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The Physical properties of the Upper Devonian/Lower Carboniferous aquifer in Fife

Groundwater Systems and Water Quality Programme

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The Physical properties of the Upper Devonian/Lower Carboniferous aquifer in Fife

B É Ó Dochartaigh

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Executive Summary

The Upper Devonian/Lower Carboniferous sandstone system in Fife is one of Scotland's most productive aquifers. Groundwater abstracted from the aquifer is used for public water supply, agriculture, and industry. This report describes the available data on the physical hydraulic properties of the aquifer and the analysis undertaken on the data, and provides an overview the magnitude and variability of these aquifer properties.

The most productive units within the aquifer system, with the highest porosity, matrix hydraulic conductivity and specific capacity, are the Knox Pulpit and the Kinnesswood formations. Matrix porosity and hydraulic conductivity are decline with depth. Even where matrix porosity and hydraulic conductivity are highest, fracture flow is dominant, constituting at least 70% of total transmissivity in all the aquifer units.

1 Introduction

1.1 PROJECT DESCRIPTION AND SCOPE

This report documents the aquifer properties of the Upper Devonian/Lower Carboniferous sandstone aquifer in Fife, eastern Scotland. The work is the output from a pilot project to prepare an aquifer properties catalogue for a single Scottish aquifer, which could stand as a model for a future catalogue of aquifer properties for larger parts of Scotland.

The specific objective of this report is to provide a source of information on the magnitude and variability of basic physical hydraulic parameters for the Upper Devonian/Lower Carboniferous sandstone aquifer in Fife, in a format that could be expanded to include other Scottish aquifers.

The approach of this study draws heavily on that used by the British Geological Survey and the Environment Agency to document the aquifer properties of major and minor aquifers in England and Wales (Allen et al. 1997, Jones et al. 2000). These studies showed that, even for the major aquifers in England, where information is relatively abundant, there are not sufficient data to produce contour maps of parameters such as transmissivity, storage and specific capacity. Instead, data analysis and interpretation were directed towards producing a database and descriptions of the overall physical characteristics of each aquifer. The descriptions of the variations and controls on aquifer properties have been an important tool in groundwater management.

1.2 PARAMETERS COVERED BY THE REPORT

The aquifer properties addressed by this report are:

- Permeability (as hydraulic conductivity)
- Porosity
- Transmissivity
- Storage (as storage coefficient)
- Specific capacity

The first four of the parameters represent the fundamental physical hydrogeological properties of an aquifer, and are in general time invariant (although it is recognised that transmissivity depends on the saturated thickness of an aquifer, which can vary with time). Specific capacity is a derived calculation, reflecting variations in the first four parameters (principally transmissivity and storage), and as such is not strictly an aquifer property. However, it is widely used for comparative purposes and as an approximation for transmissivity (Jones et al. 2000). For many Scottish aquifers, including the Upper Devonian sandstones in Fife, there are few values of transmissivity and storage available from properly conducted and analysed pumping tests. This is largely because tests have been principally carried out on boreholes destined for small-scale production, where costs of testing are generally not justifiable.

The report does not cover data resulting from geophysical borehole logging, or physical aspects of aquifers such as water levels, hydraulic gradients, hydraulic boundaries or recharge, except to comment on their importance to the basic aquifer properties named above.

1.3 BACKGROUND TO THE UPPER DEVONIAN/LOWER CARBONIFEROUS AQUIFER IN FIFE

The Upper Devonian and Lower Carboniferous sandstones in Fife have long been recognised as one of the most productive aquifers in Scotland (Figure 1). Their importance as a hydrogeological unit was first acknowledged by Earp and Eden (1961), and the aquifer was later described by Foster et al. (1976). Hydrogeological data were collated and presented in map form in the 1980s (BGS 1986), but, until the late 1990s, little analysis of the aquifer was carried out other than an MSc dissertation (Barker 1981), occasional reports on specific issues such as nitrate pollution (e.g. Frost & Sargent 1993, MacDonald 1993, Ball 1994), and the preparation of the 1:100,000 scale Aquifer Vulnerability Map of Fife (SEPA 1999). A detailed study of the aquifer, reviewing all available data, was completed in 1999, and includes a conceptual model of the groundwater system (Ó Dochartaigh et al. 1999). Since then, various aspects of groundwater chemistry have been addressed (e.g. Robins 2001, Vinten & Dunn 2001, McNeill et al. 2003). Nitrate concentrations in the aquifer were investigated prior to it being included in a newly designated nitrate vulnerable zone (Ball & MacDonald 2001). The aquifer is one of the most extensively studied in Scotland, although there are a number of areas where data, and hydrogeological understanding, remain incomplete.

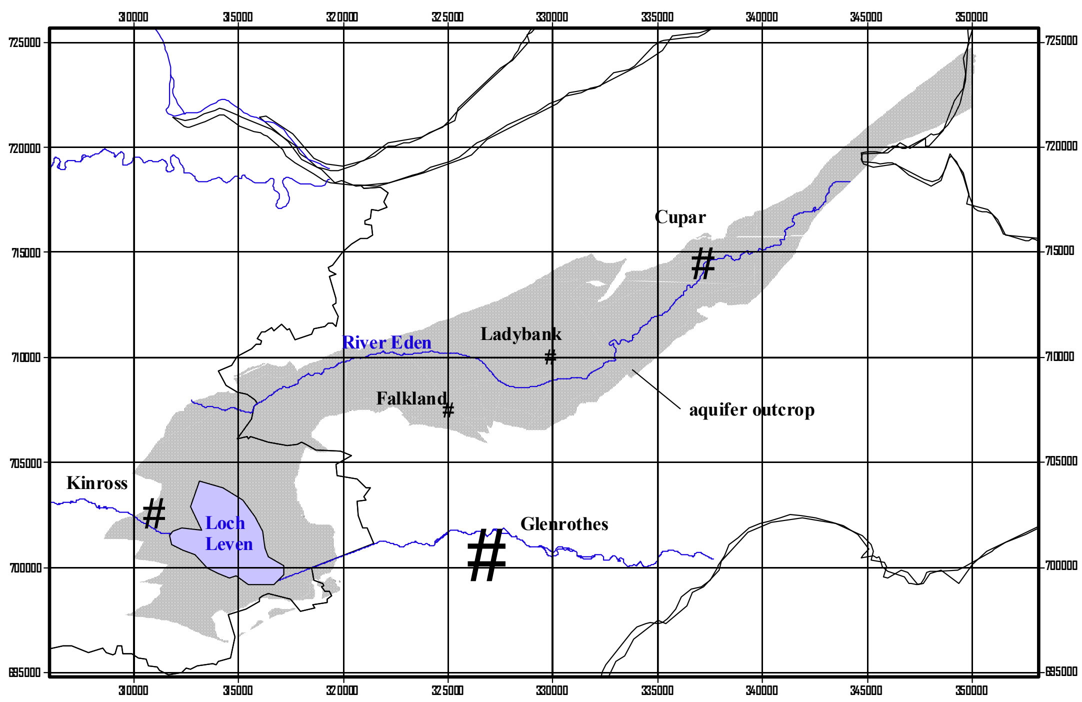


Figure 1 Location of the Upper Devonian/Lower Carboniferous aquifer in Fife

2 Geology of the Upper Devonian/Lower Carboniferous aquifer in Fife

2.1 GENERAL GEOLOGY

The oldest rocks that crop out in central Fife form part of a major basaltic andesite volcanic province of early Devonian age. Earth movements deformed and uplifted these rocks, which were subsequently eroded to produce a subdued landscape that was subsequently buried under late Devonian sedimentary rocks, largely fluvial sandstones (Stratheden Group). The oldest Carboniferous rocks (Inverclyde Group) were deposited on a low-lying alluvial and coastal plain that 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 oil shales. 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 deformation helped to create the basins in which the sediments accumulated (Ó Dochartaigh et al. 1999).

A complex pattern of events occurred during the Quaternary period, characterised by the deposition of glacial till and gravels, as well as raised marine deposits.

The Upper Devonian aquifer, as it is generally defined, comprises both the Upper Devonian Stratheden Group and the oldest part of the overlying Carboniferous Inverclyde Group (Figure 2)

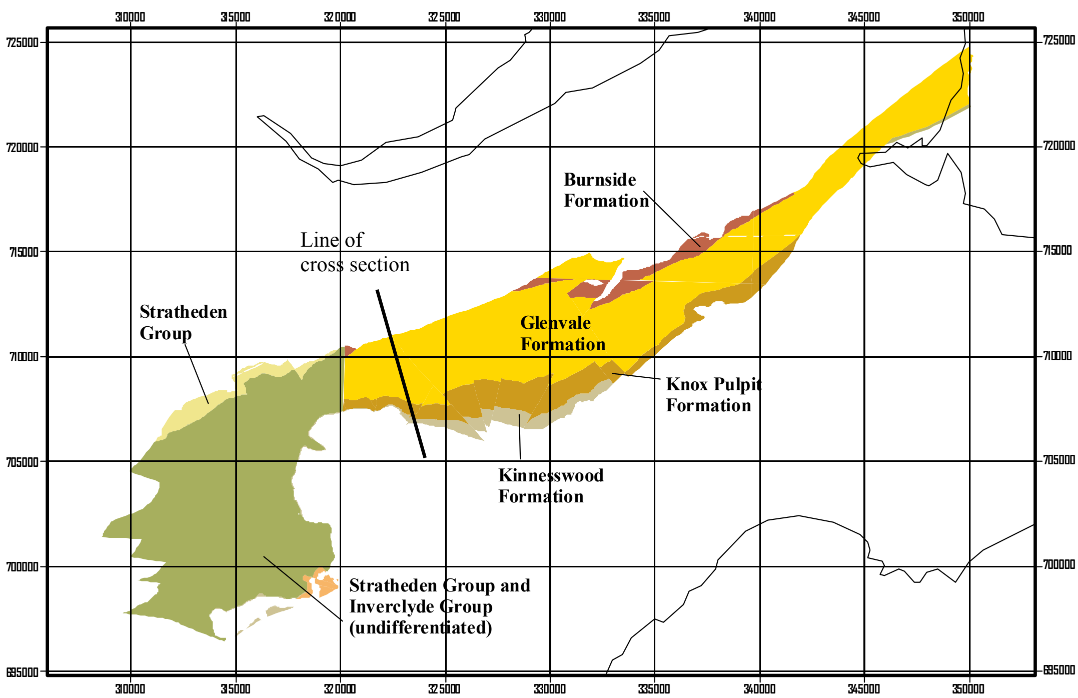


Figure 2 Outcrop of the Upper Devonian/Lower Carboniferous aquifer in Fife. (See also cross section, Figure 3)

2.2 LITHOLOGY AND STRATIGRAPHY

2.2.1 Upper Devonian – Stratheden Group

The Upper Devonian Stratheden Group 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 Knox Pulpit Formation, which is the key member of the Upper Devonian/Lower Carboniferous aquifer, comprises aeolian sandstones. The relationship between the formations is illustrated by the cross section in Figure 3.

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 as beds of conglomerate up to about 2 m thick. Beds of red siltstone and silty mudstone up to 0.6 m thick occur rarely.

The sandstones and conglomerates of this unit are generally moderately- to well-cemented. The cement usually has a clay-mica matrix, but it may also quite commonly be carbonate (calcite).

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, whereas pebbles of red, cream and green silty mudstone, up to 0.15 m 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 are weakly to well cemented. The cement is usually a clay-mica matrix, but may also be calcite.

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. There is a range of cross-stratification structures and flat laminations. 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 usually weakly cemented with a clay-mica matrix.

2.2.2 Carboniferous – Inverclyde Group

The basal member of the Inverclyde Group, the Kinnesswood Formation, is generally considered as part of the 'Upper Devonian' aquifer in Fife.

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 are weakly to well cemented. The cement commonly has a clay-mica matrix but may also be carbonate (calcite and dolomite).

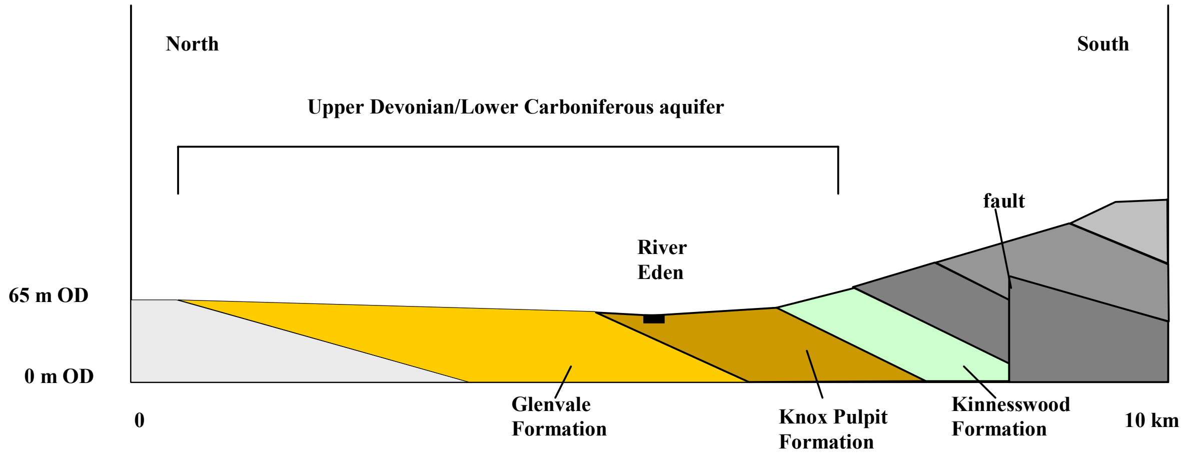


Figure 3 Cross section through the Upper Devonian/Lower Carboniferous aquifer in Fife (along line shown in Figure 2)

2.3 STRUCTURE

The Upper Devonian/Lower Carboniferous strata dip towards the southeast at angles of between approximately 5 and 10°.

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 southwest to northeast, down-throwing 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. This is the case 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 relatively small fault-bounded blocks.

3 Hydrogeology

3.1 INTRODUCTION

The sedimentary rocks comprising the aquifer form the low ground of the central Fife area and dip southeastwards beneath less permeable Lower Carboniferous rocks (Figure 3). The outcrop is narrowest between the Loch Leven basin and the Eden valley north of the intrusive rocks of the Lomond Hills (Figure 2). East of Falkland in the Eden valley the aquifer expands in width beneath the superficial deposits, before narrowing east of Cupar. On the northern edge of the Eden valley and the western edge of the Loch Leven basin Upper Devonian sandstones are downfaulted against less permeable Lower Devonian volcanic rocks.

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 the bedrock aquifer. In other areas glacial till rests 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.

The aquifer is usually unconfined, although clay deposits may partly confine the underlying sandstone aquifer. Water table contours for the aquifer were drawn for the hydrogeological map of Fife and Kinross (BGS 1986) and are reproduced in Figure 4. Water levels are highest beneath the higher ground on the margins of the aquifer, and lowest in the middle of the Eden valley. In the west of the aquifer, the relationship between the aquifer and surface water (in particular Loch Leven) is unclear. In the Eden valley, groundwater flow is thought to be largely transverse to the valley sides, discharging to the River Eden, with a component of flow longitudinally down valley towards the coast.

Public supply boreholes abstracting from the Knox Pulpit and Kinnesswood Formations in the east of the aquifer, such as Freuchie and Newton of Lathrisk, provide yields of up to 4 Ml/d each, while those constructed in the west of the aquifer in the undivided Stratheden and Inverclyde groups, such as Kinneston and the Kinnesswood boreholes, do not generally yield more than 2.5 Ml/d each.

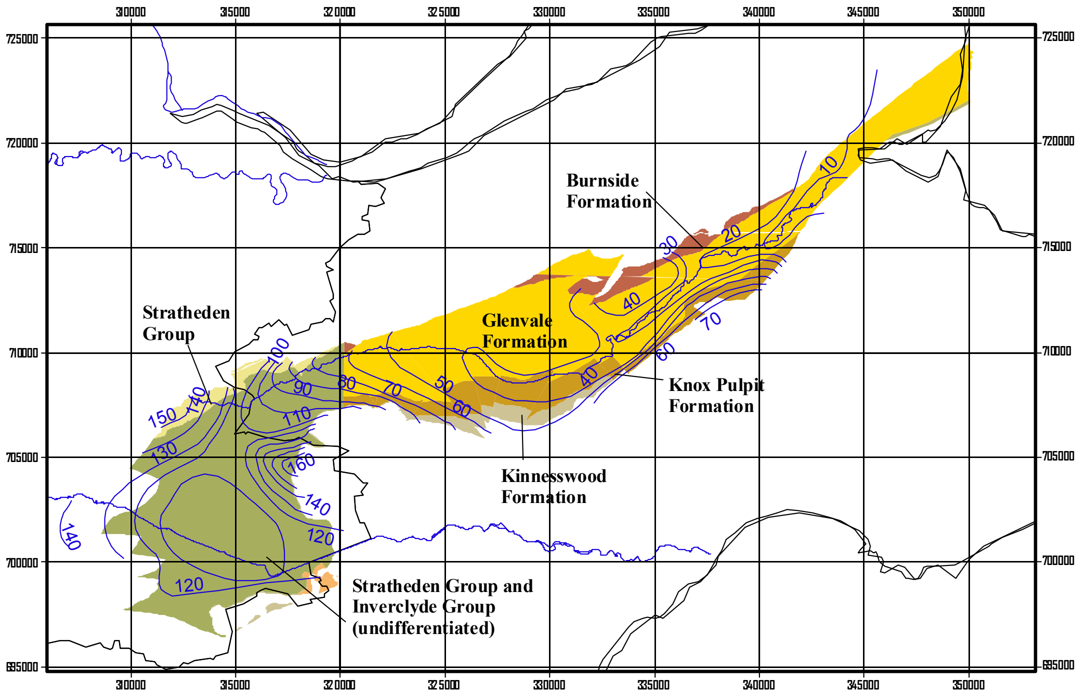


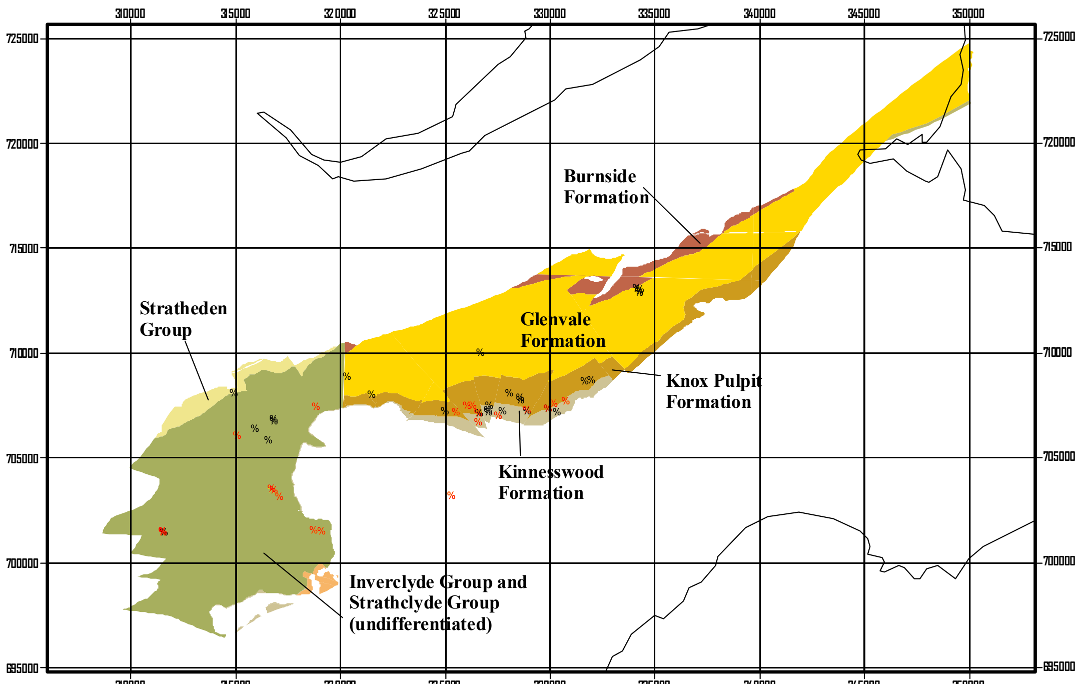
Figure 4 Water table contours in the Upper Devonian/Lower Carboniferous aquifer of Fife (from BGS 1986)

3.2 AQUIFER PROPERTIES

The Knox Pulpit Formation and the overlying Kinnesswood Formation, which crop out along the southern edge of the aquifer (Figure 2), typically show the highest porosity, hydraulic conductivity and specific capacity. The Glenvale Formation typically shows lower values. Limitations in the geological mapping and in the available data mean that not all aquifer property data can be assigned to a specific aquifer formation: many in the western part of the aquifer are classed as undivided Stratheden and Inverclyde groups.

There is considerable variation in porosity and hydraulic conductivity with depth in the aquifer. This is thought to reflect variations in grain size. Geophysical logging of boreholes has shown that even where porosity is highest (greater than 20%), fracture flow is still dominant, constituting at least 70% of total transmissivity in the Knox Pulpit Formation and even higher in the Glenvale Formation. The highest permeabilities in all units are thought to occur in the uppermost 10 to 15 m of the saturated zone, where weathering and fracture development have significantly increased secondary permeability (Ó Dochartaigh et al. 1999).

There are 50 boreholes in Fife that are or have been used for groundwater abstraction, testing or observation. Aquifer properties data are available for only 23 of these boreholes. The locations for all the boreholes are illustrated in Figure 5.



Boreholes for which aquifer properties (pumping test and core) data are available shown in red; other groundwater abstraction, testing or observation boreholes shown in black.

Figure 5 Location of known groundwater boreholes in the Upper Devonian/Lower Carboniferous aquifer in Fife

3.3 ROCK CORE DATA

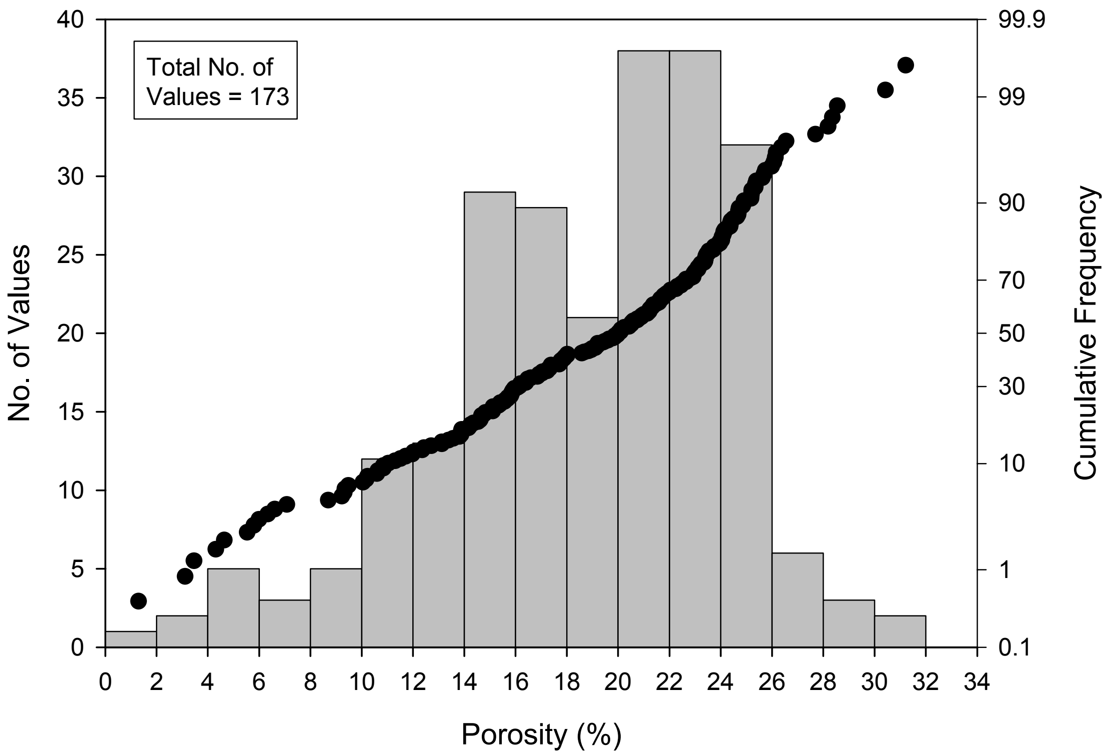
A total of 413 rock core samples from 10 boreholes in the Upper Devonian/Lower Carboniferous aquifer have been analysed for aquifer property data. From these, 413 values for porosity and 406 values for hydraulic conductivity have been obtained.

Seven of these boreholes were in the Knox Pulpit Formation; one in the Kinnesswood Formation, one in the Glenvale Formation and one penetrating both the Knox Pulpit and Kinnesswood formations.

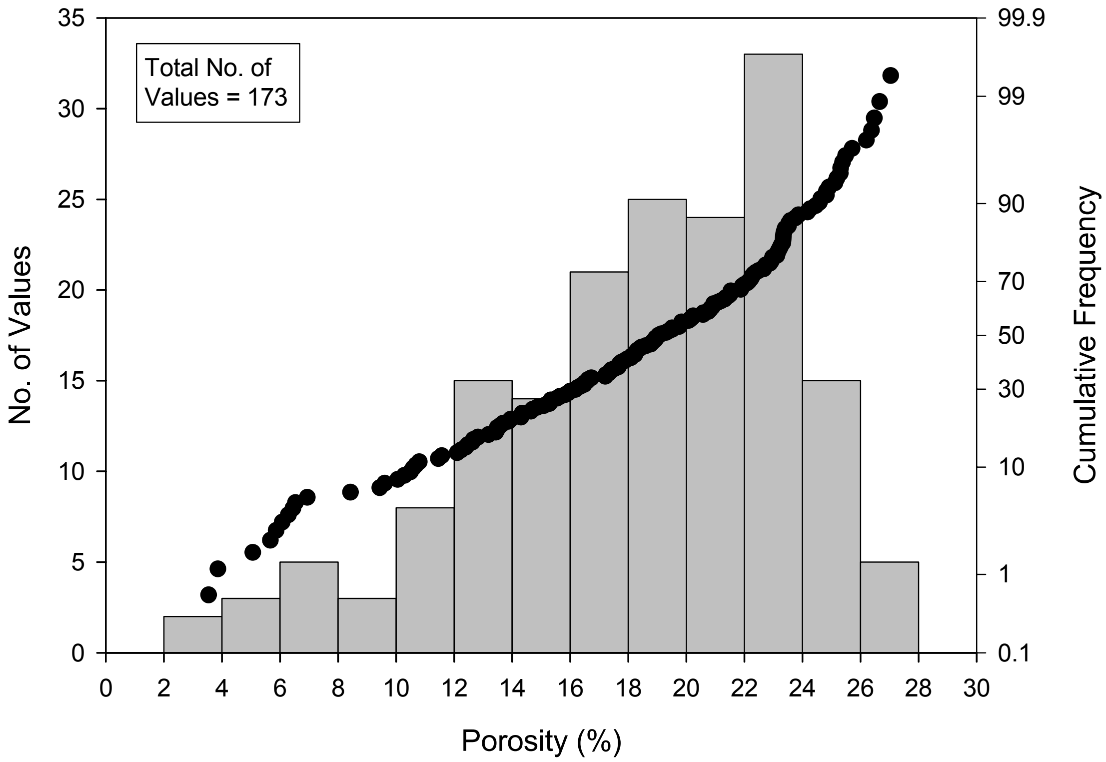
The majority of the samples (65%) were taken from less than 50 m depth. A small proportion of the samples (20%) were taken from greater than 450 m depth.

The porosity distribution for the whole aquifer is shown in Figure 6. Porosity values for the whole aquifer range from 1.3% to 31.2%, with an arithmetic mean of 18.7%. The average porosity in the horizontal direction (with an arithmetic mean of 19.4%) is very similar to the average porosity in the vertical direction (with an arithmetic mean 18.6%). There is a slight difference in the distribution of porosity values, in that horizontal porosity is more normally distributed than vertical porosity, which is slightly skewed towards the high end of the range of values.

The distribution of hydraulic conductivity data for the whole aquifer (as log values) is shown in Figure 7. Measured hydraulic conductivity ranges from 6.4×10^{-6} m/d to 4.3 m/d, with a geometric mean of 2.9×10^{-2} m/d. Hydraulic conductivity in the horizontal direction (with a geometric mean of 5.6×10^{-2}) is higher than in the vertical direction (with a geometric mean of 1.5×10^{-2}). The distribution of horizontal hydraulic conductivity is also skewed towards the high end of the range of values, whereas vertical hydraulic conductivity is more normally balanced.

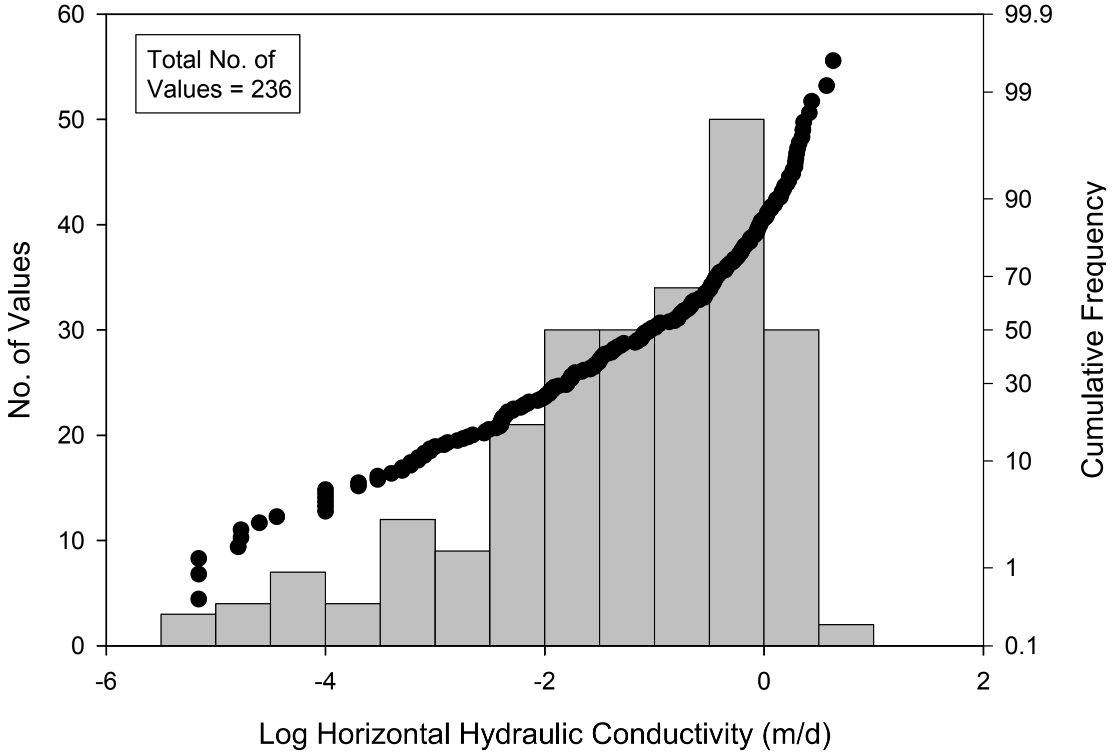


(a)

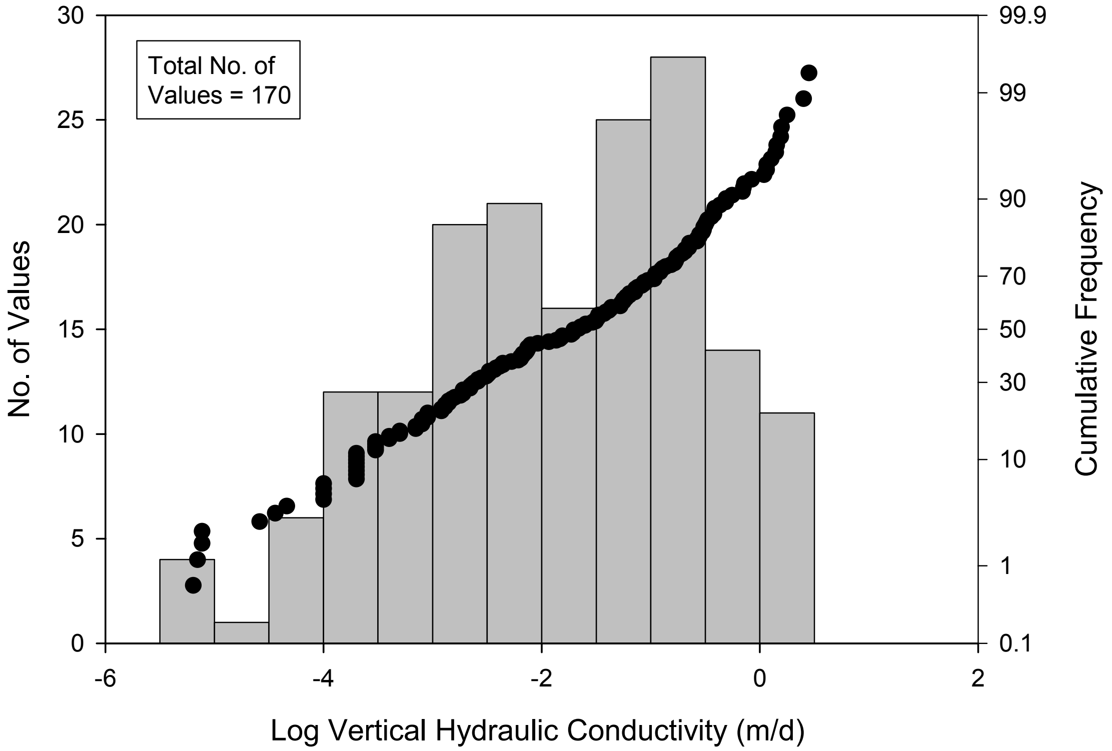


(b)

Figure 6 Distribution of porosity ((a) – horizontal and (b) – vertical porosity) data for the Upper Devonian/Lower Carboniferous aquifer in Fife



(a)



(b)

Figure 7 Distribution of hydraulic conductivity ((a) – horizontal and (b) – vertical hydraulic conductivity) data for the Upper Devonian/Lower Carboniferous aquifer in Fife, shown as log values

Porosity and hydraulic conductivity data for the aquifer are summarised by geological formation in Table 1. The distribution of vertical and horizontal hydraulic conductivity is also summarised (the differences between vertical and horizontal porosity are small enough to make comparisons of little value).

The small number of locations from which the samples were obtained, and the small number of samples for formations other than the Knox Pulpit Formation, mean that analysis of any differences between formations is uncertain.

Table 1 Summary of core aquifer properties data by geological formation for the Upper Devonian/Lower Carboniferous aquifer in Fife

Formation		**Kinnesswood Formation**	**Kinnesswood & Knox Pulpit Formation (undivided)**	**Knox Pulpit Formation**	**Glenvale Formation**
No. Locations		1	1	7	1
No. Samples		110	10	259	10
No. Porosity Values		109	10	258	34
Minimum Porosity (%)		3.1	10.6	3.5	1.3
Maximum Porosity (%)		25.2	25.2	31.2	24.4
Arithmetic Mean of Porosity		16.3	21.3	20.1	14.9
No. Hydraulic Conductivity Values		110	10	256	31
Minimum Hydraulic Conductivity (m/d)	All	7.7×10^{-6}	1.0×10^{-4}	6.4×10^{-6}	7.0×10^{-6}
	Horizontal	1.6×10^{-5}	1.0×10^{-4}	7.0×10^{-6}	7.0×10^{-6}
	Vertical	7.7×10^{-6}	4.0×10^{-4}	6.4×10^{-6}	7.0×10^{-6}
Maximum Hydraulic Conductivity (m/d)	All	5.98×10^{-1}	9.4×10^{-1}	4.3	1.8
	Horizontal	5.98×10^{-1}	9.4×10^{-1}	4.3	1.8
	Vertical	5.6×10^{-1}	2.7×10^{-1}	2.8	7.7×10^{-6}
Geometric Mean of Hydraulic Conductivity (m/d)	All	8.2×10^{-3}	3.8×10^{-2}	5.4×10^{-2}	1.3×10^{-2}
	Horizontal	1.0×10^{-2}	9.8×10^{-2}	1.0×10^{-1}	2.1×10^{-2}
	Vertical	6.6×10^{-3}	1.5×10^{-2}	6.6×10^{-3}	7.3×10^{-6}

The Knox Pulpit Formation and the undivided Kinnesswood/Knox Pulpit Formation formations have the highest average porosity. The Knox Pulpit Formation shows the widest range of porosity values. The samples from boreholes in the Kinnesswood and Glenvale formations (there is only a single borehole with data in each formation) have similar porosity ranges and average values to the Knox Pulpit Formation.

The Knox Pulpit Formation shows the widest range of hydraulic conductivity values. The Knox Pulpit Formation and the undivided Kinnesswood/Knox Pulpit formations have the highest average hydraulic conductivity, in both the horizontal and vertical directions. The

Knox Pulpit Formation, however, shows more variation between horizontal and vertical hydraulic conductivity than the undivided Kinnesswood/Knox Pulpit formations or than the Kinnesswood Formation alone. The Kinnesswood and Glenvale formations have similar average hydraulic conductivity values in the horizontal direction, but the Glenvale Formation has much lower vertical hydraulic conductivity.

There is a strong positive linear relationship between hydraulic conductivity and porosity in the aquifer (Figure 8).

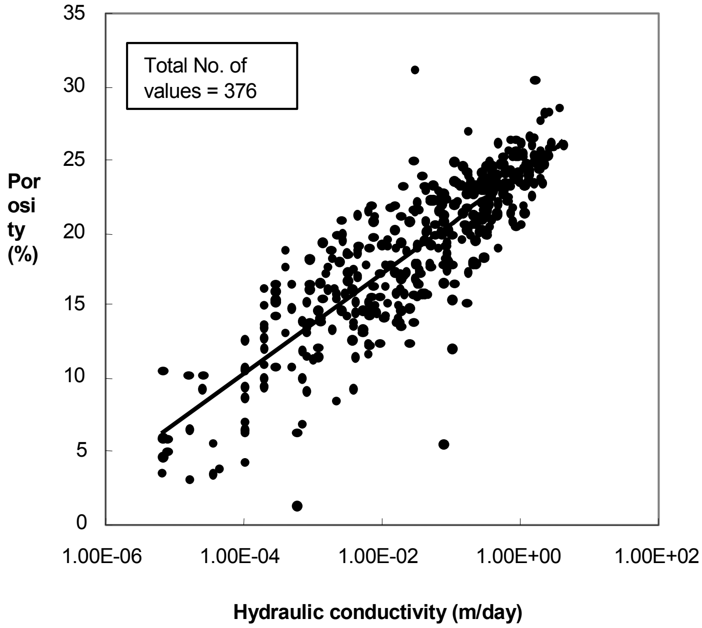


Figure 8 Correlation between hydraulic conductivity and porosity for the Upper Devonian/Lower Carboniferous aquifer in Fife

The data from core analysis also reveal differences in the distribution of porosity and hydraulic conductivity with depth in the aquifer. Most of the core samples analysed are from depths of less than 80 m, and within this group there are more samples at depths of less than 40 m than at depths of between 40 and 80 m. A small proportion of the samples are from depths of between 450 and 570 m.

Aquifer porosity varies across wide ranges with depth (Figure 9). However, the relationship between horizontal and vertical porosity does not change significantly with depth. Even allowing for the reduced number of samples, there is an overall decrease in porosity with depth. Above 40 m depth, the arithmetic mean of porosity (horizontal and vertical) is 22%; between 40 m and 80 m depth, the mean is 19%; and between 450 m and 570 m the mean is 15%.

There is a similar pattern to the depth distribution of aquifer hydraulic conductivity. Above 40 m depth, the geometric mean of horizontal hydraulic conductivity is 0.7 m/d; between 40 m and 80 m depth, the mean is 0.3 m/d; and between 450 m and 570 m the mean is 0.06 m/d. The geometric mean of vertical hydraulic conductivity is 0.3 m/d above 40 m depth; 0.05 m/d between 40 m and 80 m depth; and 0.04 m/d between 450 m and 570 m depth.

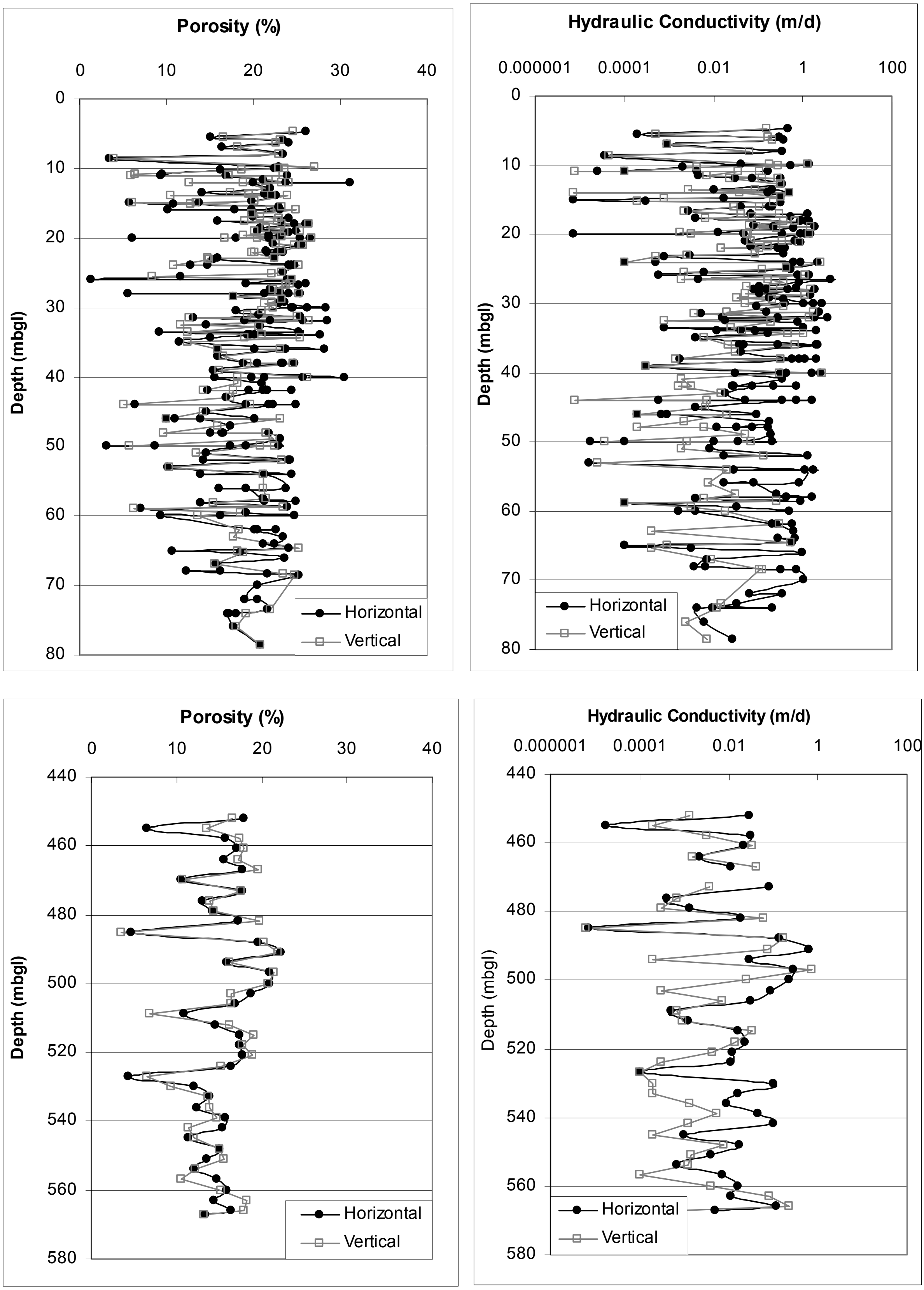


Figure 9 Variations in porosity (left) and hydraulic conductivity (right) with depth in the Upper Devonian/Lower Carboniferous aquifer in Fife. Data from horizontal and vertical core plugs are shown.

3.4 PUMPING TEST DATA

Pumping test data are available for 19 boreholes in the Upper Devonian/Lower Carboniferous aquifer in Fife. For some of the boreholes, data on more than one pumping test are available. Data for a total of 28 pumping tests are thought to be available, although in some cases it is difficult to assign data to particular tests. The tests were a mixture of constant rate and step tests. Most of the tests were carried out in the 1970s and 1980s.

The type, length and quality of the pumping tests vary, as do the amount and quality of data from each test, from full records of pumping rates, water level drawdown and recovery and calculations of transmissivity and storage coefficient, to single measurements of yield and maximum drawdown. The data have not been fully catalogued, but there is the potential for re-analysing the original data that are still available for some of the tests. For most of the tests, only the calculated hydraulic values are available, and not the original data. It is therefore not possible to assess the accuracy and reliability of most of the values.

Five transmissivity values have been calculated, for four boreholes, and four storage coefficient values, for three boreholes. There are 46 available specific capacity values for the 19 boreholes. Details of the pumping data from which the specific capacity values were calculated are not generally available, and it is unlikely that the values all relate to the same length of pumping test. Where more than one specific capacity value is available for a borehole, the geometric mean of the values has been used to produce a single preferred value for each borehole. The distribution of specific capacity data for the whole aquifer (as log values) is shown in Figure 10. Specific capacity values range from 13 m^3/d/m to 593 m^3/d/m, with a geometric mean of 76 m^3/d/m.

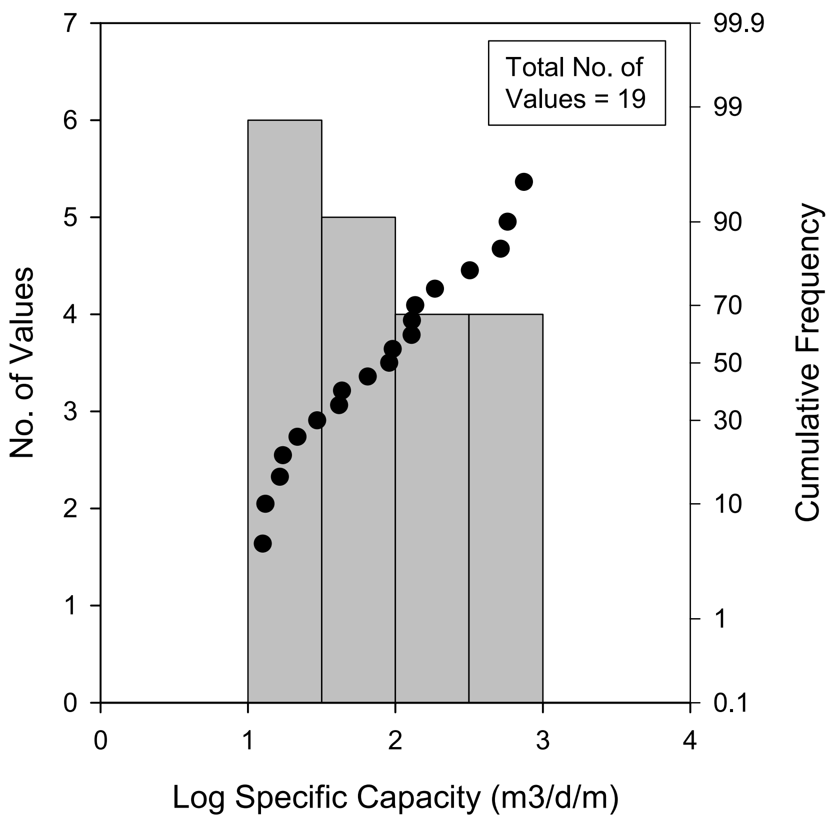


Figure 10 Distribution of specific capacity values for the Upper Devonian/Lower Carboniferous aquifer in Fife

Pumping test data for the aquifer are summarised by geological formation in Table 2. The range and averages of specific capacity values are based on the preferred values for each borehole (i.e. the geometric mean of values where more than one value exists for each borehole).

Analysis of the data is made more difficult because many of the borehole records do not state the formation they abstract from. The current geological mapping in the west of the aquifer does not allow the formations to be distinguished as the aquifer is mapped as a single formation (undivided Stratheden Group and Inverclyde Group). The small number of locations from which the samples were obtained, and the small number of samples for the Kinnesswood and Glenvale formations, mean that analysis of any differences between formations can only be tentative.

The available transmissivity values indicate that transmissivity is higher in the Kinnesswood Formation (770–850 m/d) than in the Knox Pulpit Formation and undivided Stratheden and Inverclyde groups (150–200 m/d). The available storage coefficients for the undivided Kinnesswood and Knox Pulpit formations are similar (1.2–2.7), and for the undivided Stratheden and Inverclyde groups are an order of magnitude smaller (1.0×10^{-4}).

The Kinnesswood Formation and the undivided Kinnesswood and Knox Pulpit formations show the highest average specific capacity values in the aquifer (545–593 m^3/d/m), although there are data from only a single borehole in each class, and these values may not therefore be representative. The Glenvale Formation (28.6 m^3/d/m) and the undivided Stratheden and Inverclyde groups (43.6 m^3/d/m) show the lowest average values. The Knox Pulpit Formation shows an average specific capacity of 196 m^3/d/m.

Table 2 Summary of pumping test data by geological formation for the Upper Devonian/Lower Carboniferous aquifer in Fife

Formation	**Kinnesswood Formation**	**Kinnesswood & Knox Pulpit Formation (undivided)**	**Knox Pulpit Formation**	**Glenvale Formation**	**Stratheden Group and Inverclyde Group (undivided)**	**Unknown**
No. of T values	2		2		1	
T value(s) (m/d)	770 / 850		150 / 200		250	
No. of S values	2		1		1	
S value(s)	2×10^{-3} / 2.7×10^{-3}		1.2×10^{-3}		1.0×10^{-4}	
No. of Q/s values	1	1	5	2	9	1
Minimum Q/s value (m^3/d/m)	593	545	95.3	12.6	15.8	13.2
Maximum Q/s value (m^3/d/m)	593	545	518	64.8	174	13.2
Geometric mean of Q/s value (m3/d/m)	-	-	196	28.6	43.6	-

4 Conclusion

This pilot study shows that there are enough available data for the Upper Devonian/Lower Carboniferous aquifer in Fife to undertake an analysis of its physical properties. There are likely to be sufficient available data to carry out similar analyses of aquifers in Dumfries, Strathmore, and possibly Morayshire, and it is recommended that future studies of aquifer properties concentrate on these areas. In much of the rest of Scotland, there are not sufficient data to carry out the same type of analysis, and a more regional approach is likely to be more appropriate. Regional analyses of the hydrogeology and groundwater resources of Scotland, including reference to physical aquifer properties, where available, have already been carried out (Robins 1990; Ball 1999), and at present these are likely to remain the most informative data sources.

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

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Appendix 1 Summary of boreholes with aquifer properties data

Source	Easting	Northing	Formation	Surface Level (m)	Depth (m)	Use	General yield data	Core data	No. of porosity samples	No. of hydraulic conductivity samples	Test pumping data	No. of pumping tests	Type of pumping test (s)	Draw-down data	Recovery data	Yield data from pumping tests	T values	S values	Q/s values
Balmalcolm Farm (Kettle Produce)	331960	708610	KPF	42	60	Food processing	Yes					3	CR			Yes			Yes
Balmalcolm PS	332270	708660	KPF	46	75.6	Public supply	Yes												
Balreavie OBH (No. 3)	326900	706640	KPF	85	71	Observation		Yes											
Bowhouse Farm	326960	710010	GVF		40	Farm / domestic	Yes												
Chapel Farm	330650	707140	KNW / KPF	55	60	Irrigation	Yes												
Cuthill Towers Farm	315240	708060	SIU		65	Farm	Yes												
Drumdreel Farm	320640	708810	GVF		67	Irrigation	Yes												
Easter Lathrisk OBH	328370	708020	KPF	41	61	Observation													
Falkland PS	325820	707120	KPF	75	92	Public supply	Yes	Yes			Yes	2	CR	Yes	Yes	Yes	Yes	Yes	Yes
Freuchie PS (Knowehead)	328020	707170	KNW	50	90	Public supply not in use	Yes		109	110		1	CR	Yes	Yes	Yes	Yes	Yes	Yes
Glenrothes	325620	703140	KNW / KPF					Yes	10	10									
Guardbridge											Yes	1				Yes			Yes
Hilton of Carslogie Farm 1	334480	713050	BRN / GVF		76	Irrigation	Yes												
Hilton of Carslogie Farm 2	334540	712930	BRN / GVF		75	Irrigation	Yes												
Hilton of Carslogie Farm 3	334540	712880	BRN / GVF		76	Irrigation	Yes												
Hilton of Carslogie Farm 4	334600	713010	BRN / GVF		77	Irrigation	Yes												
Kettlebridge PS	331080	707680	KPF	44	123	Public supply	Yes	Yes			Yes	2?	S, CR			Yes	Yes		Yes
Kingskettle No.1	330210	707280	KPF					Yes											
Kingskettle	330460	707570	KPF					Yes											

Source	Easting	Northing	Formation	Surface Level (m)	Depth (m)	Use	General yield data	Core data	No. of porosity samples	No. of hydraulic conductivity samples	Test pumping data	No. of pumping tests	Type of pumping test (s)	Draw-down data	Recovery data	Yield data from pumping tests	T values	S values	Q/s values
No.2																			
Kinnesswood 1 PS	317040	703490	SIU	140	122	Public supply	Yes				Yes	2?	S, CR			Yes			Yes
Kinnesswood 2 PS	317120	703410	SIU	135	122	Public supply	Yes				Yes	3?	S, CR			Yes	Yes	Yes	Yes
Kinnesswood 3 PS	317410	703090	SIU	135	120	Public supply	Yes				Yes	1	S			Yes			Yes
Kinneston PS	319400	701490	SIU	117	91	Public supply not in use	Yes				Yes	1	CR			Yes			Yes
Kinross			U								Yes	1	CR			Yes			Yes
Knowehead No. 13	327830	706960	KNW	55	91	Observation		Yes											
Mawcarse (Middleton)	315400	706000	GVF					Yes	34	31	Yes	1	CR			Yes			Yes
Moors of Kinnesswood	316860	705810	SIU	170	36.6	Farm	Yes												
Myreside Farm	326350	707440	KPF	50	60	Irrigation	Yes				Yes	1	CR			Yes			Yes
Newton of Falkland No.4 (Newton Common)	326600	707440	KPF	50	60	Observation		Yes				1	OBH	Yes	Yes				
Newton Maltings OBH	326910	0707110	KPF	55	60	Observation													
Newton Maltings PS (No. 14)	326880	707080	KPF	55	90	Public supply	Yes	Yes			Yes	2	CR	Yes	Yes	Yes			Yes
Newton of Lathrisk Farm	327420	707480	KPF	45	61	Irrigation	Yes												
Newton of Lathrisk OBH	327360	0707140	KPF	55	60	Observation													
Newton of Lathrisk PS	327370	707250	KNW / KPF	50	90	Public supply	Yes												
Orkie Farm 1	329200	707270	KNW / KPF		118	Food processing	Yes				Yes	1	CR			Yes			Yes
Orkie Farm 2	329200	707180	KNW / KPF		70	Food processing	Yes												
Orkie Gas Works	330200	707280	KNW / KPF		86	Irrigation	Yes												
Riggs Farm 1	328910	707740	KPF	41	34	Farm / domestic	Yes												
Riggs Farm 2	328880	707850	KPF	41	60	Irrigation	Yes												

Source	Easting	Northing	Formation	Surface Level (m)	Depth (m)	Use	General yield data	Core data	No. of porosity samples	No. of hydraulic conductivity samples	Test pumping data	No. of pumping tests	Type of pumping test (s)	Draw-down data	Recovery data	Yield data from pumping tests	T values	S values	Q/s values
Scotlandwell PS	319030	701500	SIU	118		Public supply not in use					Yes	1	CR			Yes			Yes
Smith Anderson	325300	707210	KPF		77	Industrial	Yes												
Todd and Duncan 1	311840	701490	SIU		91.4	Industrial	Yes				Yes	1	CR			Yes			Yes
Todd and Duncan 2	311840	701480	SIU		107	Industrial	Yes				Yes	1	S			Yes			Yes
Todd and Duncan 3	311840	701430	SIU		85	Industrial	Yes				Yes	1	S			Yes			Yes
Todd and Duncan 4	311860	701390	SIU		105	Industrial	Yes												
Upper Urquhart Farm	319140	707430	SIU		121	Irrigation	Yes				Yes	1	CR			Yes			Yes
Wester Gospetry Farm 1	316210	706340	SIU		116	Irrigation	Yes												
Wester Gospetry Farm 2	317140	706740	SIU		116	Irrigation	Yes												
Wester Gospetry Farm 3	317120	706820	SIU		116	Irrigation	Yes												
Wester Kilgour	321770	708000	GVF	100	76	Poultry	Yes												

KPF – Knox Pulpit Formation
KNW – Kinnesswood Formation
BRN – Burnside Formation
GVF – Glenvale Formation
SIU – Strathclyde Group and Inverclyde Group (undivided)
U – Unknown

CR – Constant Rate pumping test
S – Step test