Final Report

Project WFD27

Scottish Aquifer Properties: 2006 Interim Report

June 2006

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

SNIFFER
SCOTLAND & NORTHERN IRELAND FORUM FOR ENVIRONMENTAL RESEARCH

Dissemination status

Unrestricted

This document was produced by:

British Geological Survey
Murchison House
West Mains Road
Edinburgh EH9 3LA
UK

SNIFFER's project manager

SNIFFER's project manager for this contract is:

Elaine Simpson, Scottish Environmental Protection Agency

This is a co-funded project between BGS and SNIFFER. The steering group members are:

Derek Ball, British Geological Survey
Malcolm Graham, British Geological Survey
Brighid Ó Dochartaigh, British Geological Survey
Kirsty Irving, SNIFFER
Elaine Simpson, Scottish Environmental Protection Agency

SNIFFER
First Floor, Greenside House
25 Greenside Place
Edinburgh EH1 3AA

Company No: SC149513
Scottish Charity: SCO22375

www.sniffer.org.uk

British Geological Survey
Keyworth
Nottingham NG12 5GG
☎ 0115-936 3241
Fax 0115-936 3488
e-mail: sales@bgs.ac.uk

www.bgs.ac.uk

EXECUTIVE SUMMARY

WFD27, CR06/073N: Scottish Aquifer Properties: 2006 Interim Report (June, 2006)

Project funders/partners: SNIFFER, BGS, SEPA

Background to research

The Scottish Aquifer Properties project is co-funded by the British Geological Survey (BGS) and the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER). The Scottish Environment Protection Agency has provided the funding via SNIFFER. The project will last for two years and commenced in April 2005.

Objectives of research

The ultimate aim is to produce a manual and database of aquifer parameters in Scotland with a comprehensive range of data on all areas of hydrogeological significance. This interim report acts as a manual for the initial database (not publicly available until the end of the full project) and provides stand-alone documentation of the aquifer parameter information collated and analysed to date. The final report will be an updated, fuller version of this document and will provide additional analysis of the data.

Key findings and recommendations

- There are currently almost 3000 records entered in the database, each representing an individual borehole, shaft, well or spring. There are some adjustments still to be made in the format of the database, however, the available output is fairly comprehensive, both in terms of the range of data included and the spatial extent covered by it.
- Yields have been entered for more than 1000 records. Nearly 200 entries have specific capacity values and around 80 have transmissivity data. Nearly 50 boreholes have data on porosity, permeability or hydraulic conductivity.
- The majority of data were taken from BGS digital data sources, sourced primarily from borehole records, borehole drilling and pump installation companies, Scottish Water, mineral water companies, SEPA and consultants.

The following activities are planned for Year 2 of the project:

- Continued input of BGS data to the database. A summary of these data, along with appropriate analysis, will be presented in a final report at the end of the two-year funding period.
- Collation of remaining external data from mineral water companies and other sources.
- Collection of core samples from existing core at local drillers, for porosity and permeability analyses. Existing core samples in the BGS collection are limited in geographical extent. Samples taken from other locations will improve overall coverage.
- Collection of new core from new boreholes. This will involve using private borehole projects to ‘add-on’ extra work by funding core collection during the drilling process. The selection of which boreholes to use for this work will be made after drilling companies have informed BGS of where they are about to drill. Emphasis will be made towards boreholes located in the Devonian aquifers of Strathmore and Moray where few samples are currently available. To date, the majority of the core samples are from Carboniferous formations in the Midland Valley.

- The development of the database to allow the public to access the information, ideally being hosted on the BGS website, along with a set of other GIS-based data sets which currently reside there.
- Discussions are to continue on a strategy for maintaining the database at the end of the current two-year funding period. This may involve a system of licensing of the data, which would finance continued updates of the product.

Key words: Report; Scotland; aquifer properties; database; hydrogeology

TABLE OF CONTENTS

List of Tables

List of Figures

1. INTRODUCTION

The Scottish Aquifer Properties project is co-funded by the British Geological Survey (BGS) and the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER). The Scottish Environment Protection Agency has provided the funding via SNIFFER. The project will last for two years and commenced in April 2005. The ultimate aim is to produce a manual and database of aquifer parameters in Scotland with a comprehensive range of data on all areas of hydrogeological significance. This interim report acts as a manual for the initial database (not publicly available until the end of the full project) and provides stand-alone documentation of the aquifer parameter information collated and analysed to date. The final report will be an updated, fuller version of this document and will provide additional analysis of the data.

The tasks carried out in 2005/06 comprised:

- Determination of the parameters to be included in the database, and ownership issues
- Identification of data sources
- Design and creation of a database structure in Oracle for aquifer properties data
- Collation of data in BGS records and reports
- Input of data to the database
- Gap analysis and examination of BGS core samples to determine the feasibility of testing and hence obtaining new core data
- Writing of interim report and delivery of interim dataset to SNIFFER and SEPA

1.1 Summary of progress

- There are currently almost 3000 records entered in the database, each representing an individual borehole, shaft, well or spring. Although there are some adjustments still to be made in the format of the database, the available output is fairly comprehensive, both in terms of the range of data included and the spatial extent covered by it.
- The majority of data was taken from BGS digital data sources within the GDI (geoscience data index). This data has primarily come from borehole records, borehole drilling and pump installation companies, Scottish Water, mineral water companies, SEPA and consultants.
- Approximately 98% of all yield values, 95% of all specific capacity values, 70% of all transmissivity values and 90% of all core data (porosity, permeability and hydraulic conductivity) in the database have been obtained from existing BGS digital data.
- The remaining data were taken from BGS reports where data had not already been incorporated into BGS digital data sources, such as Wellmaster.
- It is likely that around 80-90% of the data currently available have already been entered into the database. There remain around 400 boreholes which have not been registered with ‘SOBI’ (Single Onshore Borehole Index) numbers, the referencing system used to enter data in this project, and can therefore not be added to the database at this point. There is also some core data from drilling companies still to be input.
- No additional core test data not previously entered into the GDI has been incorporated, as it was discovered that the existing BGS cores were of too small a diameter to test and were mainly from low productivity aquifers.

2. THE DATABASE: EXPLANATION OF FIELDS IN OUTPUT TABLE

The database has been created to hold the information relevant to all parties concerned. Within BGS, this is an oracle platform to allow integration with other BGS corporate databases. For export to SNIFFER/SEPA, a flat table format allows the data to be easily interrogated, with the potential to form a GIS layer. Fields containing confidential BGS information have been marked and will not be made publicly available. Other fields are to be made available to BGS and SEPA only.

Each field has been populated according to a set of rules agreed by the steering group. All fields included in the flat table to be exported to SEPA/SNIFFER at this interim stage are described below.

2.1 Borehole ID

Each borehole is identified by its SOBI (single onshore borehole index) number. This comprises the 10km quarter sheet containing the borehole, the record type (e.g. borehole journal (BJ), site exploration borehole (SE)), an identifying number and a suffix to distinguish between boreholes located at the same site or drilled as part of the same project.

2.2 Borehole Name

An additional informal name has been assigned to each borehole as a further means of identification (e.g. Whiting Bay A1).

2.3 BNG_Easting & BNG_Northing

12-figure British National Grid references locate each borehole.

2.4 Start_Height

The elevation of the top of the borehole in metres above ordnance datum is given.

2.5 Source_Type

Each entry has been classified as either a borehole, spring, shaft or well. Clearly, there is liable to be some overlap between the latter two categories. Tunnels and adits have been classified as shafts. In cases where a borehole has been drilled at the base of an existing well or shaft, the entry has been classified as a borehole.

2.6 Dia_Depth

This field was originally to be used to give both the diameter and depth of each borehole. To allow searches based on borehole depth to be conducted, only the latter parameter (in metres) has been entered in this field.

2.7 Dia_Depth_Summary

Borehole diameters (in metres) and the associated range of depths covered by them (in metres below ground level) are listed.

2.8 General_Superficial_Code

The mapped superficial deposits at each borehole’s location are given. The descriptions are based on the latest BGS 1:50 000 maps and have been grouped into more general headings to facilitate analysis.

2.9 General_Bedrock_Code

The mapped bedrock at each borehole's location is given. Descriptions are based on the latest BGS 1:50 000 geological maps and have been grouped into more general headings. Descriptions are more detailed for hydrogeologically more significant units. Formations or groups which belong to more than one stratigraphical period have been entered only once to facilitate analysis of the data (e.g. although the Inverclyde Group is present in both the Devonian and Carboniferous periods, it has been classified as belonging to the Carboniferous period only).

2.10 Drift_Thick

The depth to rockhead is given, in metres.

2.11 Site_WS_Comments

Information on water strikes is given, including the depth of the main water strike, if known.

2.12 Site_WS_Summary

The depths, in metres below ground level, of all recorded water strikes are given, as a comma-separated list.

2.13 Confined

Where enough information is available, the aquifer units have been classified as being either confined, semi-confined or unconfined. Data on water strikes, rest water levels and borehole lithologies have been used to make this assessment. Springs, for obvious reasons, have not been classified in this way.

2.14 Strat_1, Strat_2, Strat_3

For bedrock aquifers, the stratigraphy of the aquifer is given, based on geological system (Strat_1), Group (Strat_2) and Formation (Strat_3). In cases where the exact formation is unknown, for example, or where a number of formations contribute significantly to the yield of the borehole, only the Period and Group are given. The same rule applies where there is no single, clear stratigraphical group acting as the aquifer unit. In general, Groups and Formations are provided where it is felt they are of particular hydrogeological significance. This format allows users to include varying levels of detail when conducting searches based on aquifer stratigraphy. Where the main aquifer is a superficial deposit, the type of deposit is given in the Strat_1 field.

At the current stage of development of the database, codes are provided for each of these fields (e.g. SAG refers to the Stratheden Group). A translation of each of these codes can be found in the glossary. A full stratigraphical description will be included in the final version of the database.

2.15 Lithology

The lithology considered to be contributing the greatest proportion of a borehole's yield is given. Where there is insufficient lithological information, or where there is more than one potentially productive lithology present, more general terminology may be used, such as 'sedimentary rock (SR)', as opposed to 'sandstone (SDST)'. Due to the heterogeneous nature of many superficial deposits, mixtures of different sediment types have been used in some cases (e.g. some alluvial deposits are classified as being ‘sand and gravel (SAGR)’).

As with the stratigraphic fields, only a code is given in each field at present, with the translations found in the glossary. Full lithological descriptions will be included in the final version of the database.

2.16 Aq_Tapped

Areas containing a number of highly permeable units of rock are commonly treated as being single aquifers, as they share similar characteristics (e.g. the ‘Fife’ or ‘Strathmore’ aquifers). This field gives these aquifer units, where applicable. The codes used can be found in the glossary. The final database will include the full names of these aquifers.

2.17 Aq_Tapped_Type

The aquifer is classified based on the dominant flow mechanism present (intergranular/fracture) and its productivity (very low/low/medium/high/very high). The result is a composite 2-4 letter code describing the characteristics of the most productive unit penetrated by the borehole. Translations of these codes can be found in the glossary.

2.18 SEPA_Ref_Summary

A list of numerical references, showing the data sources used for this borehole record, is given. These numbers refer to a dictionary of references used, which will be supplied to SEPA in conjunction with the database.

2.19 Tran_PV

The preferred value (PV) of transmissivity for the borehole is given in m^2/day. This is normally chosen to be the value with the highest associated quality category. Within the same quality category, observation borehole (OBH) data is given priority over abstraction borehole (PBH) data for constant rate tests. Multiple OBH values of the same quality are averaged geometrically, multiple PBH values are averaged arithmetically. All other data, including step test data, is averaged arithmetically.

Transmissivity values calculated using OBH data are included in the records for both observation and abstraction boreholes.

2.20 Tran_Qual_Cat

The quality of the preferred transmissivity value is given. Constant rate tests of >= 1 day duration are given an ‘A’ (good or very good). Constant rate tests of < 1 day duration or those with fluctuating rates, as well as step tests are given a ‘B’ (average or moderate). Slug tests or tests of unknown type or length are given a ‘C’ (poor).

A number of other studies take into account the techniques used to interpret hydrogeological data when assessing the quality of parameter values. For most boreholes in Scotland, however, this information is not available and the test methodology has instead been used as the primary criterion for assessing data quality.

Additional information on the assignment of quality categories is given in the following section.

2.21 Tran_Comment

Additional comments relating to transmissivity are given.

2.22 Tran_Min, Tran_Max, Tran_No_Vals

The minimum, maximum and total number of transmissivity values entered for each borehole record are given.

2.23 Stor_PV

The preferred storativity value for the borehole is given (dimensionless). The criteria used for this parameter is the same as that used for transmissivity.

2.24 Stor_Qual_Cat

The quality of the preferred storativity value is given. The criteria are the same as those used for transmissivity.

2.25 Stor_Comment

Additional comments relating to storativity are given.

2.26 Stor_Min, Stor_Max, Stor_No_Vals

The minimum, maximum and total number of storativity values entered for each borehole record are given.

2.27 Rwl_Normal_Annual_Range

The normal minimum and maximum water levels in metres below ground level (mbgl) for the borehole is given. In the majority of cases, this information was not available from the data sources used, as many borehole records give one-off water level readings.

2.28 Rwl_Max_Annual_Range

Based on readings from a number of years, the largest annual range is determined and the minimum and maximum water levels (mbgl) are given. These data were not generally available from the data sources used to date.

2.29 Rwl_Comments

Additional comments relating to borehole rest water level are given.

2.30 Rwl_Min, Rwl_Max, Rwl_No_Vals

The minimum, maximum and total number of rest water level values entered for each borehole record are given.

2.31 Spec_Cap_PV

The preferred specific capacity value for the borehole is given in m^3/day/m. It is calculated from the preferred values of yield and drawdown, or if more than one preferred value exists, a geometric mean of these values.

2.32 Spec_Cap_PV_Yield

The yield value used to calculate the preferred value of specific capacity is given in m^3/day.

2.33 Spec_Cap_Qual_Cat

The quality of the preferred specific capacity value is given. This is based on the quality of the yield value used to calculate it.

2.34 Spec_Cap_Comment

Additional comments relating to specific capacity are given.

2.35 Spec_Cap_Min, Spec_Cap_Max, Spec_Cap_No_Vals

The minimum, maximum and total number of specific capacity values entered for each borehole record are given.

2.36 Yield_PV

The preferred yield value for the borehole is given in m^3/day. The value with the highest quality category is chosen. Where more than one value of the highest category exist, an arithmetic average of these values is taken.

2.37 Yield_Qual_Cat

The quality of the preferred yield value is given. A pumping test of >= 1 day duration and with a drawdown of < 20% of the saturated borehole depth is given an ‘A’. Normal operational yield (NOY) data spanning >= 2 years is also given an ‘A’, as is high quality spring flow data averaged over >= 1 year. Where the drawdown is > 20% of the saturated borehole depth, or where the test length is < 1 day, a ‘B’ is assigned to the data. NOY data of < 2 years is also given a ‘B’, along with other spring flow data of 1-5 years duration. Non-pumping test data, unknown data sources and spring flow data of < 1 year duration are given a ‘C’ rating.

2.38 Yield_Comment

Additional comments relating to yield are given.

2.39 Yield_Min, Yield_Max, Yield_No_Vals

The minimum, maximum and total number of yield values entered for each borehole record are given.

2.40 Porosity_PV

The preferred value of core sample porosity is given as a percentage. The value with the highest quality category is chosen. Where more than one value of the highest category exist, an arithmetic average of these values is taken.

2.41 Porosity_Qual_Cat

The quality of the preferred porosity value is given. Data taken from a known laboratory, with known quality standards are given an ‘A’; data from a known lab with unknown quality standards is given a ‘B’; data from an unknown source is given a ‘C’.

2.42 Porosity_Comment

Additional comments relating to porosity are given.

2.43 Porosity_Min, Porosity_Max, Porosity_No_Vals

The minimum, maximum and total number of porosity values entered for each borehole record are given.

2.44 Perm_Vert_PV

The preferred value of core sample vertical permeability is given in millidarcies. The value with the highest quality category is chosen. Where more than one value of the highest category exist, a harmonic mean of these values is taken.

2.45 Perm_Vert_Qual_Cat

The quality of the preferred vertical permeability value is given. The criteria are the same as those used for porosity.

2.46 Perm_Vert _Min, Perm_Vert _Max, Perm_Vert _No_Vals

The minimum, maximum and total number of vertical permeability values entered for each borehole record are given.

2.47 Perm_Horiz_PV

The preferred value of core sample horizontal permeability is given in millidarcies. The value with the highest quality category is chosen. Where more than one value of the highest category exist, an arithmetic mean of these values is taken.

2.48 Perm_Horiz_Qual_Cat

The quality of the preferred horizontal permeability value is given. The criteria are the same as those used for porosity.

2.49 Perm_Horiz _Min, Perm_Horiz _Max, Perm_Horiz _No_Vals

The minimum, maximum and total number of horizontal permeability values entered for each borehole record are given.

2.50 Perm_Comment

Additional comments relating to permeability are given.

2.51 Hyd_Vert_PV

The preferred value of vertical hydraulic conductivity is given in m/day. The value with the highest quality category is chosen. Where more than one value of the highest category exist, a harmonic mean of these values is taken.

2.52 Hyd_Vert_Qual_Cat

The quality of the preferred horizontal hydraulic conductivity value is given. Where the value has been obtained from core sample testing, the criteria are the same as those used for porosity. Where the hydraulic conductivity has been calculated from a pumping test, the quality of the transmissivity value is used.

2.53 Hyd_Vert _Min, Hyd_Vert _Max, Hyd_Vert _No_Vals

The minimum, maximum and total number of vertical hydraulic conductivity values entered for each borehole record are given.

2.54 Hyd_Horiz_PV

The preferred value of horizontal hydraulic conductivity is given in m/day. The value with the highest quality category is chosen. Where more than one value of the highest category exist, an arithmetic mean of these values is taken.

2.55 Hyd_Horiz_Qual_Cat

The quality of the preferred horizontal permeability value is given. The criteria are the same as those used for vertical hydraulic conductivity.

2.56 Hyd_Horiz_Min, Hyd_Horiz Max, Hyd_Horiz _No_Vals

The minimum, maximum and total number of vertical permeability values entered for each borehole record are given.

2.57 Hyd_Gen_PV

The preferred value of overall hydraulic conductivity is given in m/day. This is calculated as a geometric mean of vertical and horizontal hydraulic conductivities from the highest available quality category.

2.58 Hyd_Gen_Qual_Cat

The quality of the preferred overall hydraulic conductivity value is given. The criteria are the same as those used for vertical hydraulic conductivity.

2.59 Hyd_Gen_Min, Hyd_Gen_Max, Hyd_Gen _No_Vals

The minimum, maximum and total number of vertical permeability values entered for each borehole record are given.

2.60 Hyd_Comment

Additional comments relating to hydraulic conductivity are given.

3. NOTES ON QUALITY CATEGORISATION

In interpreting the guidelines given on quality categorisation and preferred values (outlined in the appropriate data fields above), the following rules have been used. These often concern the presence (or absence) of a pumping test, in cases where its occurrence has not been mentioned explicitly.

- Where a value for a parameter is given in the absence of any other information on a borehole (e.g. Pumping frequency, rest water level, pumped water level, yield, mention of pumping test), it is treated as being of poor quality (Quality category 'C').
- Where there is a value for both rest water level and pumped water level, a pumping test is assumed to have been carried out (Quality category 'A' or 'B').
- Where there is a value for rest water level and yield, a pumping test is assumed to have been carried out.
- Where the yield is given, along with an operational frequency of 24 hours per day and the absence of a rest water level reading, the value is assumed to be the normal operational yield for the well, in the absence of other information (Quality category 'A' or 'B').
- If information provided shows internal inconsistencies or other clear errors, the data is normally treated as being poor (Quality category 'C'), unless the errors do not put the reliability of the relevant parameters in doubt (e.g. data can be verified from another source; error is trivial, such as a spelling mistake).
- Where seasonal variability is quantitatively described, rest water levels are assumed to have been obtained through reliable monitoring of the borehole (Quality category 'A').
- Where there is information to suggest that the value of a parameter has changed since the value provided (e.g. 'has suffered from declining yields'), values of rest water level and yield are deemed to be of poor quality (Quality category 'C').
- Where a step test has employed a large number of discharge rates, interpreter discretion has been used to determine which yield values lie significantly below the maximum sustainable yield of the borehole. These values have not been included in calculations of preferred yield.

This guidance is in addition to the original guidelines given. Therefore, in the absence of pumping test duration, for example, the pumping test is assumed to have lasted for less than one day, and is assigned a 'B', rather than an 'A'. The same principles have been applied to the guidelines above, and where there is cause for reasonable doubt, the lower data quality category is assigned to any value. Given the array of various data formats encountered, some level of interpreter discretion has been employed in categorising the quality of data.

4. ANALYSIS OF DATA

It is clear from Table1 that the majority of entered data are from four main groups of aquifer – Permian, Carboniferous, Devonian and superficial. This is to be expected, as these highly productive groups are present in the most heavily populated parts of the country where groundwater is most easily exploited. While there is a large quantity of yield data available, the other parameters are under-represented. Gathering further specific capacity, transmissivity and core sample data is a priority for Year 2 of the project.

Table 1 Number of boreholes containing data on a range of aquifer properties, for both superficial deposits and bedrock stratigraphical periods.

Age or type	Yield	Specific capacity	Transmissivity	Porosity	Permeability	Hydraulic conductivity
Superficial	151	28	15	1	1	1
Tertiary	0	0	0	0	0	0
Cretaceous	0	0	0	0	0	0
Jurassic	0	0	0	0	0	0
Triassic	1	0	0	0	0	0
Permian	68	36	31	13	11	13
Carboniferous	545	46	2	15	15	15
Devonian	236	62	32	13	13	11
Silurian	51	1	0	0	0	0
Ordovician	24	1	0	0	0	0
Cambrian	0	0	0	0	0	0
Precambrian	8	0	0	0	0	0
Unknown	271	15	3	7	7	7

Figure 1 shows a good correlation between the measured mean arithmetic yield values in each type of aquifer and the expected level of productivity (for explanation of codes used, see Appendix). The major discrepancy between values of FVL-type aquifers containing mine workings and those with no mining highlights the dramatic effect on borehole yield of encountering old workings. The lack of data on FM and IFVL type aquifers suggests that more data collection is required in this area.

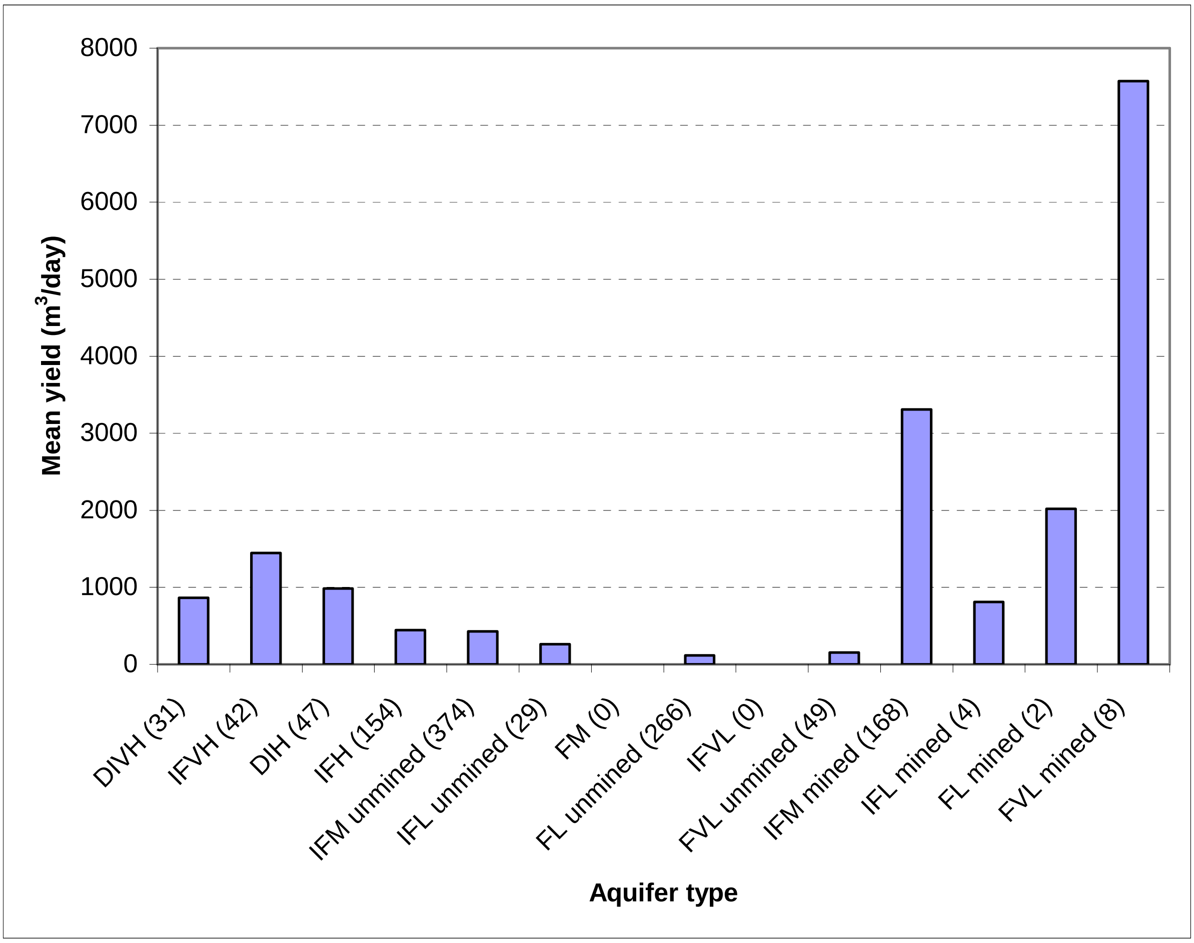

Figure 1 Mean yield values for different aquifer flow categories. The number of data points for each flow type is given in brackets

More than two-thirds of all yield values lie below 1000 m^3/day, as shown by Figure 2. There is a further sharp decline in the number of yields above 3000 m^3/day, with nearly 90% of all values below this amount. A high proportion of values are less than 50 m^3/day, representing the large number of shafts, wells and springs used for domestic or agricultural supply.

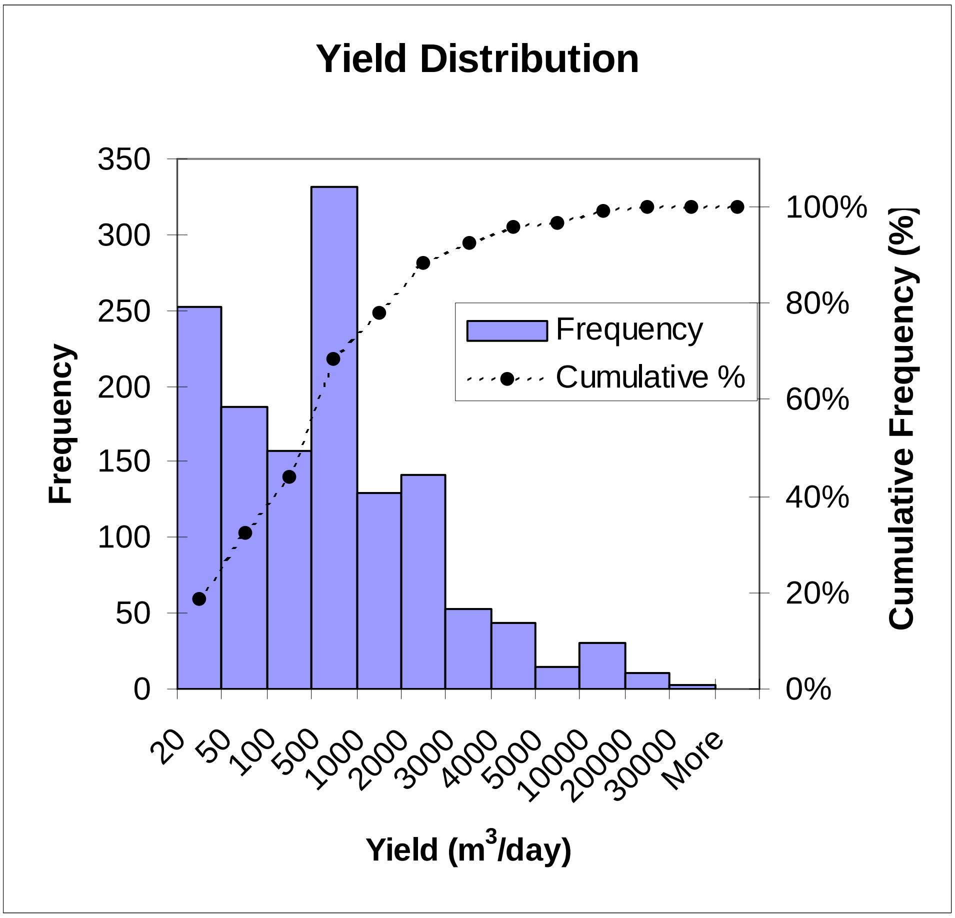

Figure 2 Cumulative frequency and frequency distribution of yields

4.1 Devonian

Tables 2 a)–c) suggest that the Strathmore Group is the most productive of the Devonian groups, showing values of transmissivity and specific capacity which are well above average for the Devonian as a whole. There is a reasonable quantity and spread of data for the Devonian across Scotland owing to the exploitation of this aquifer for agricultural purposes.

Table 2 Parameter values and quantity of data for Devonian groups, classified by: a) transmissivity b) yield (nil values indicate dry boreholes) and c) specific capacity

a) Transmissivity (m^2/day)

Group	T values	Min. Value	Max. Value	Arithmetic Mean	Median
Arbuthnott-Garvock	5	3.76	200	48.4	4.05
Stratheden	2	49.3	51.85	50.6	50.6
Strathmore	9	1.74	863	172.2	100
Other Devonian	21	0.93	721	132.7	58
All Devonian	37	0.93	863	127.9	51.85

b) Yield (m^3/day)

Group	Yield Values	Min. Value	Max. Value	Arithmetic Mean	Median
Arbuthnott-Garvock	64	0.9	1745	415	122.5
Stratheden	14	17.3	3602	631.1	276.3
Strathmore	25	0.35	1955.5	489.5	129
Other Devonian	136	0	3456	396.7	95
All Devonian	239	0	3602	425	112.3

c) Specific capacity (m^3/day/m)

Group	S.C. Values	Min. Value	Max. Value	Arithmetic Mean	Median
Arbuthnott-Garvock	13	0.16	492	72.01	44
Stratheden	3	78.4	182.5	129.9	138
Strathmore	13	2.7	856	180.5	112.5
Other Devonian	37	0.79	769.5	84.8	43.2
All Devonian	66	0.16	856	100.6	51.3

4.2 Carboniferous

Tables 3 a)-d) show that while there is a large quantity of yield data available for the Carboniferous, much of it from mine dewatering, there is a need to obtain more transmissivity data. The effects of coal mining on yield are again highlighted. In its absence, the Carboniferous strata are shown to be less productive overall than the rocks of the Devonian. None of the transmissivity values for the Carboniferous relate to boreholes penetrating old mine workings. They are higher than the average transmissivity recorded for the Devonian, although this may not be representative of Carboniferous aquifers overall, given the limited amount of data.

Table 3 Carboniferous data, by group, for a) transmissivity, b) yield, c) specific capacity and d) yield from mine workings

a) Transmissivity (m^2/day)

Group	T values	Min. Value	Max. Value	Arithmetic Mean	Median
Clackmannan	0	0	0	0	0
Coal measures	0	0	0	0	0
Inverclyde	2	530	760	645	645
Strathclyde	1	70.3	70.3	70.3	70.3
Other Carboniferous	0	0	0	0	0
All Carboniferous	3	70.3	760	453.4	530

b) Yield (m^3/day)

Group	Yield values	Min. Value	Max. Value	Arithmetic Mean	Median
Clackmannan	190	0	22248	2058.7	527
Coal measures	124	0	20131.2	1994.8	1209.6
Inverclyde	14	19.9	5356.8	1482.4	610.9
Strathclyde	158	0	6549.1	399.4	110.5
Other Carboniferous	59	0.08	14256	669.2	259
All Carboniferous	545	0	22248	1325.4	362.9

c) Specific capacity (m^3/day/m)

Group	S.C. Values	Min. Value	Max.Value	Arithmetic Mean	Median
Clackmannan	12	1.4	1319.6	180.6	40.3
Coal measures	6	0.8	207.7	86.4	94.2
Inverclyde	6	8.7	608.7	304.3	381.1
Strathclyde	19	0.3	436	79.5	20.5
Other Carboniferous	4	7.9	166.9	74.1	60.8
All Carboniferous	47	0.3	1319.6	134.4	44.03

d) Carboniferous yields from old workings/no old workings (m^3/day)

Status	Yield values	Min. Value	Max. Value	Arithmetic Mean	Median
Mine workings present	189	40.6	22248	3337.1	1987.2
Mine workings not present	356	0	5356.8	396.3	129.6

4.3 Permian

Tables 4 a) – c) show the Permian to include highly productive aquifers. There is also a large volume of data available for the Permian, due mainly to the large amount of work carried out for public supply on Arran and in Dumfries and Galloway.

Table 4 Permian data classified by group, for a) transmissivity, b) yield and c) specific capacity

Transmissivity (m^2/day)

Group	T values	Min. Value	Max. Value	Arithmetic Mean	Median
Stewartry	13	94	3979	749.9	450
Other Permian	18	5	2594	387.3	115.7
All Permian	31	5	3979	539.4	252.3

Yield (m^3/day)

Group	Yield values	Min. Value	Max. Value	Arithmetic Mean	Median
Appleby	3	112.3	216	146.9	112.3
Stewartry	33	0	5702.4	1500.9	362.9
Other Permian	32	13	3715.2	986.7	475.2
All Permian	68	0	5702.4	1199.2	349.9

c) Specific capacity (m^3/day/m)

Group	S.C. Values	Min. Value	Max. Value	Arithmetic Mean	Median
Stewartry	19	12.16	1540.7	460.1	293.8
Other Permian	17	1.97	221.8	82.9	78.6
All Permian	36	1.97	1540.7	283.4	121.4

4.4 Superfical deposits

Tables 5a) - c) display the range of values for superficial deposits. There is a large quantity of data available, showing significant variation in productivity for the various types of superficial material. Mixed alluvium and alluvial and river terrace deposits show the highest yields, whilst glaciofluvial deposits appear to be the most transmissive.

Table 5 Superficial deposits data for a) transmissivity, b) yield and c) specific capacity

a) Transmissivity (m^2/day)

Deposit	T values	Min. Value	Max. Value	Arithmetic Mean	Median
Alluvium	9	15.6	3100	832.5	570
Alluvium and River Terrace	2	350	1400	875	875
Glaciofluvial	2	761	1600	1180.5	1180.5
Raised Beach and Marine	2	75	178	126.5	126.5
All Superficials	15	15.6	3100	790.5	570

b) Yield (m^3/day)

Deposit	Yield values	Min. Value	Max. Value	Arithmetic Mean	Median
Alluvium	66	8.64	8726.4	1056.9	514.1
Alluvium and River Terrace	2	1140	1400	1270	1270
Blown Sand	1	85	85	85	85
Glaciofluvial	23	0	1296	247.9	43
Lacustrine	2	25.9	652.3	339.1	339.1
Raised Beach and Marine	24	3	2400	437.5	203
Till	27	0	518	66.8	21
Unknown superficials	6	17.3	112.3	131	60.5
All Superficials	151	0	8726.4	593.2	164.16

c) Specific capacity (m^3/day/m)

Deposit	S.C. Values	Min. Value	Max. Value	Arithmetic Mean	Median
Alluvium	14	1.7	3456	667.6	418.9
Alluvium and River Terrace	2	435	1521	978	978
Glaciofluvial	5	1.7	1450.7	691.6	921.6
Raised Beach and Marine	7	25	305	93.1	63.4
All Superficials	28	1.7	3456	550.5	729.8

4.5 Yield data – all categories

Table 6 shows the majority of yield values to be of poor quality (C), with only around 5% of values being rated as good or very good (A). This highlights the need for further data collection within Phase 2 of the project.

Table 6 Quantity and range of yield data per quality category (m^3/day)

Quality Category	Yield values	Min. Value	Max. Value	Arithmetic Mean	Median
A	77	0	7862.4	507.6	967
B	499	0	14256	777.9	311.8
C	779	0	22248	839.9	86.4

Figure 3 shows sedimentary rock to be the most productive lithology. This category was normally applied to cyclic sequences of thin sedimentary strata, as found in the Carboniferous. For this reason, it is likely that many of the highest yield values in this category are actually caused by mine dewatering and do not reflect the true productivity of the sedimentary sequences themselves. Superficial deposits containing sand or gravel are the next most productive lithologies, followed by sandstone. Crystalline rocks, having low permeability with fracture flow, give low overall mean yield values.

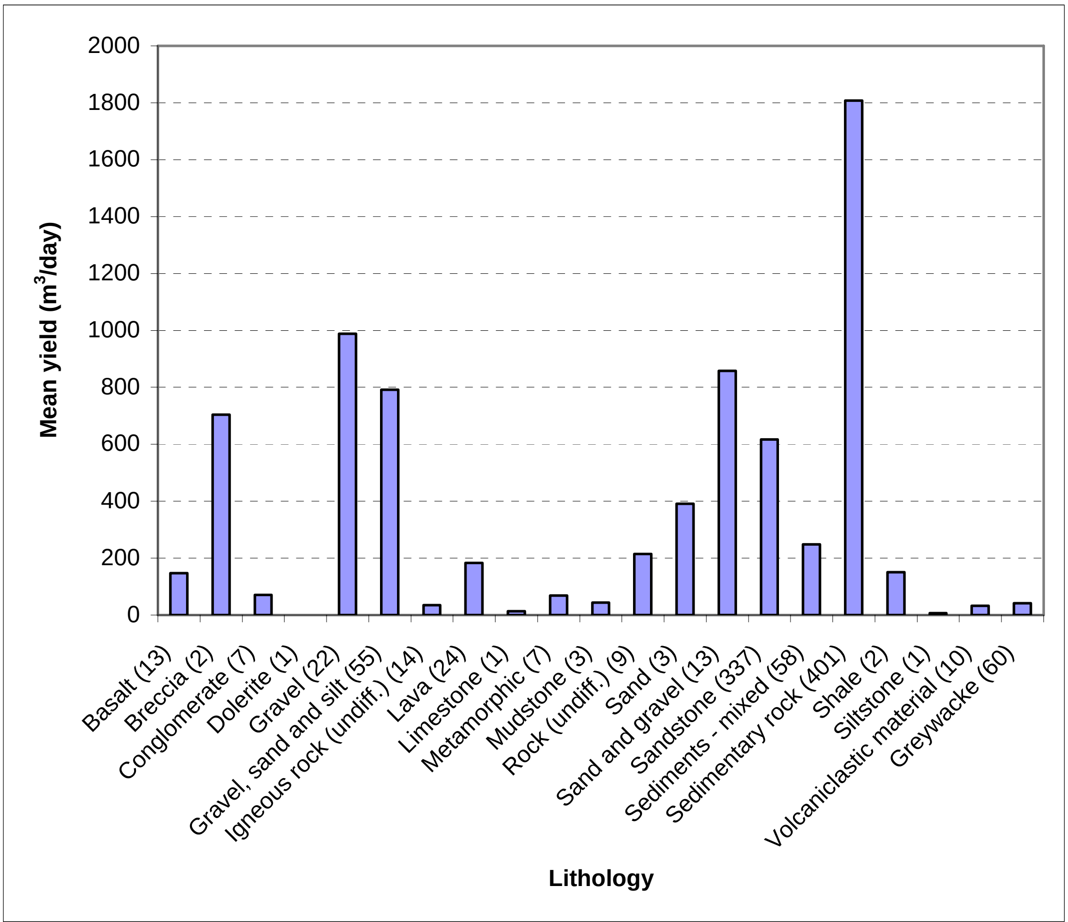

Figure 3 Mean yield values per lithology. The number of data points for each lithology is given in brackets

4.6 Specific Capacity Data

Table 7 shows the majority of specific capacity values to be of either moderate (B) or good (A) quality. The value of specific capacity seems to be slightly higher for higher quality data, suggesting a possible bias towards more thorough data collection for more productive rock units.

Table 7 Quantity and range of specific capacity data per quality category (m^3/day/m)

Quality Category	S.C. values	Min. Value	Max. Value	Arithmetic Mean	Median
A	71	2	3456	239.5	102
B	115	0.3	1564.9	205.5	46.7
C	4	0.2	89.7	42.1	39.2

4.7 Transmissivity Data

Table 8 shows the majority of transmissivity data to be of good quality. It is perhaps unsurprising that where this type of data has been collected, the quality of the data collection is high.

Table 8 Quantity and range of transmissivity data per quality category (m^2/day)

Quality Category	T values	Min. Value	Max. Value	Arithmetic Mean	Median
A	64	3.9	3979	45.6	182
B	19	1.7	1600	259	20
C	0	0	0	0	0

4.8 Core Data

Table 9 shows almost all core data to be of the highest quality. Almost all core data are derived from analyses undertaken by BGS labs with known quality standards.

Table 9 Quantity and range of core data per quality category for a) porosity (%) b) vertical permeability (millidarcies) c) horizontal permeability (millidarcies) d) overall hydraulic conductivity (m/d) (individual K values calculated from the geometric mean of vertical and horizontal K data).

a) Porosity (%)

Quality Category	Porosity values	Min. Value	Max. Value	Arithmetic Mean	Median
A	49	1.4	27	15.6	15.6
B	0	0	0	0	0
C	0	0	0	0	0

b) Vertical permeability (millidarcies)

Quality Category	Vertical k values	Min. Value	Max. Value	Arithmetic Mean	Median
A	41	0.002	996.5	57.3	0.529
B	0	0	0	0	0
C	0	0	0	0	0

c) Horizontal permeability (millidarcies)

Quality Category	Horizontal k values	Min. Value	Max. Value	Arithmetic Mean	Median
A	47	0.0025	2911.09	402.2	95.7
B	0	0	0	0	0
C	0	0	0	0	0

d) Overall hydraulic conductivity (m/day)

Quality Category	Overall K values	Min. Value	Max. Value	Arithmetic Mean	Median
A	43	1.3×10^{-06}	4	0.2	0.01
B	4	1	199.7	86.3	10
C	0	0	0	0	0

Figure 4 shows the spatial distribution of yield data. The majority of yield data in the SAPD come from the central belt of Scotland, with very little data available for the area north of the Highland Boundary Fault. There is good coverage across the main aquifers of Fife, Strathmore and the Permian basins of the southwest.

Figure 5 indicates that there is a need for higher quality yield data, particularly in the southern part of Fife, within the Carboniferous aquifers. Figure 5 also shows that, although the majority of the yield data are found within the Midland Valley, those present in other parts of Scotland are generally of higher quality, particularly in the Permian basins of the southwest where there are a number of 'A' category data points.

Figure 6 shows the distribution of specific capacity data to be similar to that of the yield data, with good coverage across the Midland Valley and a need for further data collection in the Highlands.

There is a reasonable spread of transmissivity values across Scotland, as displayed in Figure 7. Within the highly productive aquifers, the Fife Devonian aquifer is currently lacking data for several of the Scottish Water abstraction sources to the east of Loch Leven. These data will be entered in to the database in Year 2. Many of the transmissivity data are derived from BGS/Scottish Water projects across Scotland, with the remainder from other consultants reports.

Figure 8 shows there to be a limited quantity of core data for the southern part of Scotland, with an almost complete absence to the north of Fife. The collection of further samples in the Highlands and Strathmore in particular will be a priority for Year 2 of the project (2006/2007 financial year).

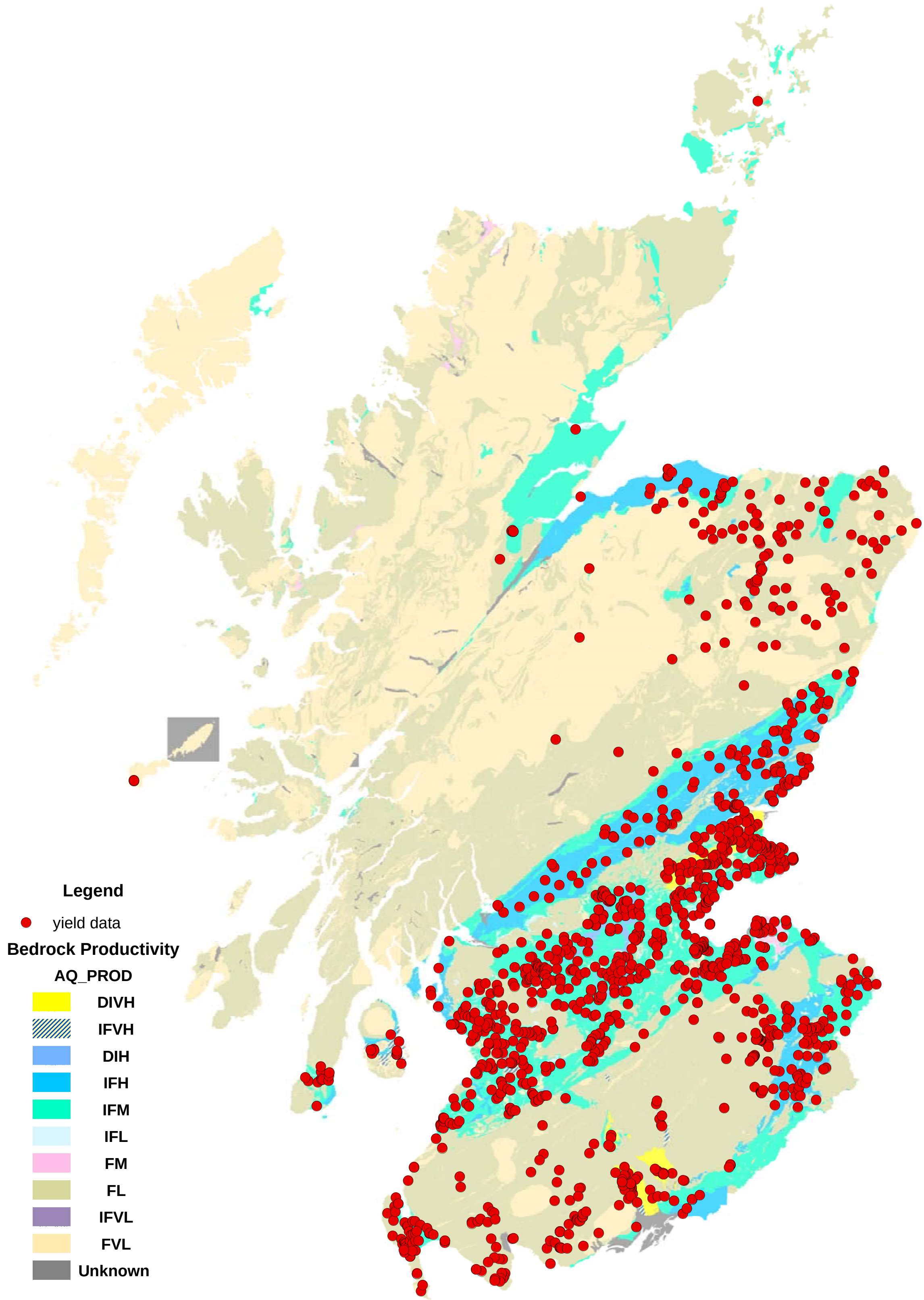

Figure 4 Spatial distribution of yield data ('AQ_PROD' codes given in appendix).

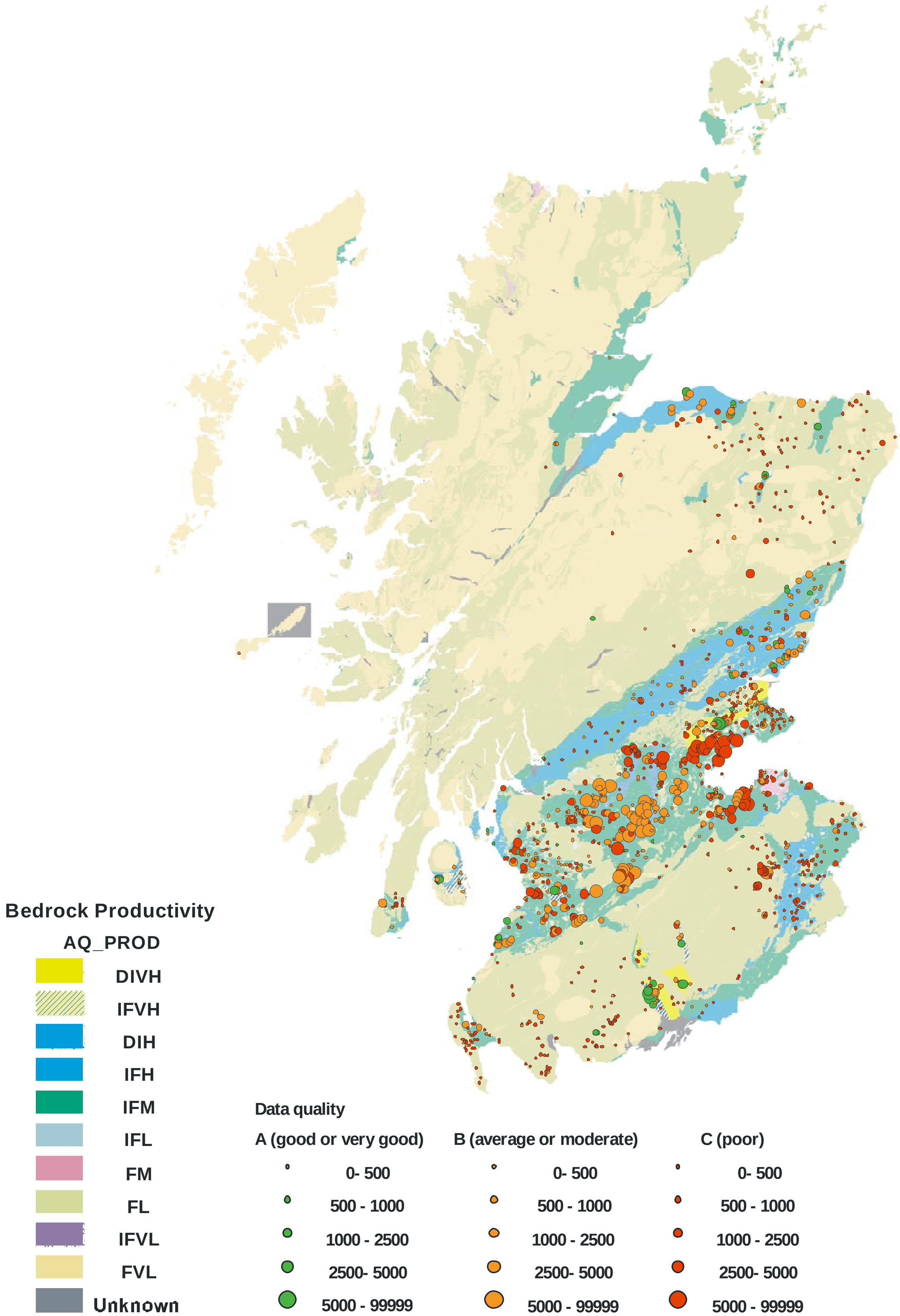

Figure 5 The distribution and quality of yield data (in m^3/day)

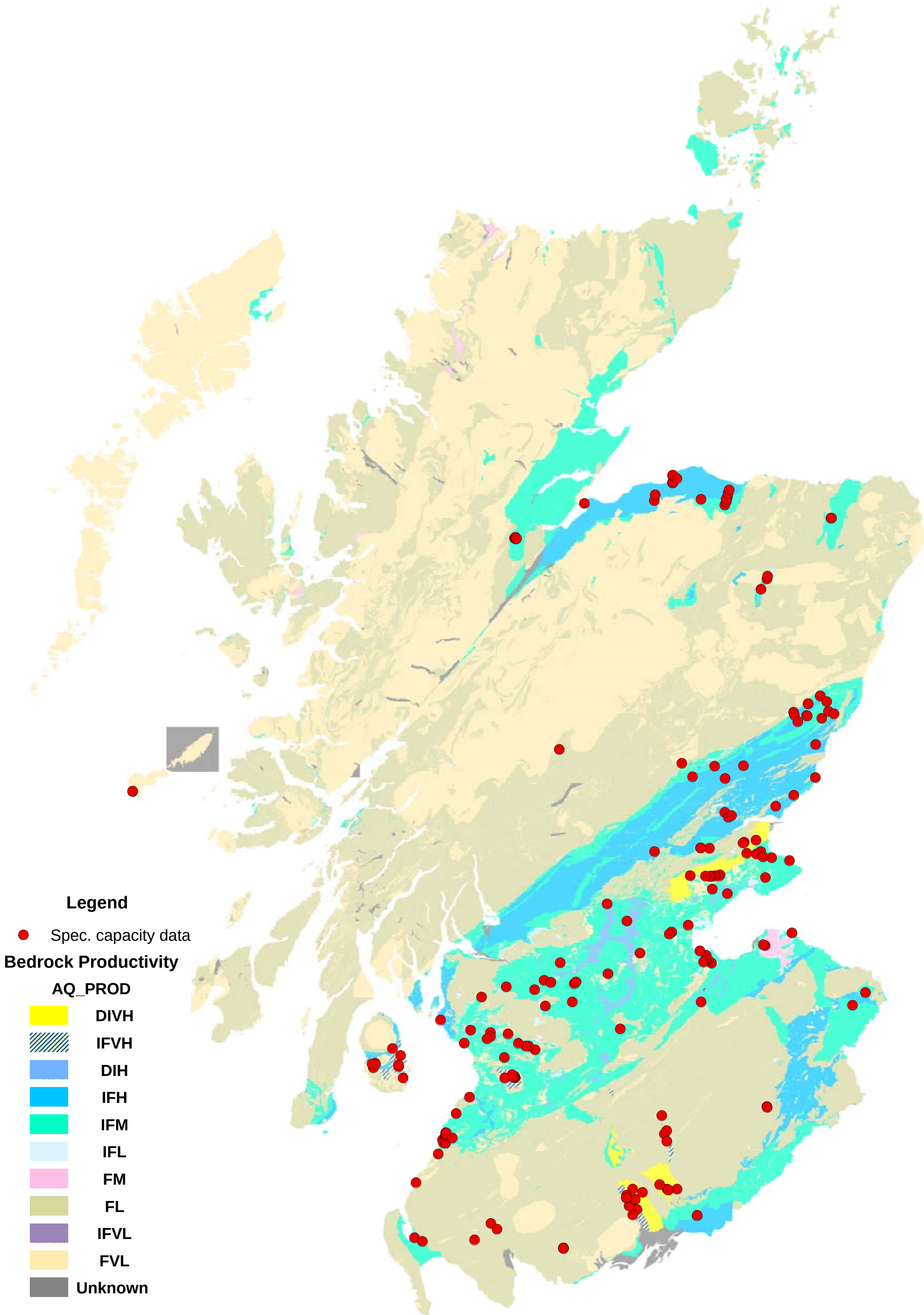

Figure 6 Spatial distribution of specific capacity data.

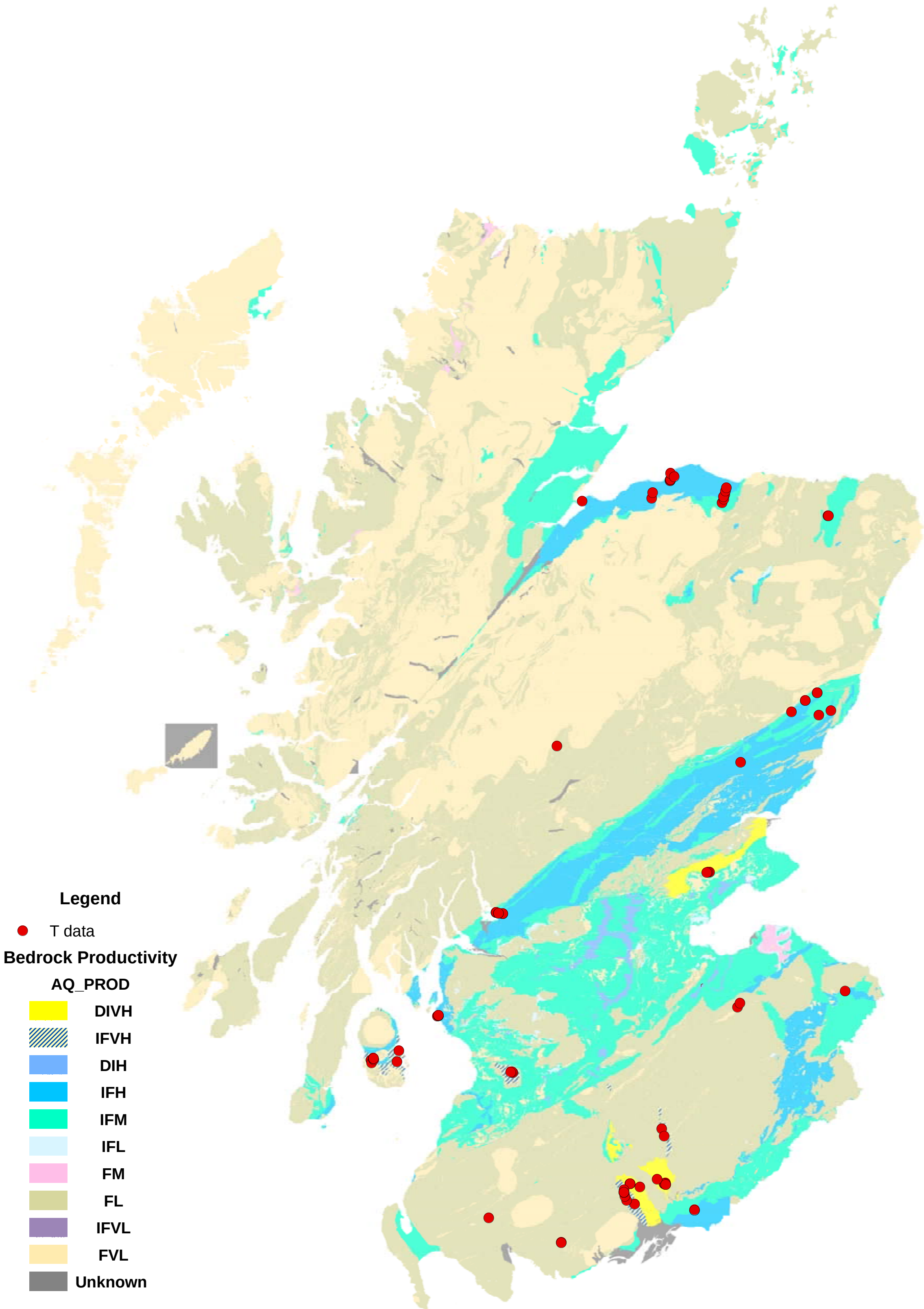

Figure 7 Spatial distribution of transmissivity data

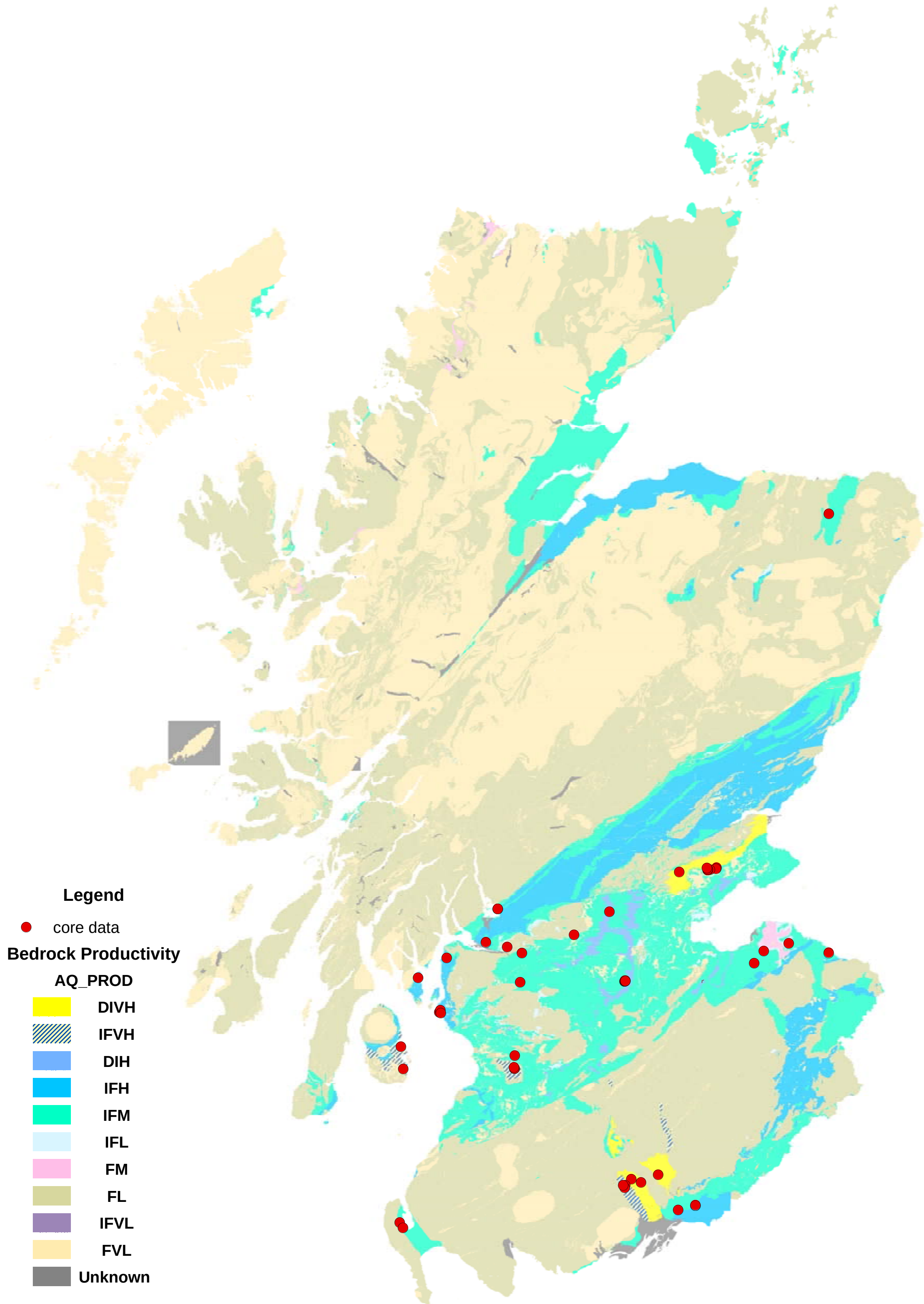

Figure 8 Spatial distribution of core data (porosity, permeability or hydraulic conductivity)

5. FURTHER WORK

For Year 2:

- Continued input of BGS data to the database. A summary of this data, along with appropriate analysis, will be presented in a final report at the end of the two-year funding period.
- Collation of remaining external data from mineral water companies and other sources
- Collection of core samples from existing core at local drillers. Existing core samples in the BGS collection have proved insufficient, whereby few samples are available for Scotland and of those present, most are of too small a diameter to have plugs taken for analysis
- Collection of new core from new boreholes. This will involve using private borehole projects to 'add-on' extra work by funding core collection during the drilling process. The selection of which boreholes to use for this work will be made after drilling companies have informed BGS of where they are about to drill. Emphasis will be made towards boreholes located in the Devonian aquifers of Strathmore and Moray where few samples are currently available. To date, the majority of the core samples are from Carboniferous formations in the Midland Valley.
- The development of the database to allow the public to access the information, ideally being hosted on the BGS website, along with a set of other GIS-based data sets which currently reside there.
- Discussions are to continue on a strategy for maintaining the database at the end of the current two-year funding period. This may involve a system of licensing of the data, which would finance continued updates of the product.

GLOSSARY

Strat_1

Bedrock Stratigraphical Periods:

CARB - Carboniferous
DEV - Devonian
JURA - Jurassic
PUND - Permian
ORD - Ordovician
PROT - Precambrian
SILU - Silurian
TER - Tertiary
TRIA - Triassic

Superficials:

ALRT - Alluvium and river terrace deposits
ALV - Mixed alluvium
BSA - Blown sand
GFDU - Glaciofluvial deposits
LAT - Lacustrine alluvium
RIRM - Raised intertidal deposits and raised marine deposits
SUPD - superficial deposits (undifferentiated)
SUPNM - superficial deposits (not mapped)
TILL - Glacial till

STRAT_2

Bedrock Stratigraphical Groups:

APY - Appleby
ATGK - Arbuthnott-Garvock
BATH - Bathgate
CKN - Clackmannan
CMSC - Coal Measures
CNFL - Caithness Flagstone
DALN - Dalradian
DRCR - Dunottar-Crawton
EDY - Eday
GAHW - Gala and Hawick
GRAM - Grampian
ICSC - Inverclyde and Strathclyde (undiff.)
INV - Inverclyde
LHG - Leadhills
M - Moine
SAG - Stratheden
SEG - Strathmore
SOHI - Southern Highlands
STEW - Stewartry
SYG - Strathclyde
WEN - Wenlock

STRAT_3

Bedrock Stratigraphical Formations:

AUC - Auchtitench Sandstone
BGN - Ballagan
CPV - Clyde Plateau Volcanic
DBR - Doweel Breccia
GEF - Glenvale Sandstone
GNE - Glenlee
KKF - Kirkcolm
KNW - Kinnesswood
LCH - Locharbriggs Sandstone
LCMS - Lower Coal Measures
LLGS - Lower Limestone
LSC - Limestone Coal
MCMS - Middle Coal Measures
MSS - Mauchline Sandstone
PPF - Portpatrick
PGP - Passage
SHIN - Shinnel
THHS - Thornhill Sandstone
UCMS - Upper Coal Measures
ULGS - Upper Limestone
WLO - West Lothian Oil-Shale

LITHOLOGY

BA - basalt
BREC - breccia
CONG - conglomerate
DOLR - dolerite
GRAV - gravel
GRSS - gravel, sand and silt
IGRU - igneous rock
LAVA - lava
LMST - limestone
MDST - mudstone
METR - metamorphic rock
PSAMM - psammite
ROCK - rock (undiff.)
SAGR - sand and gravel
SANDU - sand
SDST - sandstone
SED - sediments
SHL - shale
SLST - siltstone
SLTCLY - clayey silt
SR - sedimentary rock
STCL - silt and clay
VCSD - volcaniclastic material
WACKE - greywacke

AQUIFER TAPPED

DUMF- Dumfries (the Permian sandstone and breccia aquifer within the Dumfries Basin)
FIFE - Fife (The Upper Devonian sandstone aquifer from Loch Leven along the Eden valley to Guardbridge)
LCM - Lochmaben (the Permian basin at Lochmaben)
MCL - Mauchline (The Permian sandstone basin at Mauchline)
MOFF- Moffat (the Permian breccia/sandstone aquifer in the Annan valley at Moffat)
MORAY- Moray (Devonian Formations east of Inverness bordering the south Moray Firth coastline)
STRATH - Strathmore (Lowe Devonian strata between Loch Lomond and Inverbervie)
THH - Thornhill (Permian sandstone around Thornhill, Dumfries and Galloway)

Aquifer tapped type

DIFL Dominantly intergranular low
DIFM Dominantly intergranular medium
DIH Dominantly intergranular high
DIVH Dominantly intergranular very high
DIVL Dominantly intergranular very low
FH Fracture high
FL Fracture low
FM Fracture medium
FVH Fracture very high
FVL Fracture very low
IFH Intergranular/fracture high
IFL Intergranular/fracture low
IFM Intergranular/fracture medium
IFVH Intergranular/fracture very high
IFVL Intergranular/fracture very low
IH Intergranular high
IL Intergranular low
IM Intergranular medium
IVH Intergranular very high
IVL Intergranular very low