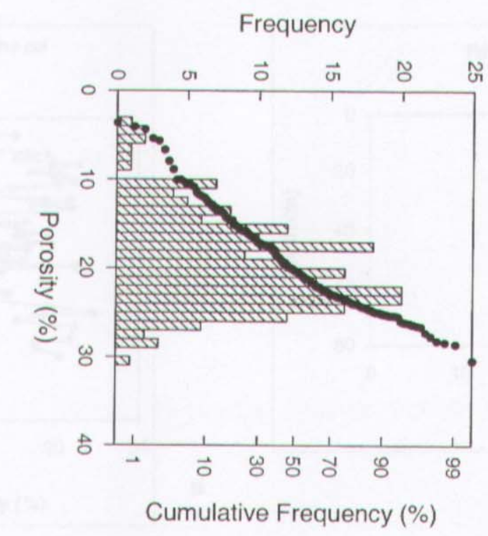

Figure 2.6 **Distribution of intergranular porosity data for samples from ten boreholes in the Upper Devonian aquifer (from unpublished BGS data)**

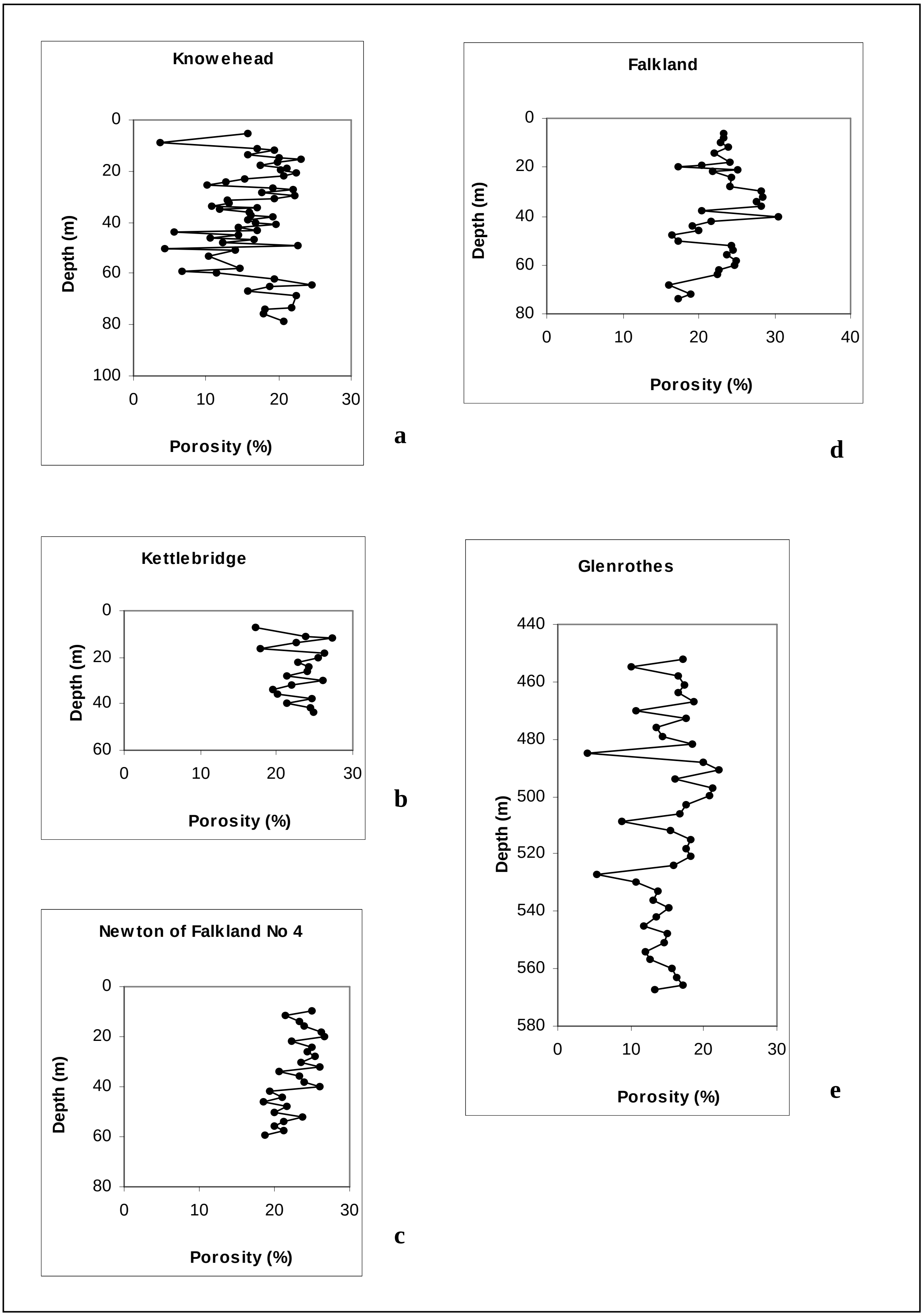

Figure 2.7 **Depth variation in intergranular porosity in five boreholes in the Upper Devonian aquifer (from unpublished BGS data)**

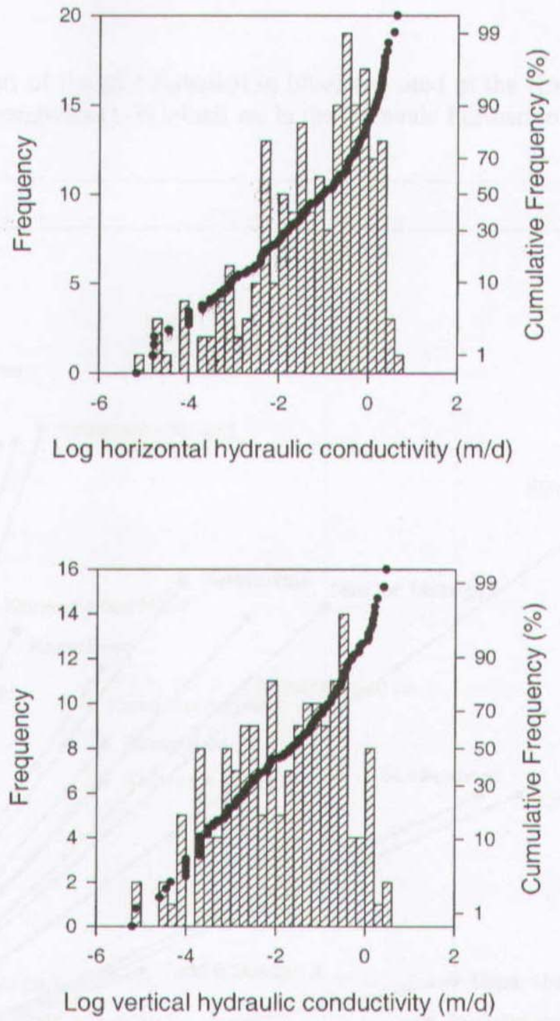

Figure 2.8 Distribution of intergranular hydraulic conductivity for samples from ten boreholes in the Upper Devonian aquifer (from unpublished BGS data)

Intergranular hydraulic conductivity

The results of laboratory intergranular hydraulic conductivity tests on core samples from the same boreholes are shown in Figure 2.8. Horizontal and vertical permeability values are shown separately to highlight heterogeneities in the aquifer matrix. These are not noticeably large, but horizontal permeability is on average twice as high as vertical. Horizontal permeability values range from 10^{-5} to 4 m/d with a geometric mean of 0.43 m/d. Vertical permeability ranges from 10^{-5} to 3 m/d with a mean of 0.19 m/d.

Yield-drawdown characteristics

A comparative plot of borehole yield-drawdown characteristics for the pumping tests described above, and for additional boreholes for which no transmissivity values exist, is shown in Figure 2.9. Most of the boreholes which plot in the lower half of the graph (labelled in red), showing low yields for relatively high drawdowns, are sited in the Glenvale and Burnside Formations. Exceptions are Upper Urquhart Farm and Scotlandwell, which are drilled in the Knox Pulpit Formation. Conversely, most of the boreholes in the upper part of the plot (labelled in blue) are sited in the Knox Pulpit Formation, except for the Kinnesswood boreholes (1-3) which are in the Glenvale Formation.

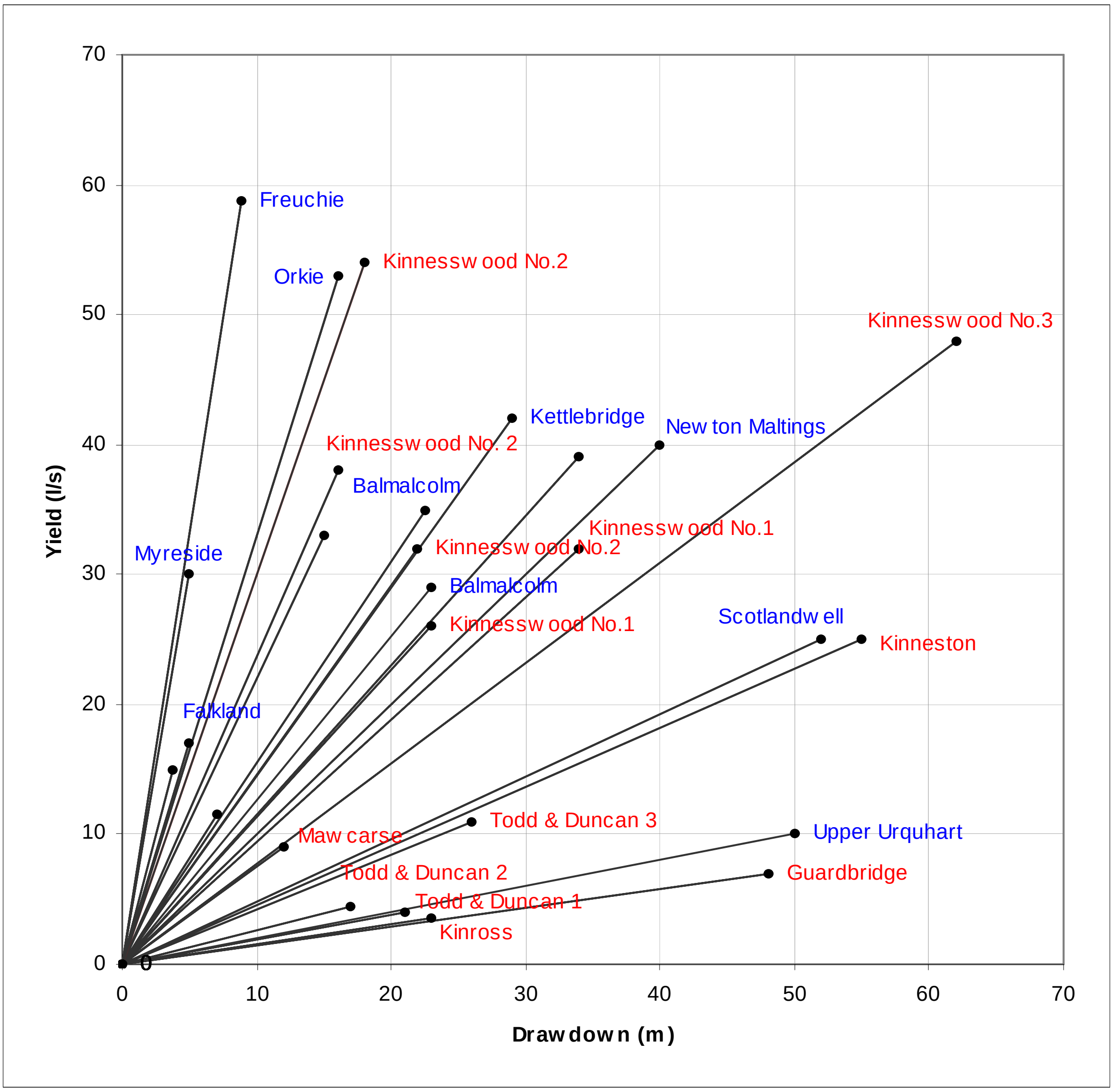

Figure 2.9 **Available yield-drawdown characteristics for boreholes in the Upper Devonian sandstone of Fife. Boreholes labelled in blue are constructed in the Knox Pulpit and/or Kinnesswood Formations; boreholes labelled in red are constructed in the Glenvale and Burnside Formations.**

Transmissivity

Pumping tests have been carried out at a number of sites in the Upper Devonian aquifer, in the majority of cases with a single observation borehole. Some of these have provided values for overall transmissivity of the major aquifer units (Table 2.2). Transmissivity in the Knox Pulpit Formation is generally around 200 m^2/day. The very high transmissivity value for the Freuchie borehole in the Kinnesswood Formation may be explained by the fact that the area is highly faulted. In comparison, testing of the Kinneston borehole gave a very low transmissivity of only 12 m^2/d.

Table 2.2 **Summary of the results of pumping tests in Upper Devonian aquifer units which provided transmissivity values**

Pumping test site	Geological formation	Date	Groundwater level (m AOD)	Testing rate (l/s)	Transmissivity (m^2/day)
Falkland	Knox Pulpit Formation	Sept 1974	55	15	200
Freuchie	Kinnesswood Formation	April 1980	42	59	800
Kettlebridge	Knox Pulpit Formation	Oct 1974	36	33	150
Kinneston	Glenvale Formation	Oct 1981	No data	25	12
Kinnesswood No. 2	Glenvale Formation	March 1974	128	38	250

Borehole geophysics

Four boreholes in the Falkland area were logged in December 1997. The results from two of these, Newton Maltings and Knowehead, are shown in Figures 2.10 and 2.11.

In general the formation logs show fining-upwards sandstone units between 4 and 8 m thick. Caliper and fluid logging suggest that fractures or bedding-parallel fissures exist which supply significant inflows to the boreholes. In the Newton Maltings borehole (Figure 2.10) a major inflow at 60 mbgl (-5.5 m OD), seen on the pumped fluid ECQ/TEMPQ and flowmeter logs, supplies some 90% of total flow. A smaller inflow at 50 mbgl (+4.5 m OD) is suggested by higher EC measurements and cooler temperatures. Similarly, in the Knowehead borehole (Figure 2.11), cooling evident at 8 to 16 mbgl (+39 – 47 m OD) and 25 mbgl (+30 m OD) is also indicative of inflow to the borehole. Conductivity is highest near the surface, decreasing with depth, which may be indicative of contamination from surface water. This borehole also shows the highest conductivities of all the four boreholes logged. The overall cooling of water with depth (unlike the Newton Maltings log) is unusual.

Conclusions

The relatively high yields and field transmissivity values of the main aquifer compared with low laboratory permeability measurements suggest that secondary permeability provides the major route for groundwater flow. This observation is supported by down-hole geophysical logging, and fracture flow is estimated to account for up to 70% of total transmissivity. Flow logging indicates that the majority of fracture inflows occur within 60 to 70 m of the ground surface. At greater depths secondary voids also occur, but to a lesser extent. In the Kettlebridge borehole, for example, which is 123 m deep, only 10% of the total yield derives from below 100 mbgl (Foster et al, 1976).

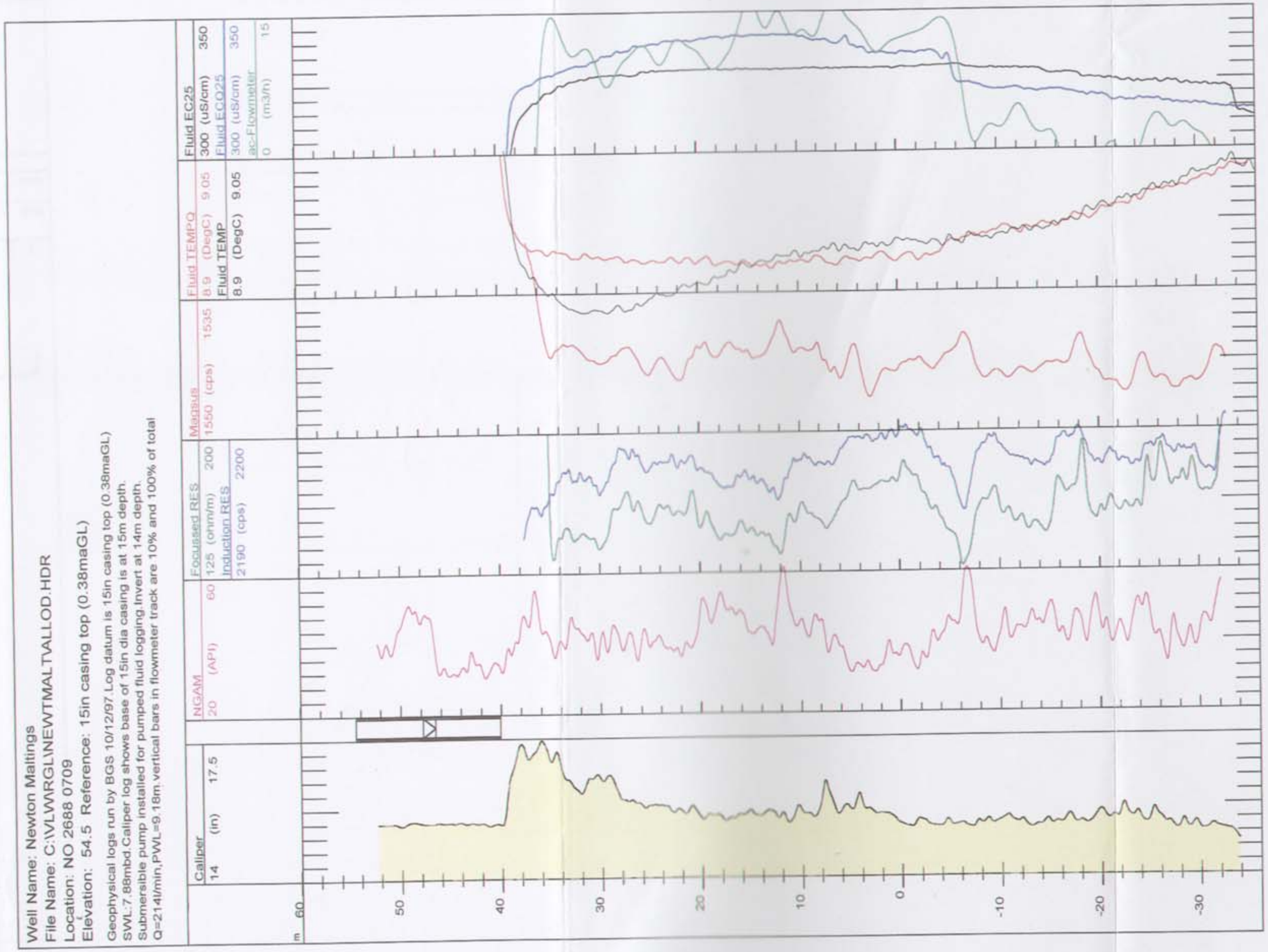

Figure 2.10 Downhole geophysical log of Newton Maltings borehole

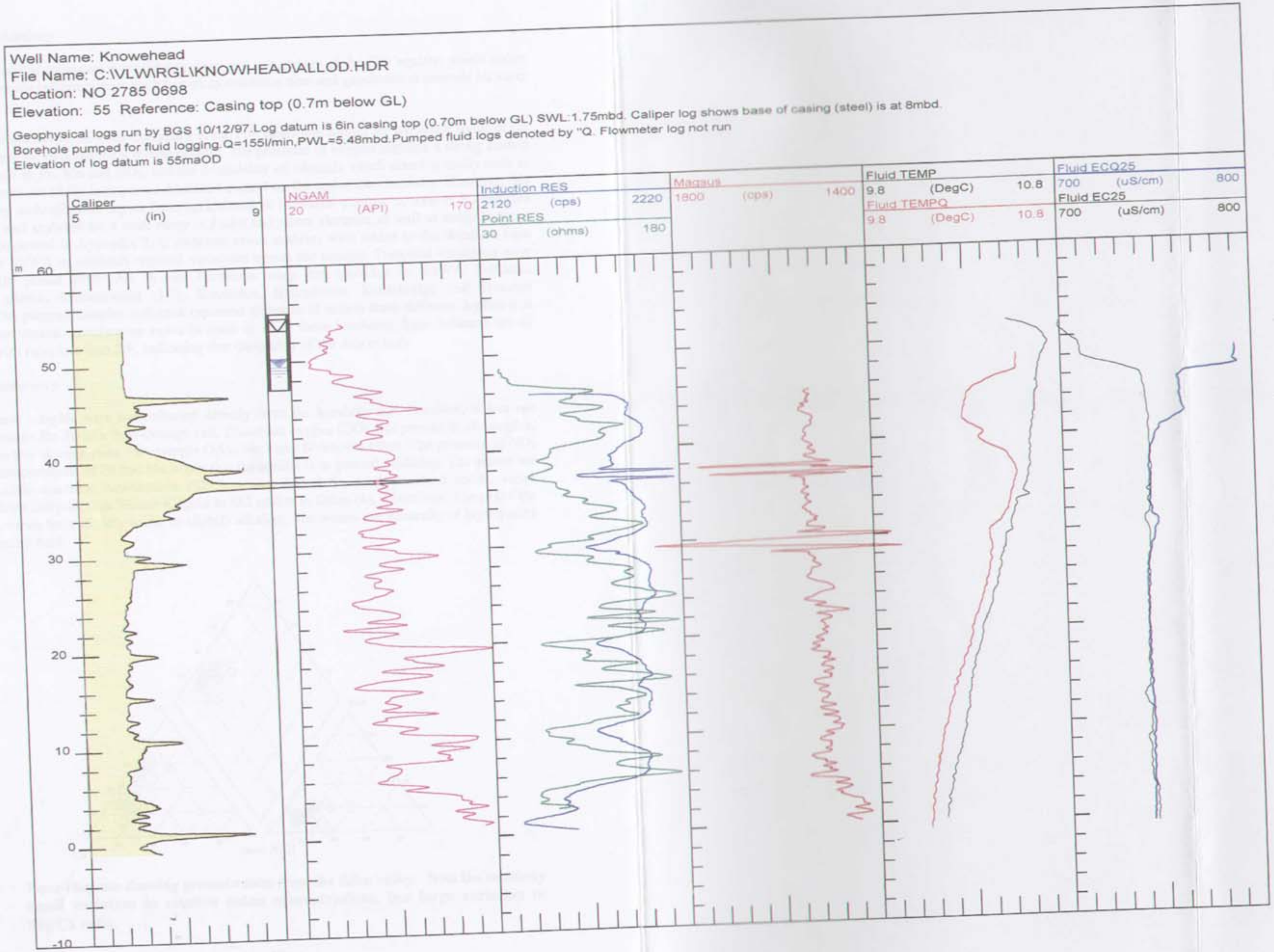

Figure 2.11 Downhole geophysical log of Knowehead borehole

2.2.4 *Hydrochemistry*

There is little detailed information on the petrology and mineralogy of the Fife aquifer, which makes it difficult to provide information on such factors as residence time and geochemical controls on water quality.

The main baseline controls on water chemistry in the Fife sandstone aquifer are the redox status of the groundwaters and the mineralogical phases present. The presence of oxygen imposes a strong control on elements such as Fe, Mn and NO_3, and the availability of minerals which dissolve easily such as calcite or dolomite are likely to impose a dominant control on the major ion chemistry. However, this is influenced by anthropogenic inputs from agricultural or industrial sources. A total of 13 samples were collected and analysed for a wide range of major and minor elements as well as stable isotopes and these are presented in Appendix 2. In addition, seven analyses were added to this database from the archives of ESWA to establish regional variations across the aquifer. Temporal variations were studied over the period 1995-1998 in nine boreholes using data provided by ESWA: Falkland, Newton of Lathrisk, Kinnesswood (1-3), Kinneston, Balmalcolm, Kettlebridge and Freuchie Knowehead. The pumped samples collected represent mixtures of waters from different depths; it is likely that some vertical stratification exists in some or all of these boreholes. Ionic balances are all less than 4% with most less than 2%, indicating that the quality of the data is high.

General characteristics

Most of the new samples were not collected directly from the borehole and, therefore, it was not possible to measure the Eh in a flow-through cell. Dissolved oxygen (DO) was present in all samples, although it was low at some sites, for example Orkie No.1 and Bowhouse Farm. The presence of NO_3 and the low concentrations of Fe and Mn imply that the aquifer is in general oxidising. The waters are fresh, but specific electrical conductance (SEC), a measure of the total dissolved solids, varies significantly from 209 μS/cm at Wester Kilgour to 682 μS/cm in Orkie No. 2 borehole. The pH of the groundwaters varies from slightly acidic to slightly alkaline. The waters are generally of high quality but are moderately hard.

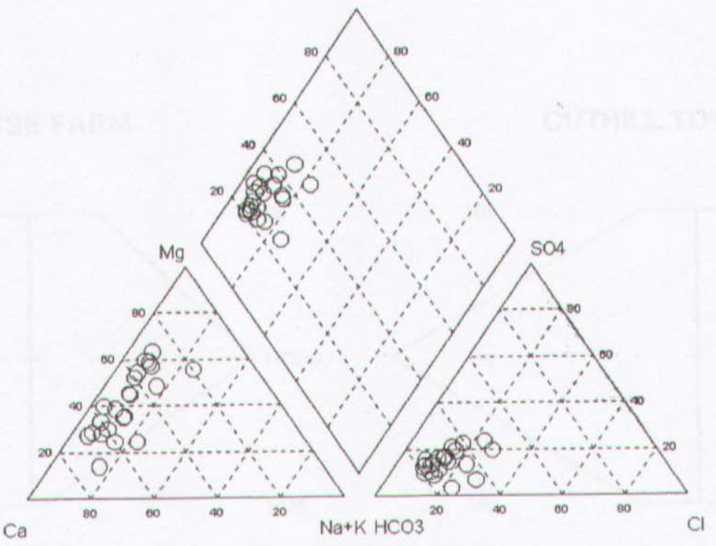

Figure 2.12 **Piper diagram showing groundwaters from the Eden valley. Note the relatively small variation in relative anion concentrations, but large variation in Mg/Ca ratio.**

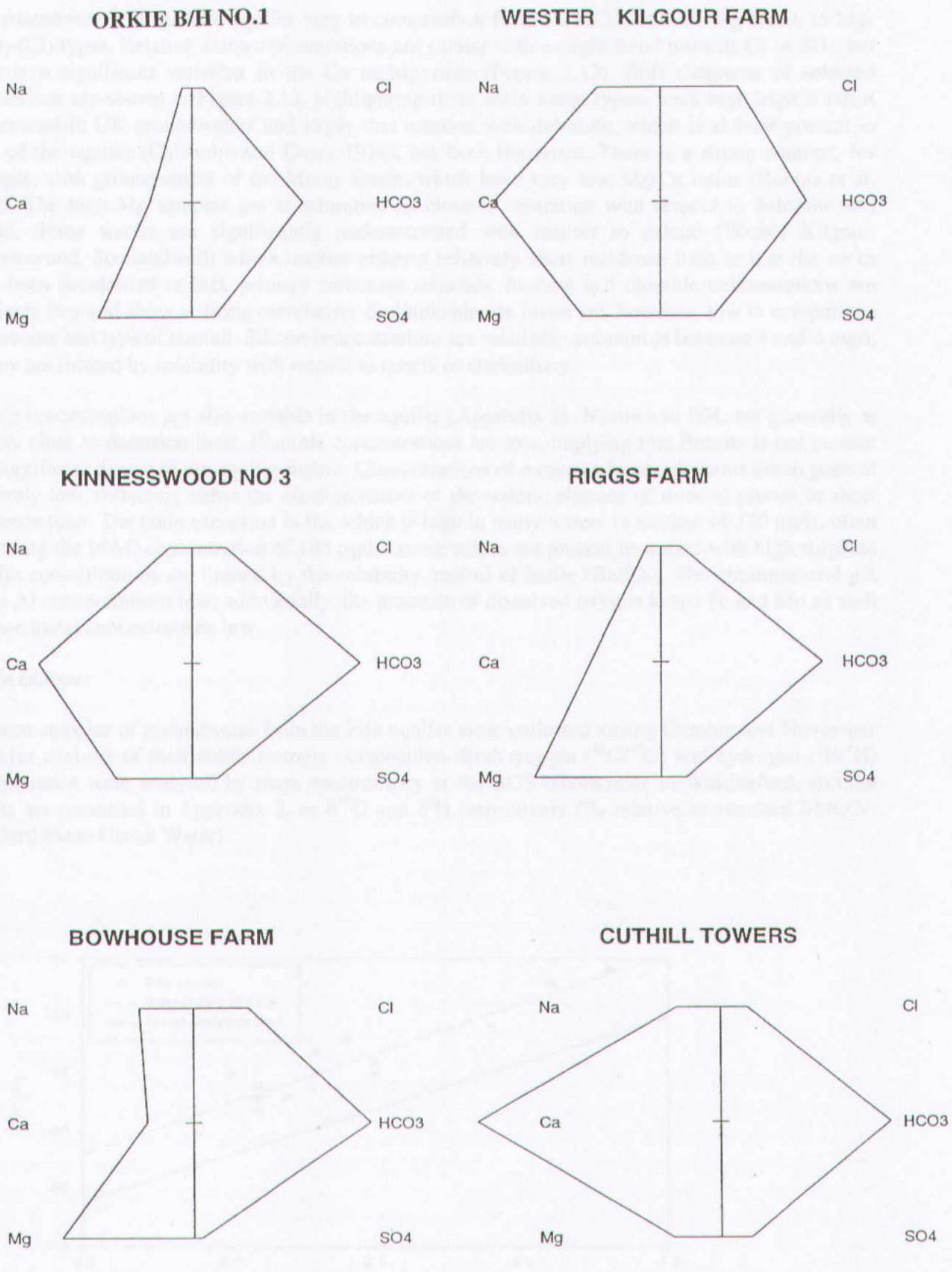

Figure 2.13 Stiff diagrams of abstracted water from selected boreholes in the Fife aquifer

The groundwaters of the Fife aquifer vary in composition from Ca-HCO_3 and Ca-Mg-HCO_3 to Mg-HCO_3-(Cl) types. Relative anion concentrations are similar with a slight trend towards Cl or SO_4, but there is a significant variation in the Ca to Mg ratio (Figure 2.12). Stiff diagrams of selected abstractions are shown in Figure 2.13, highlighting these main water types. Such high Mg/Ca ratios are unusual in UK groundwaters and imply that reaction with dolomite, which is at least present in parts of the aquifer (Chisholm and Dean, 1974), has been important. There is a strong contrast, for example, with groundwaters of the Moray Basin, which have very low Mg/Ca ratios (Robins et al, 1989). The high Mg samples are at saturation or close to saturation with respect to dolomite and calcite. Some waters are significantly undersaturated with respect to calcite (Wester Kilgour, Kinnesswood, Scotlandwell) which implies either a relatively short residence time or that the rocks have been decalcified or lack primary carbonate minerals. Sodium and chloride concentrations are relatively low and show a strong correlation. Sodium/chloride ratios are, however, low in comparison to seawater and typical rainfall. Silicon concentrations are relatively constant at between 4 and 6 mg/l, as they are limited by solubility with respect to quartz or chalcedony.

Nitrate concentrations are also variable in the aquifer (Appendix 2). Nitrite and NH_4 are generally at or very close to detection limit. Fluoride concentrations are low, implying that fluorite is not present to a significant degree in the aquifer matrix. Concentrations of minor and trace elements are in general relatively low, reflecting either the alkaline nature of the waters, absence of mineral phases or short residence time. The main exception is Ba, which is high in many waters (a median of 170 µg/l), often exceeding the MAC concentration of 100 µg/l. Lower values are present in waters with high sulphate and Ba concentrations are limited by the solubility control of barite ($BaSO_4$). The circumneutral pH keeps Al concentrations low; additionally, the presence of dissolved oxygen keeps Fe and Mn as well as trace metal concentrations low.

Stable isotopes

Thirteen samples of groundwater from the Fife aquifer were collected during October and November 1998 for analysis of their stable isotopic composition. Both oxygen ($^{18}O/^{16}O$) and hydrogen ($^2H/^1H$) isotope ratios were analysed by mass spectrometry at the BGS laboratories in Wallingford, and the results are presented in Appendix 2, as $\delta^{18}O$ and δ^2H respectively (‰ relative to standard SMOW: Standard Mean Ocean Water).

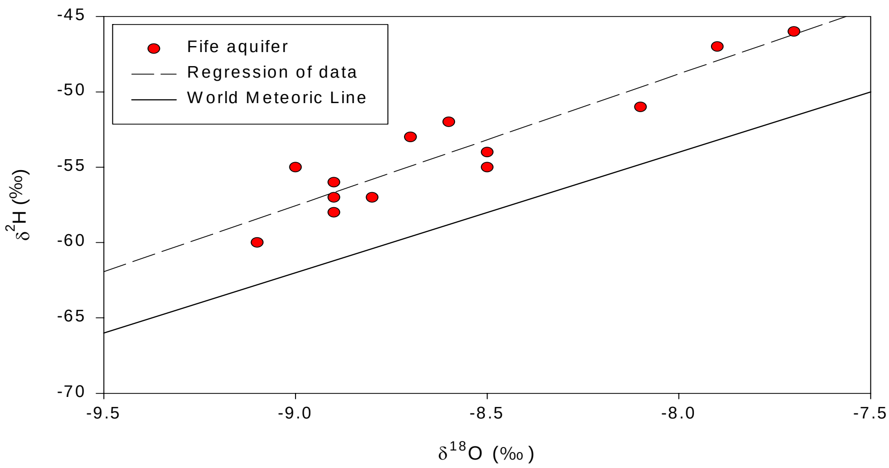

Figure 2.14 Plot of stable isotopes δ^2H and δ^{18}O for Fife groundwaters.

The range of values measured for the Fife groundwaters are typical of UK aquifers Darling et al, 1995; Dennis et al, 1997) and when plotted against each other (Figure 2.14) show a linear correlation such that $\delta^2H = 8.74\ \delta^{18}O + 21.1$ ($R^2 = 0.87$). The data show a slight enrichment of deuterium (^2H) relative to the global meteoric water line (Craig, 1961) and that given by Evans et al. (1978) to represent meteoric water from Maritime Europe. This δ^2H enrichment of approximately +5‰ may be due to fractionation processes operating in the unsaturated zone during recharge.

Previous authors have used the $\delta^{18}O$ value of groundwaters as an indicator of recharge temperature (Andrews, 1993; Darling et al, 1997; Dennis et al, 1997), as water precipitated during colder climates has a more negative $\delta^{18}O$ signature (depleted in ^{18}O). Using the $\delta^{18}O$/temperature variation of Evans et al. (1978) as 0.23‰/°C over the measured $\delta^{18}O$ range (-7.7 to -9.1) yields a recharge temperature range of approximately 6°C. If the correlation of $\delta^{18}O = 0.19 \times T(°C) - 9.7$ for the East Midlands Triassic sandstone aquifer (Andrews, 1993) is used for the Fife aquifer, recharge temperatures which range from 3.2 to 10.5°C can be obtained. Altitudinal variations also cause variations of approximately 0.2 – 0.3 ‰/100m in $\delta^{18}O$ (Darling, pers. com.) which could account for the range in isotopic compositions. It is likely that the lighter signature is an indicator of recharge from the higher ground since none of these waters are likely to represent palaeowaters recharged during former colder climates. This interpretation will only be confirmed by ^{14}C and/or tritium isotopic analysis for the Fife aquifer groundwater. It is interesting that there are isotopic variations in groundwaters from the same locality, such as for Orkie and Kinnesswood. Such differences may provide valuable information on physical parameters including recharge history and flowpaths, but more detailed study is required on the depth variations in groundwater flow and water chemistry.

Depth trends and temporal variations

There are little data to provide direct evidence of depth variations in water chemistry. However, changes in temperature and SEC measured during geophysical logging imply that differences in residence time and water chemistry are likely to occur. In addition, at sites where boreholes are drilled to different depths, significant differences in chemistry occurs between the boreholes. The Orkie No. 1 borehole, at 118 m depth, for example, has lower SEC, Cl and NO_3 but higher K/Na than the No.2 borehole at 70 m depth, which may be a consequence of inputs of shallow polluted water to the aquifer. High nitrate concentrations during initial pumping at some boreholes also indicate a contribution of polluted water from shallow depths. Knowledge of the degree of stratification is important because individual fractures are likely to contribute water of variable quality. Further work (geophysical combined with geochemical) is essential in order to establish if such depth variations exist, both in individual boreholes and the aquifer as a whole.

Temporal trends for the period 1995 to 1998 are shown in Figure 2.15. The temperature of groundwater fluctuates seasonally, with summer temperatures generally being 2-4°C higher than winter (Figure 2.15). Most elements, e.g. Cl (Figure 2.15), show little trend over this period. By contrast, in some boreholes sulphate shows a decrease (Figure 2.15). However, data for most elements are sparse. There is also no apparent long-term trend in nitrate concentrations over the same period (Figure 2.16), but there are significant short-term fluctuations. It is considered likely that these fluctuations are caused at least in part by mixing of waters from different depths as evidenced by the large variations found during pumping as mentioned above. However, when viewed over a longer time scale, trends of increasing nitrate are clear in most boreholes (Figure 2.17). The absolute concentrations and relative rates of increase of nitrate are different for different boreholes. This is the case even for boreholes situated close to each other (such as at Orkie and Kinnesswood) and most likely reflects variable contributions of groundwater from different depth or from individual fractures which have differences in water quality.

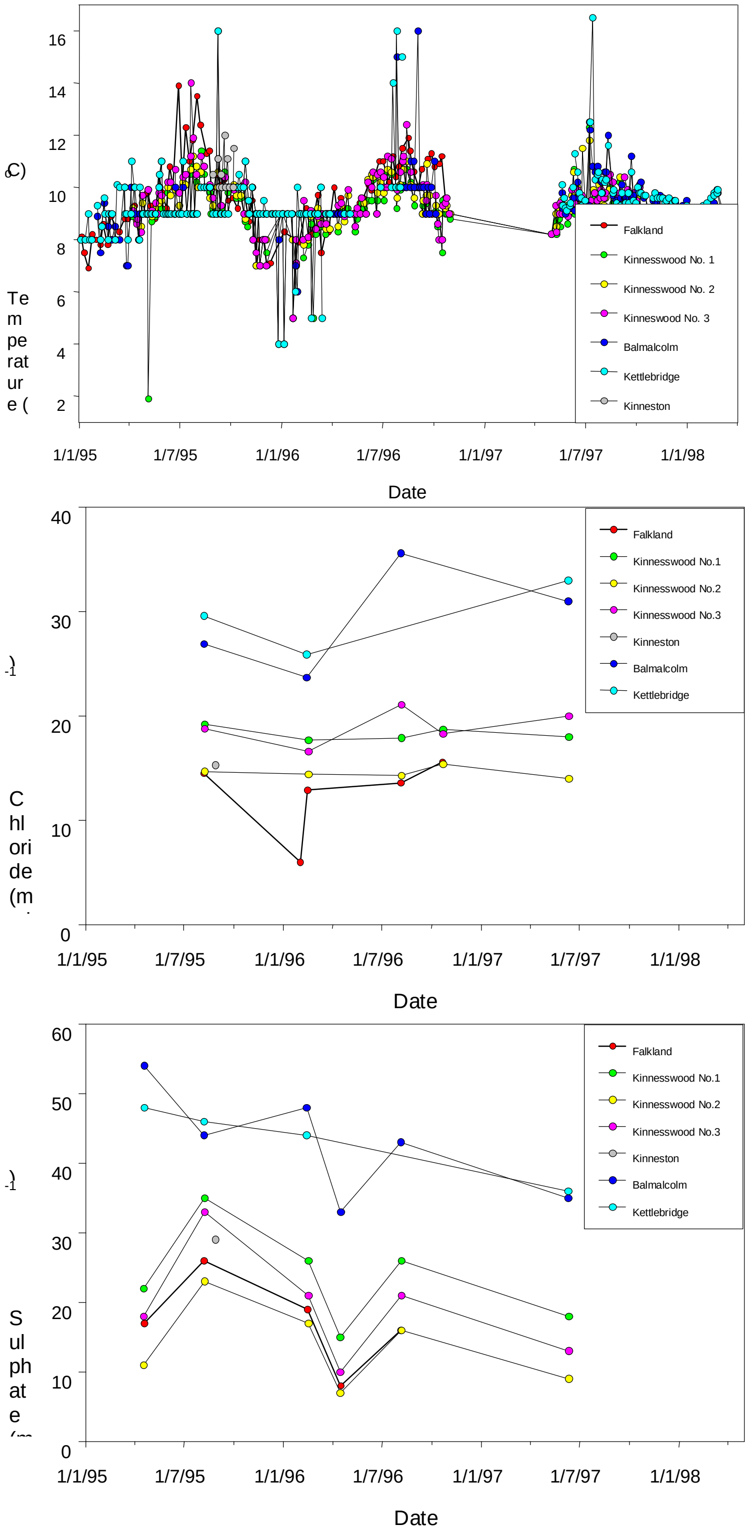

Figure 2.15 **Temporal trends for T (°C), Cl and SO_4 from selected boreholes in the Fife aquifer**

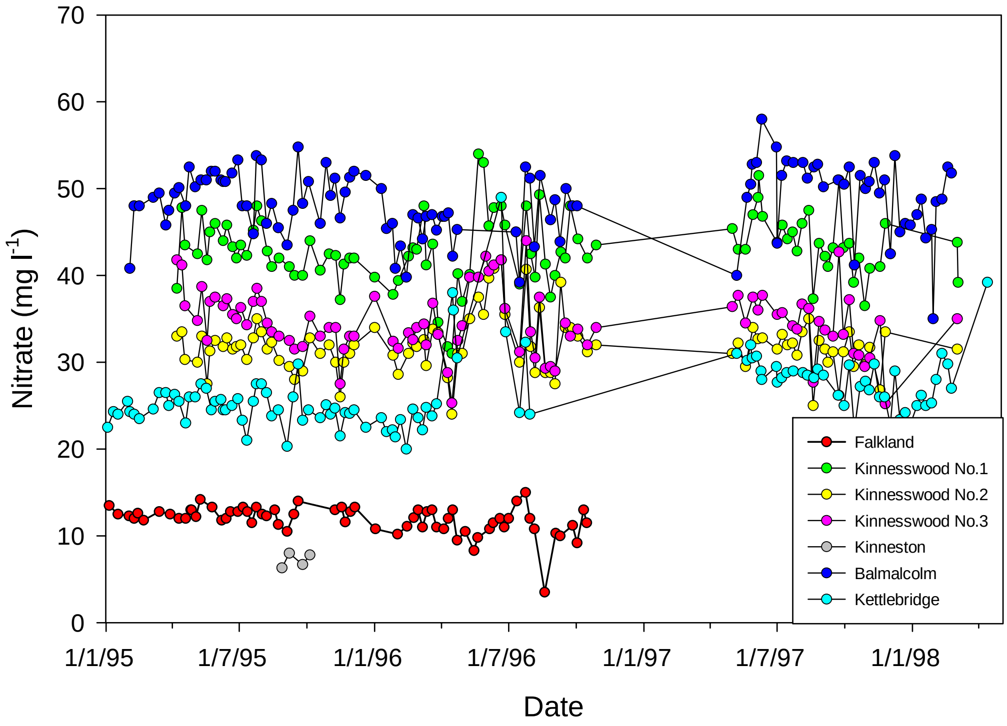

Figure 2.16 Temporal trends for individual analyses of NO_3 over the period 1995 to 1998 in selected boreholes

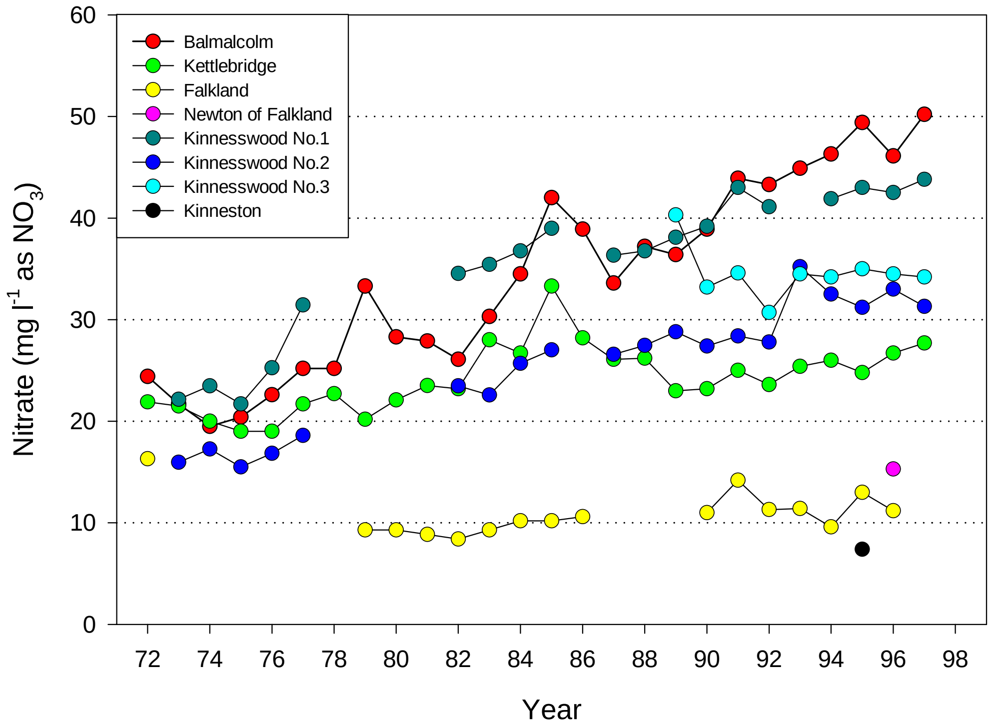

Figure 2.17 Nitrate trends in selected boreholes showing long term trends from 1972 to 1997

Areal variations

Regional variations existing in the Fife aquifer are controlled by a number of factors including bedrock and drift mineralogy, residence time and amount of recharge. Increased residence time provides for increased contact of water with aquifer minerals, with a consequent trend towards an increase in total dissolved solids. This is strongly affected by heterogeneities in mineralogy and facies changes in the aquifer. Minerals have different rates of reaction, with carbonate minerals being the fastest to dissolve and silicate minerals the slowest. Superimposed on this are the effects of anthropogenic inputs which may mask trends due to natural processes, and dilution due to recharge.

The general direction of groundwater flow in the Eden Valley is along the Eden valley from south-west to north-east. There is also a component perpendicular to the valley strike towards the river. For simplicity selected elements have been plotted against easting in Figures 2.18 and 2.19, in order to reveal any chemical changes along the valley. Data from the Leven basin (Kinnesswood, Kinneston, Todd and Duncan and Scotlandwell) are also plotted for comparative purposes. The stable isotopes show a significant variation considering the limited area over which sampling was done. It is likely that the lighter (more negative) signature is an indicator of recharge from higher ground, as well as winter recharge on lower ground as discussed earlier. Field pH and SEC show a general increase eastwards from Wester Kilgour towards Balmalcolm and similar increases are also noted for HCO_3 and SO_4. The increase in TDS is thought to be partly a function of bedrock weathering (higher pH, HCO_3, Sr, Sr/Ca) but may also be a consequence of mixing with shallower, more polluted groundwater. Mg and Mg/Ca ratio show an increase followed by a decrease eastwards and this seems to tie in with outcrop of the Kinnesswood Formation which contains dolomite. Ba is highest in the Leven basin, correlating with an area of lower sulphate. In the Eden valley, where sulphate is higher, the waters are at, or close to, saturation with respect to Ba, and this keeps concentrations low. It is not clear at present whether higher sulphate concentrations in the Eden valley are due to pollution or to reaction with aquifer minerals.

The regional differences in groundwater quality are due, therefore, to a combination of factors of which mineral weathering and agricultural pollution are the dominant controls. There does appear to be a change in the Eden valley eastwards towards a higher TDS, and possible more evolved, groundwater. It should be remembered, however, that the abstracted water is a mixture of waters from different depths (and probably different residence times). Further information is required to assess vertical variations in individual boreholes before more detailed conclusions can be drawn. More information is also necessary to relate water quality to geology and mineralogy, which are poorly constrained.

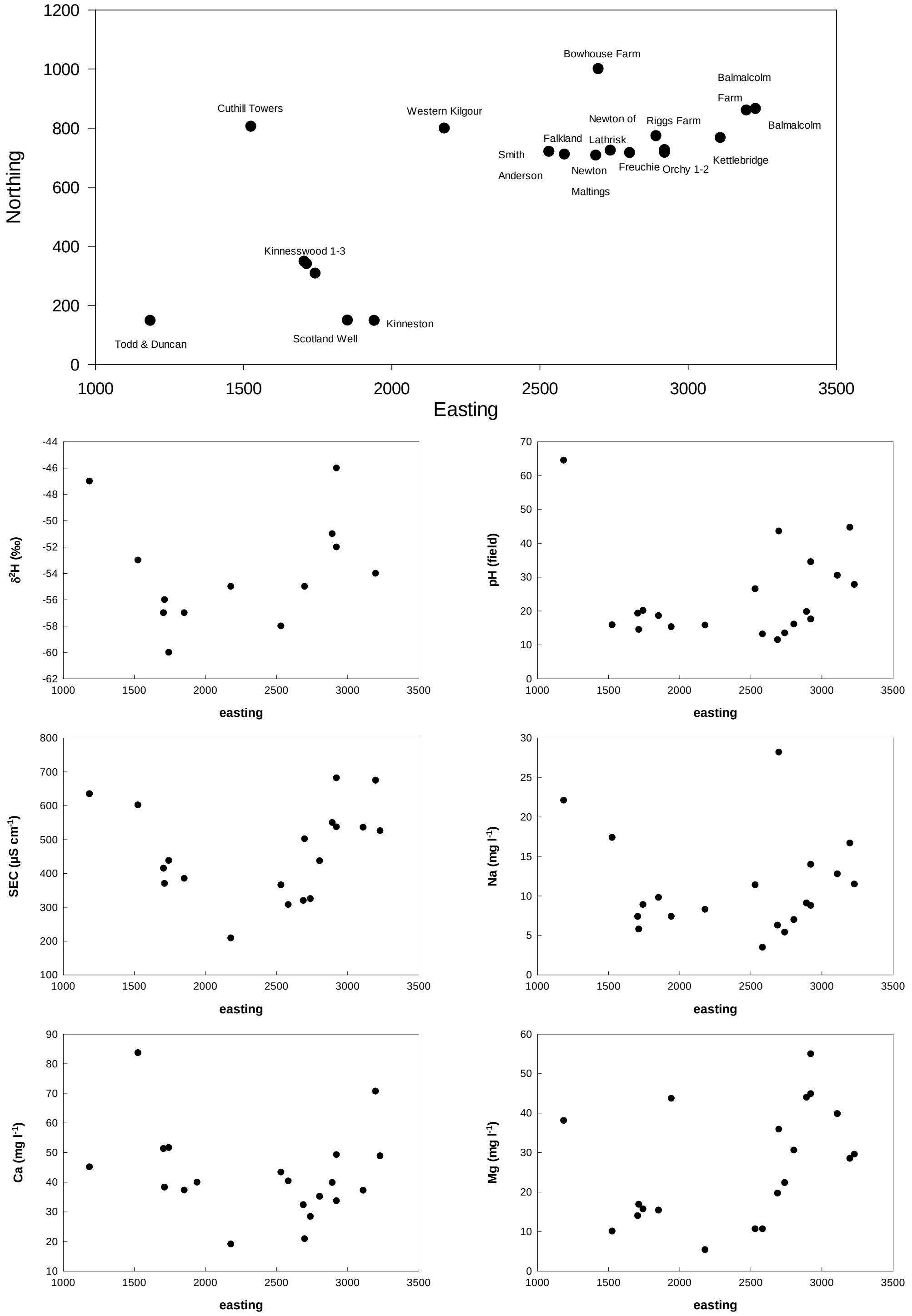

Figure 2.18 Regional variations of selected parameters plotted against easting

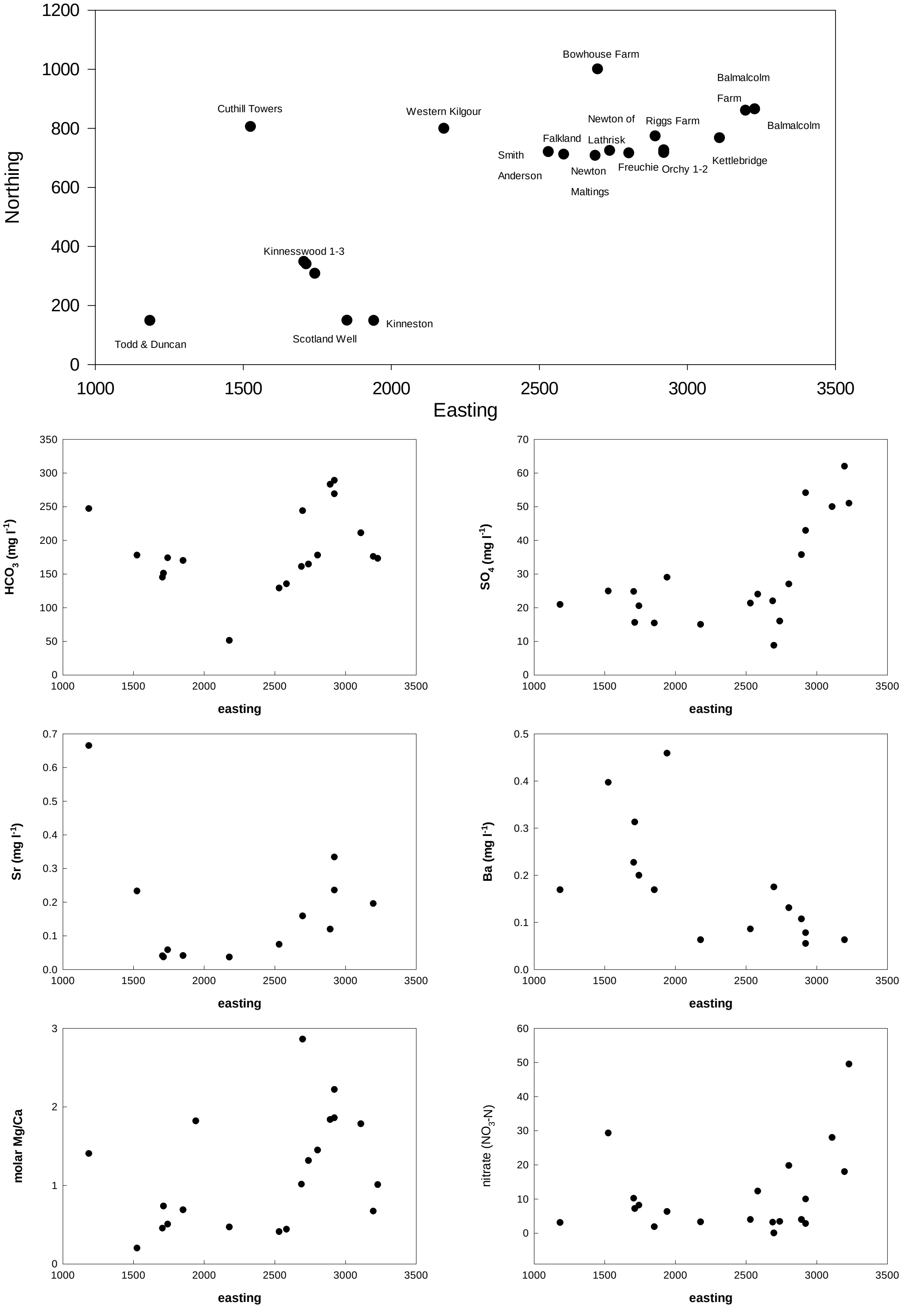

Figure 2.19 Regional variations of selected parameters plotted against easting

2.3 Conceptual Model of the Aquifer System

2.3.1 Introduction

The Knox Pulpit Formation is generally the most productive aquifer unit of the Upper Devonian in Fife. However, the overlying Kinnesswood Formation and underlying Glenvale and Burnside Formations, although showing lower permeability, also yield significant groundwater supplies.

The conceptual model considers the whole of the Upper Devonian sandstone from the Loch Leven basin to Kemback in the north-eastern part of the Eden valley. The Eden valley surface catchment is drained by the river Eden. River flow hydrographs indicate that groundwater makes a significant contribution to flow in the Eden (see Figure 2.20). Groundwater level observations suggest that shallow groundwater flow in the Eden valley is dominantly across the valley towards the river Eden (see Figure 2.4), with groundwater discharge on the lowest lying ground adjacent to the river, and probably to a lesser extent directly through the permeable bed of the Eden itself. The overall hydraulic gradient suggests that there is also a component of groundwater flow down-valley out of the catchment. Chemical analyses of borehole waters suggest that groundwaters at depth may be evolving in this direction.

The surface water regime of the Leven basin is likely to be dominated by Loch Leven, although the detailed hydrology of the basin is not well understood. The water level in the loch is regulated by means of an engineered channel from the south-eastern corner of the loch to the river Leven, and most of the water entering the loch is likely to leave the basin this way. A certain proportion of water from the loch is likely to drain from its north-eastern edge to the river Eden by means of a small ephemeral stream. Although flow through the main outflow channel is monitored, other outflows, and the total surface inflows to the loch, are not, so that it is impossible to establish a proper water balance for Loch Leven. It is also difficult to assess the contribution of groundwater to the loch. A proportion of recharge is likely to discharge to the loch, but local topography and available groundwater level observations suggest that a significant proportion of recharge flows to the Eden valley.

Uncertainties as to the exact nature of groundwater-surface water interactions across the aquifer and the degree of groundwater transfer between the Leven basin and the Eden valley mean that it is difficult to characterise the hydrogeological system in the area. To gain a better understanding of the aquifer a catchment-wide water balance was undertaken. This is a bulk model which does not account for lateral variations within the catchment. It does, however, provide an overall picture of the probable hydrogeological regime.

The water balance considers the Eden valley and the Leven basin. The boundaries of the model in the Eden valley are taken as the Eden surface catchment as monitored at Kemback, an area of 307 km^2. The extent of the Leven basin is more tentative: for the model an area of 190 km^2 is taken, bounded to the north and north-west by the surface water divide of the Leven basin, and to the south-west, south and east by a line outside of which streams drain away from Loch Leven. The outcrop of Upper Devonian aquifer makes up 40% of the Eden valley catchment and just over 50% of the Leven basin.

The data used in the water balance model are described in the next section.

In addition to the conceptual model, numerical models have been devised for parts of the aquifer. An exercise to model the capture zone of the Balmalcolm borehole for a groundwater protection study using FLOWPATH was done by MacDonald (1993). Similar capture zone modelling for the Kinnesswood boreholes using QuickFlow was done by Frost and Sargent (1993). A recent preliminary numerical model developed by the BGS covered a larger area of the central section of the aquifer, including the main abstraction areas around Falkland and Kettlebridge. This model is based generally on the conceptual model of the aquifer described here, and although it uses unsubstantiated boundary conditions it broadly supports the conceptualisation. The results reflect what is currently understood of the prevailing groundwater flow regime, and corroborate the importance of the river Eden. However, as yet the hydrogeology of the Fife aquifer is not understood in enough detail to be able to design numerical models with real confidence. Digital modelling serves to help illustrate and confirm the broad understanding of the aquifer, but more data are needed before any single model can be used to accurately represent the system.

2.3.2 Data

The hydrological data used in the conceptual model are described below. Values for the data are given in Appendix 3.

From the point of view of the water balance the most important meteorological data are rainfall and evapotranspiration. A number of long term (20 to 30 year) rainfall series are available for the central Fife region. Average annual rainfall values for the Fife region generally and for the low-lying Eden valley range between 730 and 795 mm. Much of the Leven basin is at a higher altitude (up to over 450 m AOD), and rainfall is correspondingly higher, at between 910 and 940 mm/a. There are fewer long term evapotranspiration series, either potential or actual, but what data exist are fairly consistent, giving an average annual evapotranspiration across the region generally and in the Eden valley of about 470 mm, and in the Leven basin of about 440 mm. It is difficult to select accurate rainfall and evapotranspiration values even for small catchments such as these, as natural spatial and temporal variations are common and may be significant. Evapotranspiration is particularly difficult to calculate over large areas.

River flow in the Eden is monitored continuously at Kemback and a long-term discharge series is available. The gauging station lies below the confluence of the river Eden and the Ceres Burn. A significant amount of the streamflow passing through the gauging station is therefore likely to originate as baseflow from Carboniferous rocks, and does not recharge the Devonian aquifer. A short extract from this record for the period from January 1996 to September 1998 is shown in Figure 2.20. Historical data from a gauging station at Gateside near the top of the Eden valley is also available. A third gauging station at Pitlesssie gave unreliable data and was abandoned. Flow in the river Leven is monitored near its mouth at the coast, but the volume of water leaving Loch Leven at the sluices is not known.

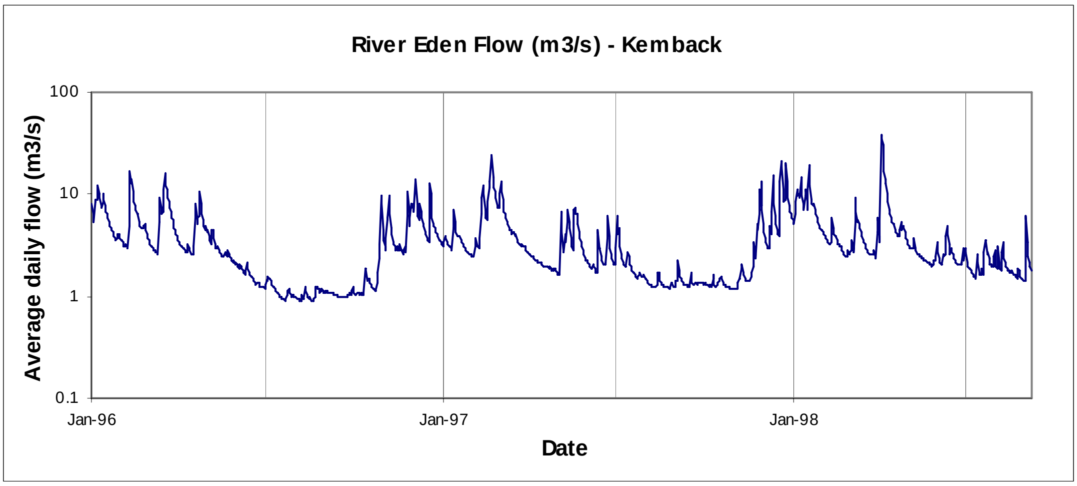

Figure 2.20 Flow in the river Eden at Kemback from January 1996 to September 1998 (data from SEPA).

Effluent discharges from waste water treatment plants and private establishments to the river system in Fife are licensed by SEPA, East Region. The majority of the water is assumed to be imported to the catchment, as the majority of public water supply is obtained from reservoirs outside of the catchment. Nevertheless, the total volume of effluent discharged – a maximum of 670 Ml/a - is almost insignificant in comparison with the total flux of water in the catchment, and is not taken into account in the water balance.

Information on groundwater abstractions is kept by ESWA and the British Geological Survey. Table 2.3 shows current abstraction rates for different purposes, and total abstraction volumes, assuming average pumping regimes.

Table 2.3 Current groundwater abstractions from the Upper Devonian aquifer

Abstraction type	**Normal abstraction rate when pumping (Ml/d)**	**Average volume abstracted (Ml/a)**	**Pumping regime**
Farm/domestic	0.5	204	Pumping all year round
Industrial	5	1734	Pumping all year round
Irrigation	20	2402	Pumping 4 months of the year
Public supply	19	3492	Pumping 6 months of the year
Total	**45**	**10 769**	

Groundwater abstracted for public supply is pumped directly into the main supply network. Returns of any public water supply to the catchment are assumed to be accounted for as effluent discharges. Irrigation in the areas is carried out almost exclusively by spray irrigators. An often-used rule of thumb for spray irrigation suggests that 30% of water supplied to spray irrigators returns to the water table as recharge. Water abstracted for food processing is used for food washing and then discharged via spray irrigators onto grassland. Assuming that none of this water is consumed in the industrial process, the same '30 percent' rule of thumb can be applied to this process.

The volume of groundwater flowing down-gradient through the aquifer can be estimated from the groundwater head distribution using the Darcy's Law. Because measured values of horizontal hydraulic conductivity are not uniform, and particularly because the groundwater head distribution is not accurately known across the whole aquifer, the calculated values vary. Groundwater flow from the Leven basin into the Eden valley is estimated to be between approximately 3 000 and 6 000 Ml/a. Estimates for groundwater flow out of the Eden valley catchment at Kemback in the north-east range from about 200 to 3 500 Ml/a. Both of these ranges of figures are tentative, but it seems likely that the total down-gradient flow through the aquifer is small in comparison with both recharge and discharge to the river Eden and Loch Leven.

Recharge to the Upper Devonian aquifer is fairly complex. Both direct and indirect recharge are thought to be important, with indirect recharge occurring through the beds of losing streams descending from the surrounding hills. Direct natural recharge to the aquifer is determined by three factors: the amount of effective rainfall, the vertical hydraulic conductivity of superficial deposits, which determines the volume of water which can percolate down to the aquifer, and the transmissivity and hydraulic gradient in the aquifer, which determine how much water can move away from the recharge area. The graph in Figure 2.21 illustrates the close correlation between groundwater level rise (caused by recharge at the water table) and effective rainfall, also showing how groundwater level rise closely follows changes in soil moisture deficit.

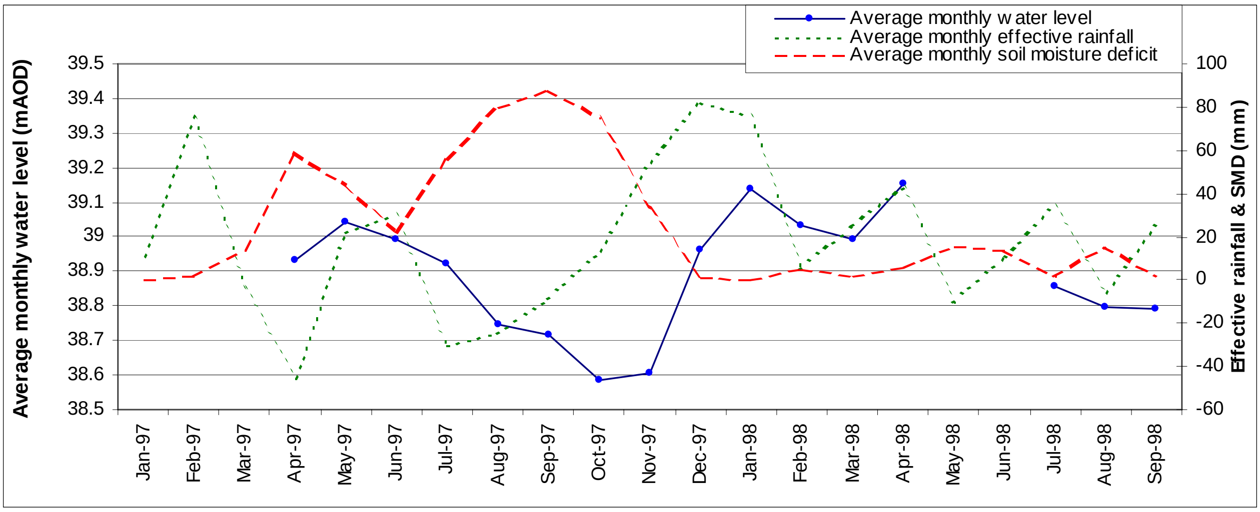

Figure 2.21 Average monthly groundwater level at Knowehead observation borehole plotted with effective rainfall and soil moisture deficit (data from SEPA and MORECS)

There is no unique accepted way of estimating recharge. As part of this exercise three techniques were used to estimate recharge to the aquifer in the Eden valley catchment, and one of these methods to estimate recharge to the aquifer in the Leven basin. The aim was to obtain a reasonably accurate working value for recharge (for details see Appendix 4). Estimates for the Eden valley range between 115 and 145 mm/a, while for the Leven basin the estimated recharge is between 175 and 210 mm/a depending on the variables used. These values represent the lower end of what is generally felt to be a typical range for recharge to aquifers on Britain’s eastern coast. In the water balance figures of 140 mm/a for the Eden valley catchment and 210 mm/a for the Leven basin were used.

2.3.3 Water balance

The water balance developed for the Upper Devonian aquifer is illustrated in the flow diagram in Figure 2.22. Some of the values shown can be checked against external data: particularly rainfall and evapotranspiration (and therefore effective rainfall), groundwater abstraction, flow leaving the catchment in the river Eden, and baseflow to the river Eden. No other values can be verified by observational data.

Total groundwater recharge has been calculated by integrating recharge estimates over the surface areas of the Eden valley and Loch Leven catchments. Recharge can then be divided between groundwater abstraction, baseflow to surface water and groundwater throughflow leaving the Eden valley catchment at Kemback. Baseflow to surface water is further subdivided between Loch Leven and the river Eden. It is important to note that the gauging station at Kemback records baseflow from both the Devonian aquifer and the Carboniferous rocks of the Ceres Burn subcatchment. Only a proportion of the baseflow to the river Eden passes through the Devonian aquifer. Surface water runoff is similarly split between Loch Leven and the river Eden. A small proportion (10%) of the flow to Loch Leven is assumed to leave the loch via an ephemeral stream to flow to the river Eden. The remainder of water in the loch leaves via the engineered sluices to the river Leven. Water in the river Eden flows out of the catchment through the gauging station at Kemback.

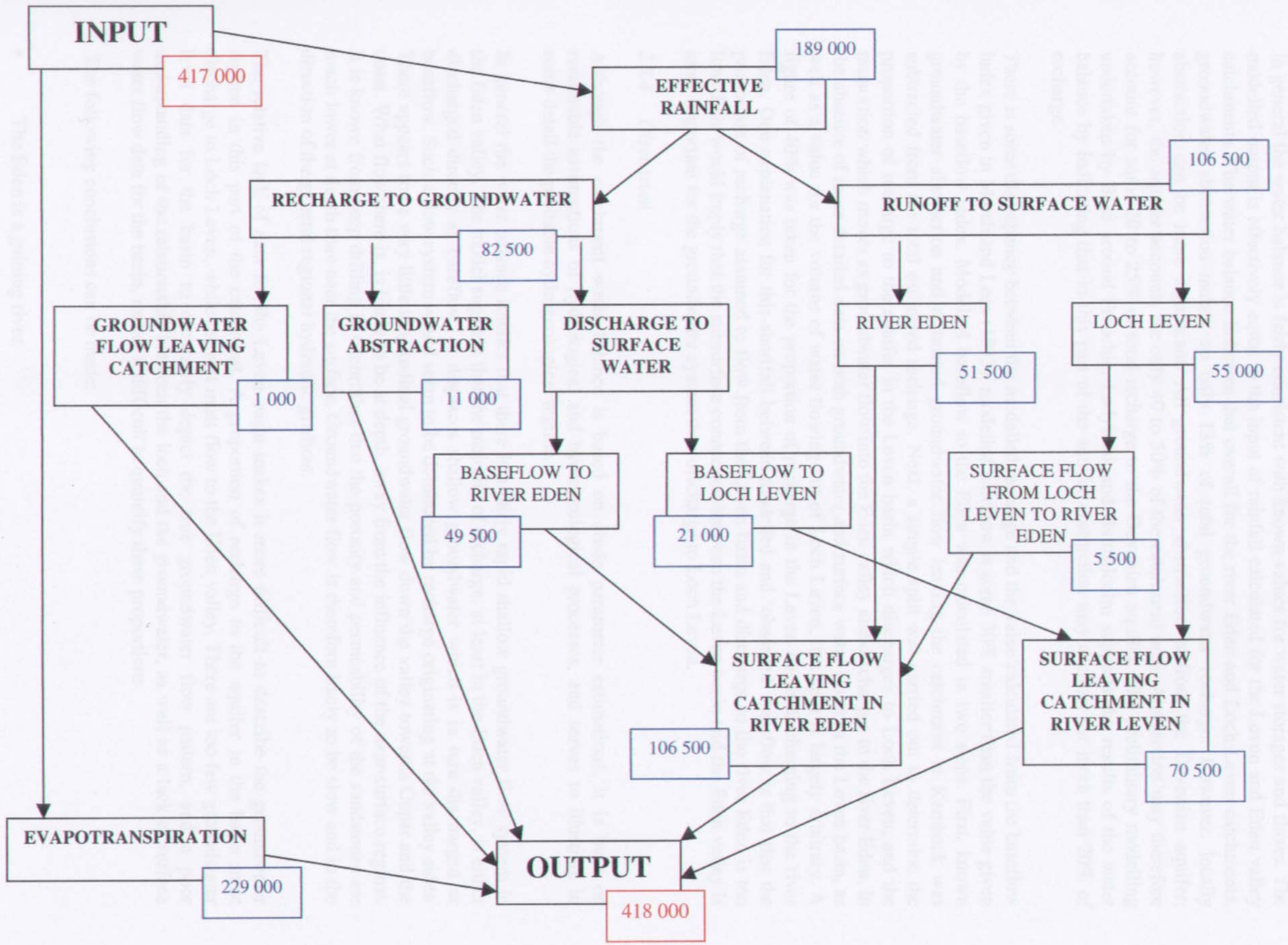

Figure 2.22 Flow chart illustrating the water balance for the River Eden and Loch Leven catchments in Fife. All figures in Ml/a.

In general the water balance is fairly consistent with known values for water storages and fluxes. The modelled output is effectively equal to the input of rainfall calculated for the Leven and Eden valley catchments. The water balance indicates that overall for the river Eden and Loch Leven catchments, groundwater abstraction makes up only 13% of total groundwater recharge. However, locally abstraction can be more significant. All groundwater abstraction is from the Devonian aquifer; however, the aquifer accounts for only 40 to 50% of the catchment area. Abstraction may therefore account for some 20 to 25% of total recharge to the Devonian aquifer. The preliminary modelling undertaken by BGS around Freuchie, Ladybank and Balmalcolm supports the results of the water balance by indicating that in this part of the aquifer abstraction may account for more than 20% of recharge.

There is some discrepancy between the modelled recharge and the value calculated from the baseflow index given in Marsh and Lees (1993): modelled baseflow is some 30% smaller than the value given by the baseflow index. Modelled baseflow to the Eden was calculated in two steps. First, known groundwater abstraction and estimated groundwater flow leaving the catchment at Kemback was subtracted from the total estimated recharge. Next, a simple split was carried out to determine the proportion of recharge to the aquifer in the Leven basin which discharges to Loch Leven, and the proportion which moves as groundwater flow into the Eden valley and discharges to the river Eden. In the absence of more detailed data on both groundwater and surface water flows in the Leven basin, as well as a value for the volume of water flowing out of Loch Leven, this split is largely arbitrary. A figure of 40% was taken for the proportion of recharge in the Leven basin discharging to the river Eden. One explanation for this shortfall between modelled and ‘observed’ baseflow is that that the proportion of recharge assumed to flow from the Leven basin and discharge to the river Eden is too low. This would imply that the subsurface connection between the Leven basin and the Eden valley is more important for the groundwater system than discharge to Loch Leven.

2.3.4 Discussion

Although the catchment water balance is based on crude parameter estimations, it is built on reasonable assumptions of hydrological and hydrogeological processes, and serves to illustrate in some detail the probable hydrogeological regime.

In general the water balance implies that there is a fairly rapid shallow groundwater flow system in the Eden valley. The model suggests that the majority of recharge, at least in the Eden valley, is either discharged directly as baseflow, or displaces shallow groundwater which is in turn discharged as baseflow. Such a flow system would seem to be dominated by recharge originating at the valley sides. There appears to be very little longitudinal groundwater flow down the valley towards Cupar and the coast. What flow there is, is likely to be at depth, away from the influence of the near-surface regime. It is known from deep drilling in Glenrothes that the porosity and permeability of the sandstones are much lower at depth than near the surface. Groundwater flow is therefore likely to be slow and in the direction of the general regional hydraulic gradient.

The relative lack of data for the Leven basin makes it more difficult to describe the groundwater regime in this part of the catchment. A proportion of recharge to the aquifer in the basin must discharge to Loch Leven, while the rest must flow to the Eden valley. There are too few groundwater level data for the basin to accurately depict the true groundwater flow pattern, and a poor understanding of the relationship between the loch and the groundwater, as well as a lack of surface water flow data for the basin, makes it difficult to quantify these proportions.

The following conclusions can be made:

- The Eden is a gaining river.

- There is little groundwater throughflow out of the catchment.

- The river Eden is the major control on the groundwater regime in the valley, with shallow groundwater flow dominantly from the edges of the valley towards the Eden.

- The deeper groundwater regime may be dominated by slow flow down-valley under the regional hydraulic gradient.

- Loch Leven is likely to exert a significant control on the groundwater regime in the Leven basin, but groundwater flow from the basin to the Eden valley is also likely to be important.

- Current groundwater abstraction accounts for between 10 and 25% of the input to the aquifer.

3. MANAGING THE GROUNDWATER RESOURCE

3.1 Drivers

The Eden valley aquifer is subject to the same legislative controls as elsewhere but it is also the subject of investigation by the water authority, who wish to increase exploitation of the groundwater resource. An additional concern is the existence of local pockets of nitrate-rich groundwater which relate to intensive agriculture in parts of the catchment.

The main legislative forces derive from the Groundwater Directive 80/68/EEC and the Nitrate Directive 91/676/EEC. The most recent enactment is the Groundwater Regulations (1998) which require specific site investigation to be undertaken prior to consent for the disposal of List I and List II substances (e.g. pesticide residues) to the ground. In addition, the proposed Water Framework Directive is demanding that effort be spent on identifying resources and sources to gain an integrated catchment wide understanding of surface and groundwaters.

To this end, there is a need to evaluate the nitrate pollution of the Eden catchment aquifer and to provide safeguards to prevent further pollution of the resource. There is also a need to ensure the sustainable development of the aquifer and to regulate it as necessary with mechanisms such as groundwater abstraction licensing. To achieve both of these objectives a thorough understanding of the hydraulics of the aquifer is necessary as well as the relationship between the groundwater body and surface waters. It is also necessary to understand the processes which are taking place at the surface, particularly with regard to runoff and infiltration, in the unsaturated zone, with regard to pollutant attenuation, and below the water table, in terms of groundwater flow paths and fluxes.

Although groundwater abstraction for public supply has already been considerably developed, increasing demand may lead the Water Authority to explore the possibility of increasing abstraction in the future. This will require knowledge of whether the aquifer can withstand further exploitation and where best to site boreholes for optimum yield and minimal effect on existing abstractions.

3.2 Vulnerability to Pollution

3.2.1 Groundwater vulnerability

The vulnerability of the aquifer to diffuse conservative pollutants is addressed by the 1: 100 000 map Groundwater Vulnerability of Fife and Surrounding Area (SEPA, 1999). The Devonian aquifer is classified geologically as Highly Permeable, and divided up into three soil classes. Areas of High Leaching Potential (where there is little ability to attenuate diffuse source contaminants, allowing the pollutant to move rapidly underground) broadly equate to those areas in which gravel overlies till at the surface. Areas of Intermediate Leaching Potential and Low Leaching Potential (where the downward migration of pollutants is inhibited) are largely those covered by till or alluvial clay. The new map shows most of the aquifer to be vulnerable to surface pollutants. Diffuse pollution by nitrates has affected groundwater quality for many years, and is reflected in steadily increasing nitrate levels in many boreholes.

As well as the characteristics of the superficial cover, intrinsic aquifer vulnerability is due mainly to the effects of the shallow weathered zone. This is a zone of enhanced permeability from the ground surface to 60 or 70 mbgl, which provides the majority of groundwater flow to abstraction boreholes. Relatively rapid movement of groundwater and pollutants occurs in this zone.

3.2.2 Pollution sources

External polluting activities and potential pollutant sources include intensive agriculture, mineral working, landfill and industrial production. These are discussed under separate headings below.

Agriculture

The Eden valley is one of the most intensively farmed parts of Scotland, with large areas devoted to the cultivation of vegetables. Consequently, the use of nitrogen fertilisers has been common for many years. A combination of sandy soils, intermittent clayey cover and a deep weathered zone within a shallow, highly permeable sandstone aquifer, has led to widespread contamination by nitrate. Depth sampling undertaken by ESWA at the Balmalcolm source has shown that a shallow influx of nitrate-rich water occurs which results in very high readings for nitrate for short periods after the pump has been switched on, with a gradual decrease over time as shallow groundwater is flushed out of fissures. Various solutions to the problem of reducing nitrate concentrations in Fife boreholes have been put forward. These include the use of plain casing to greater depths to exclude shallow water, and drilling to 150 m depth or more to access fresher water at depth. Both of these measures may result on lower nitrate readings, but it is likely that borehole yields will be greatly reduced by sealing off the upper weathered zone.

The difference in nitrate concentrations between the Balmalcolm and Kettlebridge boreholes may partly be explained by the nature of the surface cover. At Kettlebridge, with nitrate concentrations commonly around 25 mg/l, several layers of clay up to 1.6 m in thickness form part of a 7.5 m thick mixed superficial cover. At Balmalcolm, where the nitrate level is almost 50 mg/l, 6.5 m thickness of sand and fine gravel occurs between ground surface and rockhead, allowing local infiltration of nitrate-rich water from surrounding fields. Insufficient cement sealing around surface casing may also be a contributory factor to the ingress of local surface water. The difference in water quality may also be due partly to the greater depth of the Kettlebridge source, at 123 m compared to 75 m at Balmalcolm. A final answer to the Balmalcolm nitrate problem may only come from a detailed investigation of the borehole using geophysics, which would determine flow ingress levels and the soundness of the surface casing. In the meantime, the borehole has been reduced to dormant status.

At Kinnesswood, nitrate concentrations in boreholes 1 and 2 differ by almost 20 mg/l, with borehole 1 showing the highest concentration of over 40 mg/l. The boreholes are only 125 m apart, and their catchments areas within arable farmland are very similar. The major difference is that borehole 1 is situated 50 m downslope from Easter Balgedie Farm and contains 12 m depth of surface casing, compared to 50 m in borehole 2. The greater depth of casing in borehole 2 may be the main reason for the higher water quality.

Mineral working

There are a number of shallow sand and gravel quarries in the Ladybank area. In most cases, gravel has been worked to the level of the water table or to the upper surface of the underlying till. However, in the north of the area, wet working has occurred, resulting in the formation of Birnie Loch, a nature reserve to the south of Collessie. Due to the extremely variable level of the till surface, other gravel workings have extracted aggregate from below the water table to the east of Birnie Loch.

The removal of superficial cover and the exposure of the water table may have led to increased vulnerability of the Devonian aquifer in the Ladybank area. Any future abstraction boreholes that are located in the vicinity could, through a reduction in the hydraulic head around the borehole, cause leakage of groundwater from the upper gravel layers, possibly leading to the introduction of poorer quality water to the main aquifer.

Landfill Sites and Industrial Pollution.

There are two landfill sites in the Ladybank area, both sited on former sand and gravel quarries. The council-owned site at Melville Wood (NO 300 117) is an active landfill, but is over 4 km north from the nearest public supply source and to the north of the River Eden. A completed site at Ladybank (NO 310 100), only 1.5 km north of the Balmalcolm borehole and 2 km from Kettlebridge, is again to the north of the River Eden and apparently poses no threat to existing boreholes, but limits further development near the village.

A disused gas works at Orkie (NO 302 073) was found to have leaked waste liquors, including phenols, into the Devonian aquifer (Parker and Mather, 1976). Subsequent trial drilling for new public water supplies led to the discovery of contaminated groundwater in the vicinity of the site and detailed investigations found phenol and cyanide 400 m down the hydraulic gradient. The presence of the gas works led to the abandonment of the Orkie area for groundwater development and attention switched to the Falkland-Freuchie area. Phenols had not, however, been detected at the nearby Kettlebridge source.

3.3 Abstraction Licensing

Groundwater abstraction licensing is a valuable tool for restricting the exploitation of an aquifer to its sustainable or likely renewable yield. The Eden valley aquifer is clearly not overdrawn at the moment as the total abstraction is only a small proportion of the likely groundwater throughput. However, local areas of over development may occur. In the most highly productive part of the aquifer between Falkland and Freuchie a total of twelve abstraction boreholes exist within an area of 5 km^2. Of these, three irrigation sources are very new and two public supply boreholes will only be brought into production in 1999, so that there has not yet been a situation when all the boreholes are pumping at once. The water balance clearly shows that groundwater is abstracted at the cost of baseflow to the river Eden. Large groundwater abstractions close to the Eden may lead to local reversals of the groundwater regimes, with boreholes drawing water from the river. This may have consequences for water quality, as the surface waters entering the aquifer may be both NO_3-rich and carrying discharges from sewage treatment works. Monitoring of local groundwater and river levels during the next dry summer will be critical to assess whether over abstraction problems develop.

Although no other area of the aquifer has such a concentration of abstraction sources, it is highly likely that new sources will be developed, particularly where there is already a proven resource, such as at Kinnesswood. Uncontrolled pumping in a group of four farm irrigation boreholes in the north-east of the aquifer near Cupar has already led to high drawdowns, resulting in temporary dewatering of abstraction boreholes. Care is needed in siting new boreholes so that they do not create local areas of excessive drawdown of the water table. A more extensive network of monitoring sites is required in order to adequately assess new applications for boreholes in the Upper Devonian aquifer.

3.4 Groundwater Monitoring

3.4.1 Water level monitoring

The monitoring boreholes currently operated by SEPA are detailed in section 2.2.1. Continuous water level measurement equipment have also been installed by ESWA in all public supply boreholes to monitor both pumping and rest water levels, and these data will be archived. However, without the drilling of new observation boreholes there is little opportunity to expand this network. Existing boreholes that could be resurrected include the old trial borehole at Mawcarse and the disused abstraction source at Pitlessie Maltings. At present, the three monitoring sites near Freuchie are all affected by pumping, either for public supply or irrigation, and will be essential in monitoring the effects of abstraction. However, because there are few existing boreholes which are unaffected by local pumping, obtaining hydrographs which reflect natural groundwater variations will be difficult.

3.4.2 Water quality monitoring

Regular detailed monitoring of water quality currently takes place only at the operational public water supply sources. There is scope for expanding this network to include industrial sites where abstraction takes place throughout the year. Such sites are at Orkie Farm (NO 2910 0730), Balmalcolm Farm

(NO 3190 0865) and the private supply at Bowhouse Farm (NO 2685 1000). The Todd and Duncan factory at Kinross is another potential site. Prior arrangements to visit these boreholes regularly at six monthly or annual intervals would be required.

The sampling of summertime irrigation sites is more problematical, but essential for further work to investigate nitrate distribution in the aquifer. Added factors of sample timing complicate the monitoring process, as water quality can vary according to the length of the pumping period prior to taking the sample. It is recommended that a thorough sweep of all farm irrigation sources is carried out every five years in order to assess nitrate and phosphate contamination of the aquifer.

3.5 Source Protection Zones

The establishment of protection zones around operational public supply boreholes can be regarded as an essential part of any future aquifer management process. Source protection zones vary in size and shape according to the nature of the aquifer, rainfall, land use and amount of water pumped from the source. For each source three zones have been defined: an inner protection zone, an outer protection zone and the total catchment area (Downing 1998). The Inner Zone (Zone I) is defined by the distance a particle of water travels through the saturated zone in 50 days, based on the premise that any bacteria in the saturated zone will die within 50 days. Additionally, a minimum distance of 50 metres from the source is stipulated for this zone. The Outer Zone (Zone II) is defined as the 400 day travel time or 25% of the total catchment area, whichever is the larger. This represents the minimum time required for the dilution and attenuation of pollutants that degrade slowly. The total catchment area (Zone III) is the entire area from which the groundwater source derives its supply. The 50 and 400 day travel times are based on mean velocities of groundwater flow through intergranular aquifers. Where fractures are present, flows may be locally faster than the assumed average rate. However, the criteria as a whole are conservative, in that they relate only to flow through the saturated zone and do not account for the purifying action of the unsaturated zone. For each of the three zones a best estimate zone, a zone of confidence and a zone of uncertainty are defined.

The zones should be viewed as dynamic, as their size and shape may change with time and changing conditions, and represent areas where groundwater abstractions are at greatest risk of deterioration from development. They would not be seen as a restriction to existing land use activities, but should be viewed as a formal indicator to the planning authorities that another level of consultation and investigation would be necessary before any developments within either Zone 1 or Zone 2 could take place.

Future zones could be established for the industrial sites at Kettle Produce (Balmalcolm and Orkie Farms) where the water is used for vegetable washing. However, a lower priority could be assigned to the Todd and Duncan site and to Smith Anderson at Falkland, where usage is mainly for factory processing and washing.

3.6 Conclusions

All of the above issues need to be considered to ensure both the quantity and quality of the groundwater resource. Other questions include the derogation of wetlands and other habitats, modification of land use and external influences such as climate change. Aquifer management of these problems will be aided by the greater understanding of the hydraulics of the aquifer and may be tested once a digital model of the aquifer has been developed.

4. RECOMMENDATIONS

The conceptualisation and catchment-wide water balance for the aquifer have highlighted a number of areas for which data are lacking. These include:

- catchment specific data on effective rainfall;
- streamflow data for the river Eden upstream of Kemback, to give more specific information on river interactions with the Devonian aquifer;
- streamflow data for the Loch Leven basin;
- a wider groundwater level monitoring network to provide long term borehole hydrograph data;
- more regular water quality monitoring of private abstraction sources;
- recharge estimates for the sandstone aquifer beneath different classes of Quaternary cover and via runoff from the less permeable formations to the north and south;
- the location of the effective southern boundary of the aquifer where the Upper Devonian sandstones dip beneath Carboniferous strata;
- the effective depth of the aquifer, and the nature of any change in aquifer properties and groundwater flows with depth;
- the degree of vertical chemical stratification in individual boreholes and the aquifer as a whole.

Recommendations for future work must address data collection in all of these areas. Only then can sensible numerical modelling of the aquifer as a unit be attempted, using historical meteorological, streamflow and hydrograph data as validation. Achievement of such a model will allow a more accurate picture of the catchment water balance. In addition it will provide a powerful management tool to allow the rational licensing of groundwater abstractions, and assist in determining optimum locations for new abstraction development. It will also allow 'what if' scenarios to be run, which could help to assess the impact of proposed pumping regimes on factors such as river flows, groundwater levels or existing borehole supplies. Such a model could also be used to test the effects of potential climate changes on the hydrogeology of the catchment.

Tasks which need to be carried out in the catchment include the following:

(i) Expand groundwater level and groundwater quality monitoring within the aquifer. Monitoring should include quarterly sampling and continuous trace water level data at not less than 20 sites. This should include as a priority ESWA’s public supply boreholes, and may also require purpose drilled observation boreholes in some areas of the catchment.

(ii) Introduce records of abstraction volumes by installing meters on all abstraction boreholes, including irrigation and other private boreholes.

(iii) Introduce more detailed catchment instrumentation to provide essential basic data over a minimum two year period. This should include stream flow gauging of Eden tributaries and both inflows to and outflows from Loch Leven, meteorological stations and soil moisture profiling.

(iv) Use geophysical logging and groundwater chemistry profiles to investigate anisotropy and preferential flow horizons. Again, this may require purpose drilled boreholes.

(v) Carry out improved Quaternary mapping to investigate the role of till as an inhibitor to recharge.

(vi) Carry out surface geophysical study to help delineate catchment boundaries, particularly along the southern edge of the aquifer.

(vii) Carry out a comprehensive analysis of all available hydrochemical data as a tool to aid the understanding of groundwater hydraulics.

Further tasks may become apparent in the future, such as the delineation of source protection zones around public supply boreholes, or the instigation of abstraction licenses. Data collection as described above should eventually provide a basis on which to prepare a digital model.

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APPENDIX 1

Boreholes in the Fife Aquifer for which the Results of Laboratory Tests for Aquifer Properties are Available

Table A1.1 Boreholes for which the results of laboratory tests for aquifer properties are available, giving location and aquifer unit

Borehole	Location (NGR)	Aquifer unit	Depth range sampled (m)
Balreavie No. 3	NO 2690 0664	Knox Pulpit Formation	50 – 69
Falkland	NO 2556 0717	Knox Pulpit Formation	6 – 74
Glenrothes	NO 2562 0314	Knox Pulpit Formation	452 – 567
Kettlebridge	NO 3112 0771	Knox Pulpit Formation	7 – 44
Kingskettle No. 1	NO 3021 0728	Knox Pulpit Formation	15 – 31
Kingskettle No. 2	NO 3046 0757	Knox Pulpit Formation	10 – 34
Knowehead	NO 2784 0696	Kinnesswood Formation	5 – 79
Middleton	NO		11 – 74
Newton of Falkland	NO 2660 0744	Knox Pulpit Formation	10 – 60
Newton Maltings	NO 2690 0711	Knox Pulpit Formation	5 – 27

APPENDIX 2

Hydrochemical Data for Fife Groundwaters

LOCALITY	GEOLOGY	EAST-ING	NORT-HING	Depth	T	pH	DO	d^{2}H	d^{18}O	SEC	Na	K	Ca	Mg
					(°C)		(mg l^{-1})	(l)	(l)	(µS cm^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})
Balmalcolm Farm		3196	861	60	10.4	7.59	6.5	-54	-8.5	675	16.7	5.5	70.7	28.5
Orkie No. 1		2920	727	118	10.8	7.51	0.8	-46	-7.7	537	8.8	2.8	33.7	44.9
Todd & Duncan No. 2		1184	149	107	9.5	7.7	6.7	-47	-7.9	635	22.1	4	45.2	38.1
Wester Kilgour		2177	800	76	11	6.66	8.3	-55	-8.5	209	8.3	1.6	19.1	5.39
Orkie No. 2		2920	718	70	9.7	7.45	4.2	-52	-8.6	682	14	3.3	49.3	55
Kinnesswood No. 3	Glen Burn Member	1741	309	120	9.6	6.97	7.6	-60	-9.1	438	8.9	2.3	51.7	15.7
Kinnesswood No. 2	Glen Burn Member	1712	341	122	9.4	6.91	7.6	-56	-8.9	370	5.8	1.7	38.3	16.9
Kinnesswood No. 1	Glen Burn Member	1704	349	122	8.8	6.93	7.8	-57	-8.9	415	7.4	2	51.3	14
Scotlandwell		1850	150		8.7	6.9	7.9	-57	-8.8	385	9.8	1.3	37.3	15.4
Riggs Farm		2891	774	34	16.4	7.07	5.3	-51	-8.1	550	9.1	2.2	39.9	44
Bowhouse Farm		2696	1001	40	13.6		1.1	-55	-9	502	28.2	3.1	20.9	35.9
Cuthill Towers		1524	806	65	7.5	6.75		-53	-8.7	602	17.4	6.7	83.7	10.1
Smith Anderson		2530	721	77	8.4	7		-58	-8.9	366	11.4	2.1	43.4	10.7
Kettlebridge 15/8/94	Knox Pulpit Formation	3108	768	123		7.9				536	12.8	1.9	37.24	39.84
Balmalcolm 15/8/94		3227	866	75		7.7				526	11.5	1.5	48.9	29.6
Falkland 17/8/94	Knox Pulpit Formation	2582	712	92		7.7				308	3.5	1.4	40.4	10.7
Kinnesswood No 1 15/8/94	Glen Burn Member					7.6				387	3.6	1.7	50.5	12.4
Kinnesswood No 2 13/9/94	Glen Burn Member					7.8				340	2.4	1.5	39.2	17
Kinnesswood No 3 15/8/94	Glen Burn Member					7.6				401	5.2	2	51.3	17.2
Freuchie Knowehead 29/5/98	Kinnesswood Formation	2802	717	90		8.1				437	7	1.7	35.2	30.6
Newton Maltings 21/1/80	Knox Pulpit Formation	2688	708	90		8				320	6.3	2.3	32.4	19.7
Newton of Lathrisk 28/2/80		2737	725	90		8.2				325	5.4	1.7	28.4	22.4
Kinneston 28/8/95	Glenvale Formation	1940	149	91		8					7.4	1.9	40	43.7

A2.1 Hydrochemical data for Fife groundwaters

LOCALITY	HCO_3	SO_4	Cl	NO_3-N	NH_4-N	NO_2-N	Si	Sr	Ba	Li	B	Fe total	Mn	Cu	Zn	Al	As	F
	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$	$(mg\ l^{-1})$
Balmalcolm Farm	176	62	44.7	18	<0.01	0.036	4.1	0.196	0.063	<.003	0.04	0.007	0.005	0.025	0.023	<.04		0.07
Orkie No. 1	269	42.9	17.6	2.8	<0.01	-0.004	4.19	0.236	0.055	0.005	0.03	0.011	0.007	<.008	0.01	<.04		0.07
Todd & Duncan No. 2	247	20.9	64.5	3.1	<0.01	0.004	3.96	0.665	0.169	0.007	0.03	<.006	0.001	<.008	0.01	<.04		0.08
Wester Kilgour	51.2	15	15.8	3.3	0.02	0.004	5.11	0.0367	0.063	<.003	<.01	<.006	<.001	<.008	<.008	<.04		0.08
Orkie No. 2	289	54.1	34.5	10	<0.01	0.004	5.46	0.334	0.078	0.004	0.04	<.006	0.005	<.008	0.032	<.04		0.06
Kinnesswood No. 3	174	20.5	20.1	8.2	<0.01	-0.004	4.06	0.0585	0.2	<.003	0.01	<.006	<.001	<.008	<.008	<.04		0.06
Kinnesswood No. 2	151	15.6	14.5	7.2	<0.01	-0.004	4	0.0373	0.313	<.003	<.01	<.006	<.001	<.008	0.009	<.04		0.09
Kinnesswood No. 1	145	24.8	19.3	10.2	<0.01	0.007	4.22	0.0406	0.227	<.003	<.01	<.006	<.001	<.008	0.008	<.04		0.07
Scotlandwell	170	15.4	18.6	1.9	<0.01	-0.004	3.83	0.0413	0.169	<.003	0.01	<.006	<.001	<.008	<.008	<.04		0.06
Riggs Farm	283	35.7	19.8	4	0.01	-0.004	4.9	0.12	0.107	<.003	0.02	0.007	<.001	0.029	0.253	<.04		0.06
Bowhouse Farm	244	8.8	43.6	0.037	0.09	-0.004	3.83	0.159	0.175	0.005	0.02	0.021	0.006	<.008	<.008	<.04		0.09
Cuthill Towers	178	24.9	15.9	29.3	<0.01		5.75	0.233	0.397	0.004	0.08	0.006	0.004	0.064	0.028	<.04		0.08
Smith Anderson	129	21.3	26.5	4	<0.01		6.16	0.0746	0.086	<.003	0.03	0.02	<.001	<.008	<.008	<.04		0.08
Kettlebridge 15/8/94	210.92	50	30.5	28	-0.01							-0.01	-0.01	-0.01	-0.01	-0.005		-0.03
Balmalcolm 15/8/94	173.1	51	27.8	49.5	-0.01							-0.01	-0.01	-0.01	-0.01	-0.005		-0.03
Falkland 17/8/94	135.3	24	13.2	12.3	-0.01							-0.01	-0.01	-0.01	-0.01	-0.005		-0.03
Kinnesswood No 1 15/8/94	134.1	34	17.1	43	-0.01							-0.01	-0.01	-0.01	-0.01	-0.005		-0.03
Kinnesswood No 2 13/9/94	142.6	26	16.5	31.9	-0.01							-0.01	-0.01	-0.01	-0.01	-0.005		-0.03
Kinnesswood No 3 15/8/94	153.6	30	18.2	37	-0.01							-0.01	-0.01	-0.01	-0.01	-0.005		-0.03
Freuchie Knowehead 29/5/98	178	27	16.1	19.8	-0.01				0.131		-0.017	0.011	-0.01	0.01	0.01		0.003	-0.03
Newton Maltings 21/1/80	160.9	22	11.5	3.2	-0.005		1.21					0.03	-0.01	-0.01	0.01	-0.05		
Newton of Lathrisk 28/2/80	164.6	16	13.5	3.4								0.03	-0.01	0.01	0.01			
Kinneston 28/8/95		29	15.3	6.3	-0.01				0.459			0.011	-0.01	-0.01	-0.01			

A2.2 Hydrochemical data for Fife groundwaters

LOCALITY	Br	I	P_TO	BE	SC	Y	CO	La	V	Cd	Zr	Cr	Ni	Mo	Pb
	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})	(mg l^{-1})
Balmalcolm Farm	0.49	0.0038	<.2			0.001	<.008	0.015	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Orkie No. 1	0.074	0.0055	<.2			0.001	<.008	0.008	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Todd & Duncan No. 2	0.163	0.0067	<.2			<.001	<.008	0.009	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Wester Kilgour	0.06	0.002	0.2			<.001	<.008	<.008	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Orkie No. 2	0.143	0.0169	<.2			<.001	<.008	0.011	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Kinnesswood No. 3	0.025	0.002	<.2			<.001	<.008	0.011	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Kinnesswood No. 2	0.047	0.0017	<.2			<.001	<.008	0.008	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Kinnesswood No. 1	0.04	0.0019	<.2			<.001	<.008	0.01	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Scotlandwell	0.05	0.0024	<.2			<.001	<.008	<.008	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Riggs Farm	0.07	0.003	<.2			<.001	<.008	<.008	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Bowhouse Farm	0.42	0.007	<.2			<.001	<.008	<.008	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Cuthill Towers	0.077	0.0035	<.2			<.001	<.008	<.008	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Smith Anderson	0.065	0.0017	<.2			<.001	<.008	<.008	<.006	<.01	<.006	<.02	<.02	<.04	<.06
Kettlebridge 15/8/94			-0.003												-0.005
Balmalcolm 15/8/94			-0.003												-0.005
Falkland 17/8/94			0.036												-0.005
Kinnesswood No 1 15/8/94			0.095												-0.005
Kinnesswood No 2 13/9/94															-0.005
Kinnesswood No 3 15/8/94			0.056												-0.005
Freuchie Knowehead			-0.003							-0.001		-0.002	-0.001		-0.001
Newton Maltings 21/1/80			0.02												-0.02
Newton of Lathrisk															-0.02
Kinneston 28/8/95															-0.005

A2.3 Hydrochemical data for Fife groundwaters

APPENDIX 3

Data Sources

MORECS	Current and long term rainfall, evapotranspiration, soil moisture deficit
SEPA	Effluent discharges River flow (Eden, Leven): daily flows, long term? Groundwater level measurements
IH	River flow (Eden, Leven): monthly means & long term statistics
BGS	Scottish Well Catalogue Scottish Borehole Database (aquifer properties) Some chemistry Munro recorder groundwater level series from 1970s & 80s. Pump test and borehole yield data from 1970s & 80s Abstraction from irrigation, domestic and industrial boreholes
ESWA	Chemical data Abstraction in public supply boreholes

APPENDIX 4

Available Hydrological and Hydrogeological Data for the Fife Aquifer

Table A4.1 Available hydrological and hydrogeological data for the Fife aquifer

Parameter	Volume (Ml/a)	Period over which data were measured	Source of data
Rainfall	417 000	1931-1960; 1961-1990; 1967-1985; 1967-1994	Foster et al (1976), Frost and Sargent (1993); MORECS, Marsh T J and Lees M L (1993) and Marsh T J (1996)
Actual evapotranspiration	229 000	1931-1960; 1961-1990	Average of Foster et al (1976) and MORECS
Effective rainfall	188 000		Calculated as part of water balance (rainfall – actual evapotranspiration)
Flow in the river Eden at Kemback	121 000	1967-1994	Marsh T J (1996)
Baseflow component of river Eden at Kemback (BFI 0.62)	75 000	1967-1985	Marsh T J and Lees M L (1993)
Runoff to river Eden	34 000		Calculated as part of water balance (effective rainfall – recharge)
Runoff to Loch Leven	55 000		Calculated as part of water balance
Recharge in the Eden valley	71 000		Calculated as part of water balance
Recharge in the Leven sub-catchment	12 000		Calculated as part of water balance
Groundwater abstraction	11 000		BGS
Irrigation returns	1 000		Calculated as part of water balance
Groundwater throughflow	1 000		Calculated as part of water balance using Darcy relationship

APPENDIX 5

Techniques for Estimating Recharge

The first technique looks at the difference in groundwater levels at the start and end of the recharge season. It is based on the method used in the annual Hydrological Data Yearbooks to give a statistic termed the annual fluctuation (described in Marsh & Lees 1993), amended to take account of the porosity of the sandstones (i.e. the volume of increased storage in the aquifer). An average value for porosity was taken as 20%.

The second method is based on a soil moisture balance using monthly values of actual evapotranspiration, soil moisture deficit and precipitation from MORECS. This is described fully in Seritella (1996).

The third technique calculates the proportion of effective rainfall which will reach the aquifer through the superficial deposits, given the proportion of the catchment over which the aquifer outcrops, the proportion of aquifer outcrop covered by each type of drift deposit, and the proportion of effective rainfall which will percolate through each drift type.

Method 1 is most suitable when a single recharge peak occurs in each recharge season. When recharge is uneven throughout the year, so that poorly defined or multiple recharge peaks occur, the annual fluctuation is often unrepresentative of recharge estimated by other techniques, and recharge is often overestimated.

Method 2 assumes zero surface runoff to rivers, which although obviously incorrect, provides a first approximation for an aquifer with a shallow water table and either a generally highly permeable or no cover. It is further assumed that there are no further losses to the soil or atmosphere and that all excess rainfall becomes recharge. The method also averages values for rainfall and actual evapotranspiration over the total catchment area, of which only about half is actually underlain by aquifer. It is assumed that infiltration to the non-aquifer rocks in the catchment is minimal, so that most of the effective rainfall falling on these rocks runs off at the surface towards the river Eden or as shallow interflow to the aquifer.

Method 3 accounts for the proportion of the catchments over which the aquifer outcrops, allowing for a more realistic calculation of probable recharge to the aquifer.

The estimates given by each method for the year beginning October 1997 and ending September 1998 are shown in Table A5.1.

Table A5.1 Recharge estimates for the Fife aquifer by the different methods described above

Catchment	Method	Recharge estimate (mm/a)
Eden valley	1 (annual fluctuation)	115
	2 (soil moisture balance)	115
	3 (estimating infiltration through cover)	140
Leven basin	3 (estimating infiltration through cover)	210