BRITISH GEOLOGICAL SURVEY
Natural Environment Research Council

TECHNICAL REPORT WD/00/07
Hydrogeology Series

Technical Report WD/00/07

Reconnaissance Hydrogeological Survey of Guernsey

N S Robins, K J Griffiths, P D Merrin
and W G Darling

This report was prepared for
States of Guernsey Water Board

Bibliographic Reference

Robins N S, Griffiths K J, Merrin P D
and Darling W G 2000
Reconnaissance Hydrogeological
Survey of Guernsey
British Geological Survey Report WD/00/07

British Geological Survey Keyworth, Nottinghamshire

BRITISH GEOLOGICAL SURVEY

BRITISH GEOLOGICAL
SURVEY
KEYWORTH
NOTTINGHAM NG12 5GG
UNITED KINGDOM

TEL (0115) 9363100
FAX (0115) 9363200

DOCUMENT TITLE AND AUTHOR LIST

[Click here and type TITLE]

[Click here and type AUTHORS]

CLIENT	CLIENT REPORT #
	BGS REPORT#
	CLIENT CONTRACT REF
	BGS PROJECT CODE
	CLIENT CLASSIFICATION

	SIGNATURE	DATE		SIGNATURE	DATE
PREPARED BY (Lead Author)			CO-AUTHOR		
			CO-AUTHOR		
PEER REVIEWED BY			CO-AUTHOR		
			CO-AUTHOR		
CHECKED BY (Project Manager or deputy)			CO-AUTHOR		
			CO-AUTHOR		
APPROVED BY (Project Director or senior staff)			CO-AUTHOR		
			CO-AUTHOR		
APPROVED BY (Hydrogeology Group Manager)			OS Copyright acknowledged		
Layout checked by			Assistant Director clearance (if reqd)		

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desk at the Survey headquarters, Keyworth, Nottingham. The more popular maps and books may be purchased from BGS-approved stockists and agents and over the counter at the Bookshop, Gallery 37, Natural History Museum, Cromwell Road, (Earth Galleries), London. Sales Desks are also located at the BGS London Information Office, and at Murchison House, Edinburgh. The London Information Office maintains a reference collection of BGS publications including maps for consultation. Some BGS books and reports may also be obtained from HMSO Publications Centre or from HMSO bookshops and agents.

The Survey publishes an annual catalogue of maps, which lists published material and contains index maps for several of the BGS series.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG
% 0115-936 3100 Telex 378173 BGSKEY G
Fax 0115-936 3200

Murchison House, West Mains Road, Edinburgh, EH9 3LA
% 0131-667 1000 Telex 727343 SEISED G
Fax 0131-668 2683

London Information Office at the Natural History Museum, Earth Galleries, Exhibition Road, South Kensington, London SW7 2DE
% 0171-589 4090 Fax 0171-584 8270
% 0171-938 9056/57

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, EX2 7HU
% 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
% 01232-666595 Fax 01232-662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
% 01491-838800 Fax 01491-692345

Parent Body
Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
% 01793-411500 Telex 444293 ENVRE G
Fax 01793-411501

Contents

1. INTRODUCTION 1
    - 1.1 Background and Project Brief 1
    - 1.2 Water Use, Land Use and Social Change 2
    - 1.3 Physiography and Climate Change 2
    - 1.4 Geological Setting 3
    - 1.5 Existing Groundwater Database 6

2. GROUNDWATER RESOURCES 6
    - 2.1 Data Collection 6
    - 2.2 Water Budget 6
    - 2.3 The Bedrock Aquifer 8
    - 2.4 Recharge, Storage and Groundwater Flow 9
    - 2.5 Groundwater Demand 15

3. GROUNDWATER CHEMISTRY 15
    - 3.1 Data Collection and Field Sampling 15
    - 3.2 Regional Groundwater Chemistry 16
    - 3.3 Pollution and Potability 18
    - 3.4 Stable Isotopes 20
    - 3.5 Chlorofluorocarbons 21

4. THE RENEWABLE RESOURCE 22
    - 4.1 The Single Water Body 22
    - 4.2 Origin of the Water Resource 23

5. CONCLUSIONS AND RECOMMENDATIONS 23
    - 5.1 Conclusions 23
    - 5.2 Recommendations 24

Acknowledgements 25

References 25

APPENDIX 1 Physical Characteristics of Wells, Boreholes and Springs 26

APPENDIX 2 Inorganic Groundwater Chemistry (mg l^{-1}) 28

List of Figures

Figure 1 Cross-section of Guernsey and its geological setting 3
Figure 2 Simplified geological map of Guernsey (after Roach *et al*, 1991) 5
Figure 3 Channel Islands average monthly rainfall 8
Figure 4 Rest water level fluctuations for the States of Guernsey Water Board Wells 10
Figure 5 La Houguette 1989-1999 11
Figure 6 Groundwater level contours 13
Figure 7 Schematic groundwater flow systems 14
Figure 8 Island-wide distribution of pH, SEC, DO and Cl 17
Figure 9 Piper diagram showing major ions 18
Figure 10 Na, Ca, K and Mg plotted against rain-water sea-water trend line 19
Figure 11 Occurrence of total organic nitrogen 20
Figure 12 (a) δ-plot with meteoric water line (WML) and seawater mixing line, (b) δ^{18}O-Cl plot with seawater mixing line. 21

List of Tables

Table 1 Long term mean average rainfall data 3
Table 2 Principal geological formations, ages and rock types 5
Table 3 Summary data from public consultation 7
Table 4 Stable isotope analyses in per mil with respect to Vienna Standard Mean Ocean Water (VSMOW) 20
Table 5 CFC values for Guernsey groundwaters. Concentrations in pmol/l. 21

Executive Summary

The key findings from this study are:

- There is no evidence of any old waters or of any mineralisation indicative of long or deep flow paths from an off-island source;
- The unpredictable nature of the so called “deep aquifer” (25 m plus beneath the water table) does not warrant its further exploitation;
- The uppermost “shallow aquifer” can best be exploited by dispersed small volume sources
- The groundwater body and the surface water body are part of a single water system;
- Reduction in aquifer yield with depth provides a self protection mechanism to the aquifer;
- Based on the survey conducted there is a consensus on Guernsey that the renewable water resource is finite and that it needs safeguarding.

The annual volume of water supplied by the States of Guernsey Water Board is approximately 5 Mm^3. Additional abstraction from private sources may amount to a further 1.5 Mm^3, particularly in a relatively dry year. The public water supply derives from surface water courses and is stored in surface water reservoirs. The private abstractions draw on groundwater (wells, boreholes and springs), roof top collection and surface water abstraction. The groundwater body and the surface water body are part of a single water system. Groundwater discharge (or baseflow) from springs and seepages into streams maintains the surface water low-flows during prolonged dry weather.

The groundwater body is itself divisible into three contiguous levels. Where present, there is an upper granular aquifer within superficial deposits of alluvium and raised beach material. Beneath this is the main aquifer which is contained within the shallow weathered zone of the bedrock, which is underlain by a deeper aquifer with groundwater flow restricted to occasional dilated fractures. Bedrock mainly consists of ancient crystalline metamorphic rocks.

Generally, the water table lies within 3 to 8 metres of the ground surface, and the main aquifer, in which the majority of groundwater flow takes place, is situated in a 25 m zone immediately below the water table. Beneath this depth there is some groundwater flow in deeper fractures, but borehole yields from the greater depths are commonly less than those from the shallow weathered zone. This reduction in aquifer yield with depth provides an element of self protection, whereby baseflow discharge from the aquifer and abstraction from boreholes is automatically reduced as the water table falls.

Groundwater recharge occurs in the High Parishes and flows south to the coast and north-west to the coast. There is little potential for groundwater flow beneath the low-lying land towards the northern part of the island.

Using meteorological and catchment recharge calculations from Jersey as an analogue, the normal average annual water budget for the island can be assigned:

Rainfall = 831 mm
= Potential evapotranspiration = 613 mm
+ Streamflow = 226 mm (of which nearly 60% derive from groundwater recharge as baseflow)
+ Groundwater recharge = 128 mm

These figures do not reflect a poor rainfall year in which resource renewal may be small and infiltration may be zero. Annual variation in rainfall from the long-term mean is significant, and annual rainfall has been declining since the 1940s over Guernsey.

The groundwater contains an element of salinity derived from rainfall and sea spray, although there is little evidence of actual physical marine invasion of the aquifer. The groundwater samples were otherwise moderately mineralised with specific electrical conductance in the range 427 to 1578 $\mu S\ cm^{-1}$. Over half the 21 samples collected contained NO_3-N (nitrate) at concentrations greater than the EC maximum admissible concentration. Some of the NO_3-N may be derived from leaking cess pits, but past application of nitrogen fertilizer to cultivated land probably accounts for the majority. The average pH of the samples was 6.4. This acidity reflects the lack of carbonate material in the aquifer, other than shelly debris present in the superficial deposits.

Attempts at groundwater dating by analysis of CFC species at a small number of sites was hindered by local contamination, particularly in the vicinity of the airport. It is likely that the pumped groundwaters are mixtures of young and older water. If this is the case, then at three of the four sites sampled, between 75 and 100% of the water can be identified as young, recently recharged water, in keeping with shallow, short flow path groundwater circulation in the main weathered aquifer. At the fourth, only between 40 and 50% of the sample consisted of the young component. However, there was no evidence of any old waters or of any mineralisation indicative of long or deep flow paths from an off-island source.

There is an urgent need to create a small groundwater level and groundwater quality monitoring network. This would provide early warning of any change that may be occurring to the groundwater body. A catalogue of point source pollution risk activities is also recommended. Given consumption of about one third of the overall water resource it is also recommended that a comprehensive evaluation of the groundwater system would assist the overall management of the resource.

1. INTRODUCTION

1.1 Background and Project Brief

Water supplies in Guernsey derive largely from surface storage and are mainly provided by the States Water Board. In addition, private abstraction satisfies domestic and commercial demand amounting to between 10% and 30% of the total; much of this usage is seasonal. Private abstraction draws on groundwater, stream off-takes and roof top collection. Long term average rainfall over the island has declined since the 1940s and there is concern of over use of resources particularly at times of stress (e.g. during the years 1989 to 1992 and 1996 to 1997). Understanding of the island-wide resource is far from complete, but the optimum exploitation of the renewable resource cannot be achieved without first knowing its magnitude and provenance.

Conscious of this incomplete understanding of the water resources of Guernsey, the States Water Board commissioned the British Geological Survey to carry out a brief reconnaissance survey of the island's groundwater resources. The objectives of this study are fivefold:

(1) To determine if there is any external source of fresh water available under Guernsey, from France or elsewhere, which is independent from the island's own water budget – i.e. is not dependent on rainwater falling on the island.

(2) To review the potential for abstraction of potable groundwater from sources in unweathered rock at depths greater than about 30 m, a zone sometimes referred to as the 'deep aquifer'.

(3) To undertake an assessment of the potential for further groundwater development for use as public supply from the uppermost 'shallow aquifer' which comprises weathered bedrock and superficial deposits.

(4) To clarify the relationship between surface water and underground water resources and assess the impact of groundwater abstraction on the overall water body.

(5) To consult with members of the public, States officials, drilling contractors and other interested parties in order to achieve a consensus of understanding about the natural water resource in Guernsey in terms of its magnitude as a renewable resource, its provenance and its sustainability.

The basic fact finding at desk and field level was carried out during November and December 1999. The public consultation process was greatly enhanced by the services of Campaign Management Associates Limited who were responsible for creating press releases, media interviews and a questionnaire aimed at drawing information from private water abstractors. In addition, a literature and data review was supplemented by two intensive field campaigns. The first sampled a subset of boreholes and wells to provide a validated inventory as an indicator of groundwater potential and groundwater use. The second was a groundwater sampling campaign which provided insight into the hydrogeochemistry and relative age of the groundwaters.

Response to the questionnaire was extremely valuable. The information that was received enabled some extrapolation of the field inventory to be made and provided contact with groundwater users. It also enabled individuals to share information which they had gathered. Some of this was anecdotal, whilst other information consisted of numerical records.

1.2 Water Use, Land Use and Social Change

Guernsey is the second largest of the Channel Islands. It has an area of 63 square km and is situated 130 km from the south coast of England and 30 km from the Cherbourg Peninsula. Over 300 000 visitors come to the island each year, increasing the demand for water supply particularly during the summer months. The population reported in the 1996 census was 58 700 of which 16 200 lived in St Peter Port. The greatest housing density is concentrated around St. Peter Port and St. Sampson on the east coast of the island. The present day population is about 62 000.

The dominant land-uses on Guernsey are horticultural (glasshouses), agricultural farmland and urban. Native woodland and open countryside makes up the remainder. Horticultural activity is greatly diminished since tomato cultivation declined from the 1970s onwards. Cut flowers, pot plants and plant production have now taken over as the main horticultural products.

Households relied on shallow wells or springs prior to the introduction of mains water supply. The shallow wells intercept near surface groundwater and can provide a reliable supply, although in times of drought some have been known to dry. However, many of these wells respond rapidly to rainfall events. Other wells and boreholes may be intercepting a deeper component of groundwater.

Volume of water put into public supply peaked in 1970 at about 5.7 $Mm^3\ a^{-1}$. In recent years, public supply water consumption has amounted to between 4.7 and 5.2 $Mm^3\ a^{-1}$, with increased domestic consumption offset by a declining demand from horticulture and commercial. Quantities of groundwater and surface water abstracted for private consumption are not known, but it is thought that about 5 000 properties (of these about 250 houses rely solely on groundwater and about 1000 of the properties are commercial) have access to private sources, and it may amount to about 1 $Mm^3\ a^{-1}$. This estimate is of the same magnitude as the estimated additional usage of 30% more than the volume in public supply i.e. 1 $Mm^3\ a^{-1}$. Much of this additional usage represents supply to glasshouses. A likely long-term estimate of private abstraction from the natural groundwater system is about 1.5 $Mm^3\ a^{-1}$. Total water use may amount to about 6.5 $Mm^3\ a^{-1}$ in a normal year.

1.3 Physiography and Climate Change

The topography of the island varies considerably from north to south. The south is bounded by steep-sided cliffs and there is a distinctive plateau area in the High Parishes. The highest part of the island is Haut Nez, which is 107 metres above sea level. There is a marked topographical change to the north of the airport where the land elevation declines to the north. There are also a number of steep sided valleys, mostly trending north-west that are the surface expressions of the major NW-SE trending faults on the island. The low-lying ground in the north of the island is characterised by gently undulating topography. The north-east is the flattest part of the island and includes an area of reclaimed salt marsh.

The southern plateau is the main source for surface water drainage. Most of the streams that drain the island flow to the north-west and to the north. There is a prominent valley at Kings Mills where the Fauxquets and Les Talbots streams meet. Ultimately, these streams would discharge to the sea on the north-west coast in the vicinity of Vazon Bay, but like most of the stream discharge from the island, the water is intercepted for use in the public water supply system. One of the larger reservoirs is at St Saviour and this collects water from the Padin, Beau Valet and Choffin streams and has a capacity of 1 090 Ml. Several streams also flow towards the north-east. Topographic gradients are more subdued to the north of St. Peter Port in the Vale and St. Sampson parishes.

The other main drainage pattern is from the plateau area to the south. There are a number of steep sided wooded valleys that act as the collection system for surface water and groundwater discharge. Streams discharge to the coast at Moulin Huet Bay, Saints Bay, Petit Bot, Le Gouffre and Le Bigard. These streams are perennial, the low flows being maintained by groundwater baseflow.

The island enjoys a temperate climate with over 2 000 hours of sunshine per annum. The prevailing wind directions are from the west and south-west, although dry easterly continental air prevails from time to time. Rainfall has been monitored at six stations on the island, although only two are maintained today (Table 1). Rainfall intensity decreases from the south to north; 838 and 837 mm respectively at the Airport and Haut Nez in the south of the island to 792 and 766 at L'Ancresse and La Turquie in the extreme north-east of the island (1961-90 long term averages). However, there is a general decline in rainfall after this period. The 1990-97 average for the airport is only 789 mm (Guernsey Airport Meteorological Office, 1997) and for L'Ancresse is 722 mm.

Name	Grid ref.	Altitude	Data Range	Mean
L'Ancresse	338 830	3	1966- present	792
La Turquie	357 829	12	1935-69	766
Les Quartiers	323 804	12	1934-78	846
Haut Nez	311 762	107	1907-74	837
Airport	292 759	104	1949- present	838
Kings Mills	292 787	14	1923- present	832

Table 1 Long term mean average rainfall data

The mean annual air temperature at the airport is 10.8 °C and varies from 8.4 °C to 13.1 °C. The incidence of air frost is uncommon typically occurring on only six days per year. Ground frost occurs typically on 38 days per year, and fog for 79 days of the year. Mean wind speeds are consistently above 10 knots each month, with an average of over 12 knots. Average sea temperatures vary from approximately 8.5 °C in February and March to approximately 16.5 °C in early September. Potential evapotranspiration has not been measured, nor are appropriate meteorological data available for its reliable calculation.

1.4 Geological Setting

The geology of Guernsey has been of interest to researchers and academics for over a century. Hill and Bonney (1884) gave an early account of the Precambrian geology and this work includes the first basic geological map of the island. Roach (1966) and Roach et al (1991) are the most recent accounts of the Precambrian geology, whereas work by Collenette (1916) and Mourant (1933) analysed the Pleistocene geology of the island.

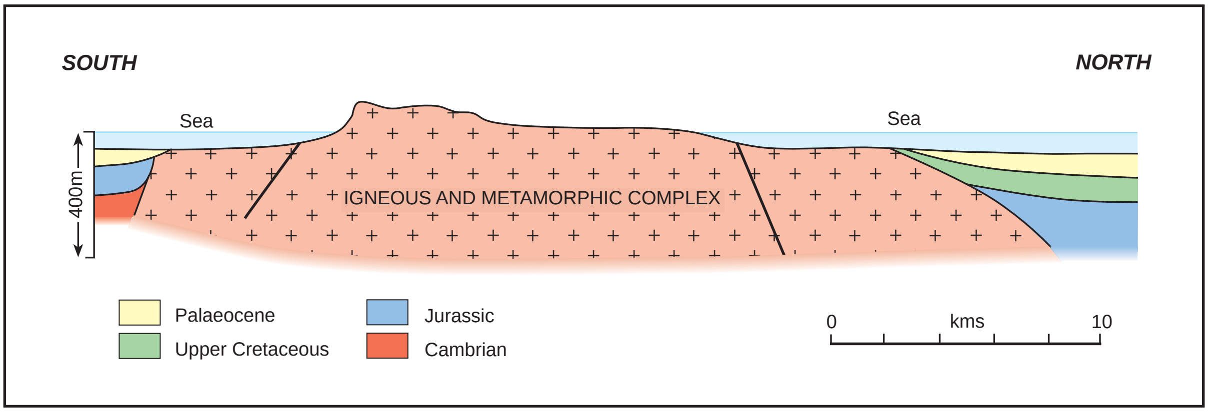

Figure 1 Cross-section of Guernsey and its geological setting

The southern part of the island consists of metamorphic sedimentary and igneous rocks with numerous intrusive dykes. This is commonly termed the Southern Metamorphic Complex. The other part of the island comprises plutonic igneous rocks that have been relatively unaltered and contain few intrusive bodies. This area is referred to as the Northern Igneous Complex. These complexes are surrounded offshore by younger sedimentary rocks ranging in age from Cambrian to Upper Cretaceous and Palaeocene (Figure 1). There are some late Palaeozoic intrusive dykes and some Quaternary deposits.

The Southern Metamorphic Complex

These are the oldest rocks on Guernsey (Figure 2) and they belong to the Precambrian Pentevrian basement sequence, which is over 2 000 million years old (Table 2). The original marine sediments and volcanic deposits have undergone deep burial and complex metamorphism. These have subsequently been intruded by granitic, granodioritic, dioritic and basic bodies and been extensively folded.

The Pentevrian rocks comprise gneisses and orthogneisses separated by thin bands of metamorphosed siltstones and sandstones that predate the gneiss. The bands rarely exceed 150 metres in thickness and comprise semi-pelitic schists and semi-psammites (Roach et al, 1991). These metasediments also occur as xenoliths within the main gneisses. The two main gneiss types in the Southern Metamorphic Complex are the granitic augen-gneisses, and the granodioritic gneisses.

The Northern Igneous Complex

The igneous rocks of the northern complex are younger than the southern metamorphosed complex and are between 550 and 700 million years old. The rocks are classified as part of the Cadomian sequence. These igneous rocks include both basic and igneous varieties (gabbros, granites, granodiorites) and represent part of a larger plutonic complex.

The principal gabbro is the St. Peter Port gabbro on the eastern side of the island, which has undergone significant recrystallization after the emplacement of a dyke swarm. The Bordeaux Diorite Group, that includes the Chouet granodiorite, comprises much of the northern section of the island. The L'Erée granite represents probably one of the oldest Cadomian intrusions on the island, and, together with the Cobo granite, are the two main granite bodies on the island.

Compared to the Southern Metamorphic Complex, the Northern Igneous Complex has few intrusions. However, the St. Peter Port gabbro does contain a number of microdiorite dykes, Roach et al (1991).

Quaternary and Recent Deposits

The topography of the island is strongly related to the reactivation of fractures and faults. Marine erosion during the Quaternary has formed a series of erosion surfaces that are now uplifted. Head, loess and blown sand deposits form extensive outcrops on inland areas and are important for soil formation. There is an extensive cover of loess over the plateau in the south of the island. It is approximately 5 m thick in the east of the island but thins to only 1 m in the west.

There are three separate raised beach deposits (Keen, 1978). The *30 metre raised beach* lies between 25 and 30 metres above sea level. It consists of sand and gravel deposits and occurs along the west coast. The *18 metre raised beach* is more prevalent than the 30 metre raised beach and has been identified at 15 localities. The *8 metre raised beach* ranges from mean sea level to 10 metres above mean sea level. It consists of sand and gravel deposits and occurs on the west and north facing coasts.

Head deposits up to 20 metres thick occur in some coastal sections and comprise reworked loess and solifluction deposits. Inland, the head is much thinner, generally less than 3 m thick, but it covers

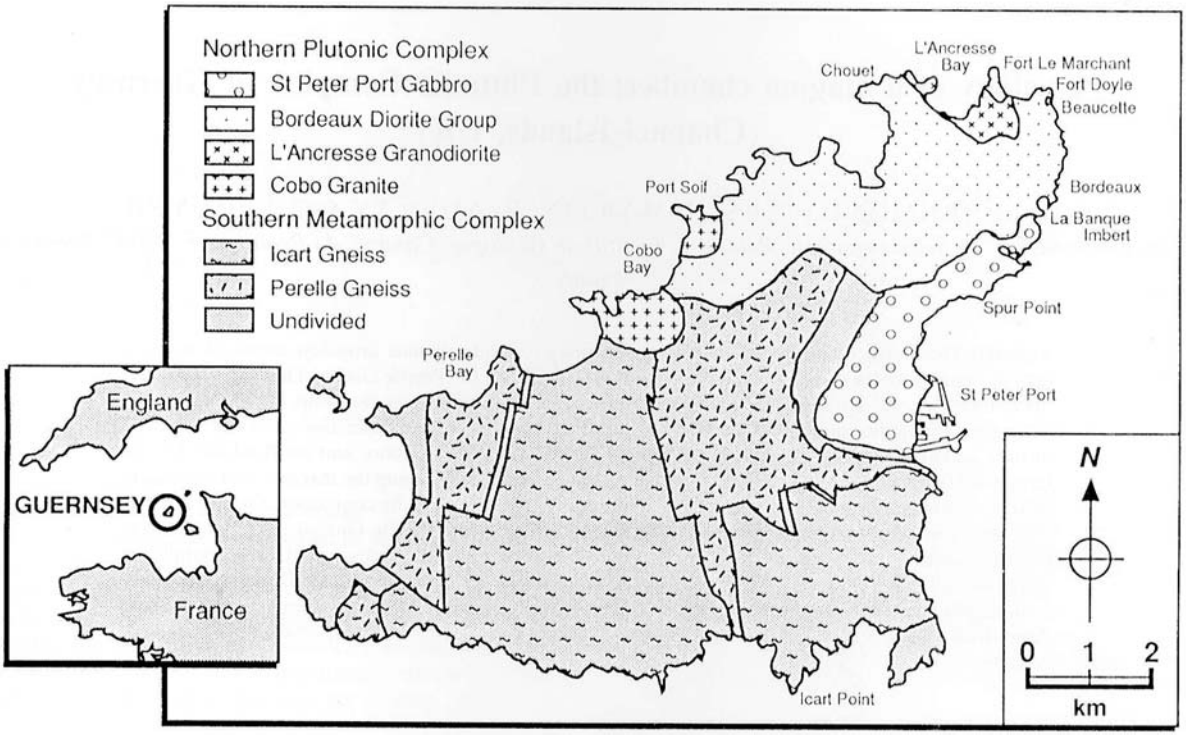

Figure 2 **Simplified geological map of Guernsey (after Roach *et al*, 1991)**

Era	Period	Age (Ma)	Lithology
Caenozoic	Quaternary	Up to 0.25	Raised beach deposits; loess, head and alluvium deposition
Palaeozoic	Carboniferous	c.300	Lamprophyre/dolerite dykes
Precambrian	Cadomian	c.550– c.700	Metamorphism; emplacement of granites, granodiorites, diorites and gabbros
	Brioverian	c.700– c.800	Pleinmont Formation
	Pentevrian	c.2000 to >2500	Sedimentary/volcanic rocks formed; igneous intrusions; metamorphism to produce gneisses

Table 2 **Principal geological formations, ages and rock types**

large areas. The upper slopes of the principal valleys in the south of the island and large parts of the centre of the island are covered by head.

Recent deposits are of both marine origin (marine alluvium and storm beach deposits), and freshwater origin (peat and alluvium). Aeolian sand is also present (Keen, 1981). The area between St. Sampson and Grand Havre was reclaimed from the sea in 1808. The Braye du Valle contains marine alluvium and some freshwater alluvium.

1.5 Existing Groundwater Database

Following the drought of 1976, a survey was commissioned by the States of Guernsey Water Board to investigate the potential surface and groundwater resources of small catchments on the south and west of the island (Hawksley, 1977). The results of this study indicated that the role of groundwater in augmenting the public supply was minimal compared to the benefit of increasing the number of surface water collection reservoirs. Jehan (1993) carried out a simple island-wide groundwater survey with a discussion of trends in groundwater quality.

Guernsey legislation does not require groundwater users to hold an abstraction licence. There is, therefore, no database of groundwater abstraction or of the present level of water consumption from private sources.

Mr Nigel Gee at La Hougette, Castel has recorded groundwater levels in his well, since 1989. The States Water Board has been monitoring water levels in their own wells since 1997. Groundwater quality data are available in a variety of forms from a variety of sources. The Environmental Health Department records were not accessed as the States retains these in confidence. Drilling company records have been used in generic form only, as these are also held in confidence on behalf of drilling company clients. The BGS borehole database contained one record for Guernsey.

2. GROUNDWATER RESOURCES

2.1 Data Collection

In order to validate the information provided by earlier studies, two data collecting campaigns were carried out. The first was an advertisement that was published in the *Guernsey Press* inviting private water users to share information about their sources. This provided valuable information which is summarised on a parish basis in Table 3. It also provided contacts that were willing to discuss their sources further and allow field inspection and groundwater sampling.

The second initiative was a field campaign to collect physical information about a sample of borehole and well sites (Appendix 1). These were distributed as evenly as possible, but were also intended to reflect different geological and topographical settings. Depth measurements were made by plumb line and static and dynamic water levels with an electric dipper. Pumping rates were estimated by timing the discharge of a known volume of water wherever possible. Details of the physical characteristics of the wells, boreholes and springs visited as part of the field inspection are provided in Appendix I.

2.2 Water Budget

The island-wide water budget is given by:

Rainfall (P) – actual evapotranspiration (AE) = streamflow (baseflow + runoff) (Q) + net groundwater recharge (ΔG)

Parish	Number of boreholes	Number of wells	Main water use	Depth of boreholes (m)	Standing water level (m)
Castel	4	1	gardens	>10	Various
Forest	2	-		>10	>5
St Peter Port	2	-	gardens	>10	Various
St Peter’s	4	3	domestic	Various	Various
St Sampson’s	2	1	garden	>10	>5
St Saviour’s	5	2	garden	>10	Various
Torteval	1	1	garden		
Vale	1	3*	domestic	3-10	2-5

*Two springs were also reported in Vale, one of them described as a former quarry.

Table 3 Summary data from public consultation

Other than rainfall, none of these parameters can be measured directly and although there is some understanding of each of them, they are not known with any degree of confidence. Rainfall is measured on a daily basis by the Guernsey Airport Meteorological Office. The 30 year mean annual rainfall is 831 mm, although it may be as much as 65 mm less in the north of the island. Variation from the mean is significant, for example in 1997, monthly rainfall varied by 11% in September and 208% in June, whilst the annual rainfall for that year was some 86% of the 30 year average. The daily rainfall varies from the mean to an even greater extent. In addition there has been an overall decline in rainfall since the 1940s, and this may represent a decline in the input to the water budget of as much as 10%.

Potential evapotranspiration is measured indirectly from a range of meteorological observations. Open water evaporation can be measured in a pan evaporimeter. However, data are not available for Guernsey, and as radiation is not currently recorded calculation of potential evapotranspiration cannot be made.

Data for the neighbouring island of Jersey are, however, quite comprehensive. Potential evapotranspiration and groundwater recharge have recently been determined through an intensive field campaign to investigate a single instrumented catchment (Robins and Smedley, 1998). Comparison of long term rainfall data for the two island airport sites (Figure 3) indicates little variation month by month, and the long term means (1961-1990) are 831 mm for Guernsey and 836 mm for Jersey (Meteorological Department, 1991). Rather than attempt crude and unjustified attempts at determining evapotranspiration for Guernsey, the existing 30-year mean data for Jersey have been transposed for use at Guernsey as follows:

$P = 831$ mm $AE = 613$ mm
$Q = 226$ mm $\Delta G = 128$ mm

Statistical analysis of streamflow on Jersey indicates that about 60% of it derives from groundwater baseflow which in turn derive from groundwater recharge and 40% from direct run-off. The function ΔG also includes change in soil moisture content, although this is likely to be small in an island wide context over the long term. The water balance can, therefore, be written:

$$P = AE + Q + \Delta G = 831 \text{ mm}$$
$$P = 614 + (226 \times 0.4) + 129 = 831 \text{ mm}$$

Note that the depletion of ΔG by borehole abstraction will have an adverse effect on Q as the baseflow contribution is lessened.

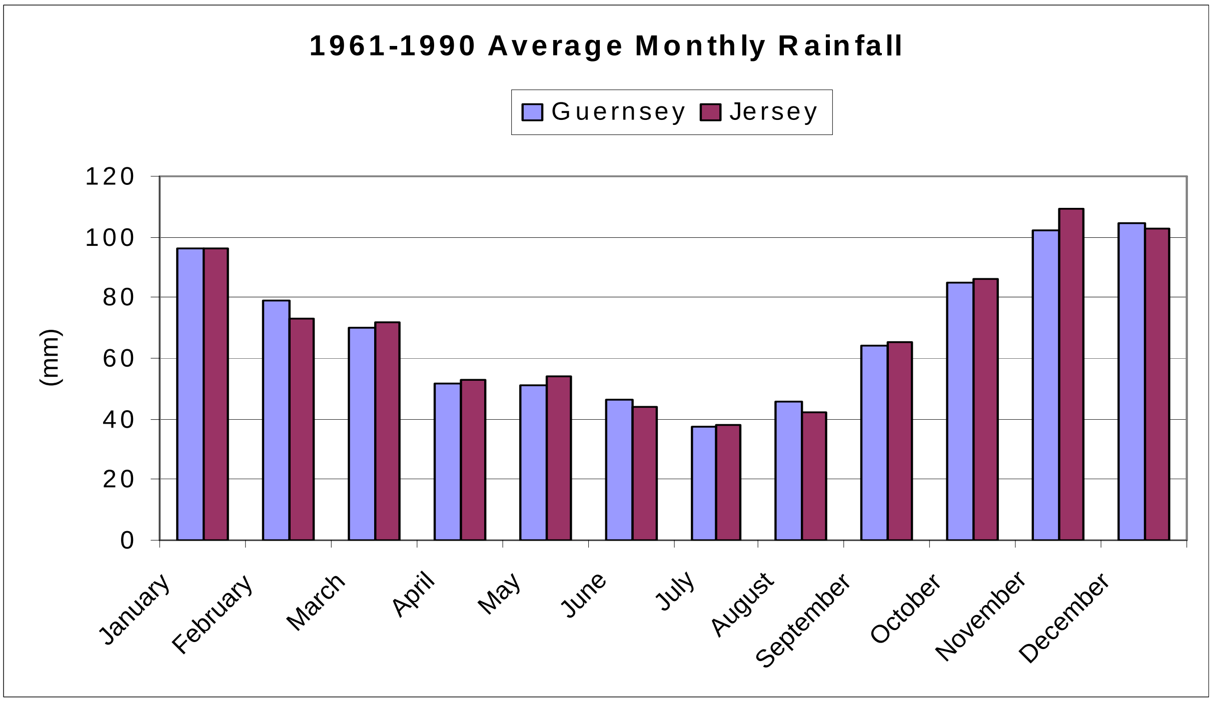

Figure 3 **Channel Islands average monthly rainfall**

2.3 The Bedrock Aquifer

The volcanic and metamorphic rocks of Guernsey originally contained little or no primary porosity or permeability. Processes that have occurred after the rocks formed have led to creation of secondary porosity and permeability in the form of fractures and joints as well as through the weathering processes.

Intrusive volcanic rocks, such as those in the Northern Igneous Complex, have a three-dimensional joint and fracture network which is independent of larger scale geological fault structures. Weathered volcanic rocks are soft and friable and have a much greater porosity and permeability than unweathered crystalline rock. The depth of the weathered zone may be over 30 metres below ground level, and is typically about 25 m thick beneath the water table. The hydraulic conductivity of an unweathered intrusive igneous rock may be several orders of magnitude less than the weathered rock. The physical properties of fractured media show extreme heterogeneity over small distances.

The gneiss of the Southern Metamorphic Complex has similar physical characteristics. However, gneiss also contains foliations caused by the preferential alignment of minerals. This creates partings which may assist in the development of joints which, in turn, may offer a conduit for groundwater flow. Fracture dilation reduces with depth due to the increasing pressure of overburden, and borehole yields decline with depth accordingly.

Although Guernsey is principally composed of Precambrian metamorphic and igneous strata, there are extensive deposits of Quaternary loess and head. Rather than a single aquifer unit, it is more accurate to envisage the groundwater system in three contiguous parts:

the Quaternary,
the weathered shallow bedrock, and
the deeper less-weathered bedrock.

The prevailing flow mechanism varies according to the strata and the degree of weathering. Loess and head deposits support intergranular groundwater flow and storage, whereas the weathered and fractured bedrock offers only secondary porosity and fracture flow.

The relatively shallow nature of the bedrock aquifer provides a useful moderating feature to the aquifer. The ability of the aquifer to transport water (the hydraulic conductivity) and the ability to store groundwater (storativity) both decrease with depth below the water table because the frequency, size and connectivity of the weathering induced fractures will decrease with depth. The effective thickness of the aquifer is rarely greater than 25 m. Consequently, the ability of the aquifer to drain as baseflow or to discharge to pumped boreholes is reduced as the water table falls. Therefore, less water is lost to streams and at the same time pumped borehole yields also begin to decline. This phenomenon is common to any aquifer because its performance (transmissivity) is dependent on the product of aquifer thickness and hydraulic conductivity, but it is particularly significant in a shallow weathered bedrock aquifer in which storativity is limited. This consequential reduction in aquifer properties as the water table falls provides the aquifer with an important self protection mechanism. Care needs to be taken at times of water stress, however, to ensure that the water table is not greatly reduced near the coast, since sea water could flow down the induced reverse hydraulic gradient beneath the island, potentially causing saline contamination of at least part of the aquifer.

2.4 Recharge, Storage and Groundwater Flow

For much of the year there is a moisture deficit in the soil and neither runoff nor infiltration can occur until the deficit is overcome by prolonged rainfall and the soil is made up to field moisture capacity. In a very dry winter (e.g. during the early 1990s) field moisture capacity is not attained and recharge does not take place.

Hydrographs for the States of Guernsey Water Board (SWB) Wells (Figure 4) and for La Hougette, Castel (Figure 5) indicate that the response of the wells to specific rainfall events is short, usually only a matter of days. This indicates rapid movement of water through the fractured weathered zone to the water table. Seasonal water level fluctuations are typically about 2 m. As mean annual recharge is about 130 mm (Section 2.2) a rise in groundwater level of 2 m (2000 mm) suggests an effective aquifer specific yield (approximating to porosity) of 130/2000 or 6.5%.

Many springs in Castel and elsewhere increase in flow following periods of heavy rain. Some boreholes have even been reported to contain suspended sediment after intensive rainfall events, this is probably sediment washed down from the surface via fractures.

The potentiometric surface of the main aquifer (Figure 6) has been constructed from water level data collected during the current survey, information collected by Jehan (1993) and the elevation of perennial streams indicated on the topographic map (assuming that perennial surface water is sustained by contact with the water table). The potentiometric surface is closely related to topography, with the highest water levels occurring in the vicinity of the airport, in the southern part of the island. The highest level measured during the field visit was approximately 97 m above mean sea level at SWB well No.5. There is a very steep hydraulic gradient from the southern plateau to the south coast, reflecting the steep topographic gradient and low transmissivity of the aquifer, which is probably thin in this area. North of the plateau, the predominant groundwater flow direction is towards the north-west, except in the St. Sampson area where the general flow direction is to the north-east. Rest water levels are commonly less than 5 m above mean sea level along the north-west coast. In the northernmost part of the island, there is a low hydraulic gradient and small groundwater flux. The

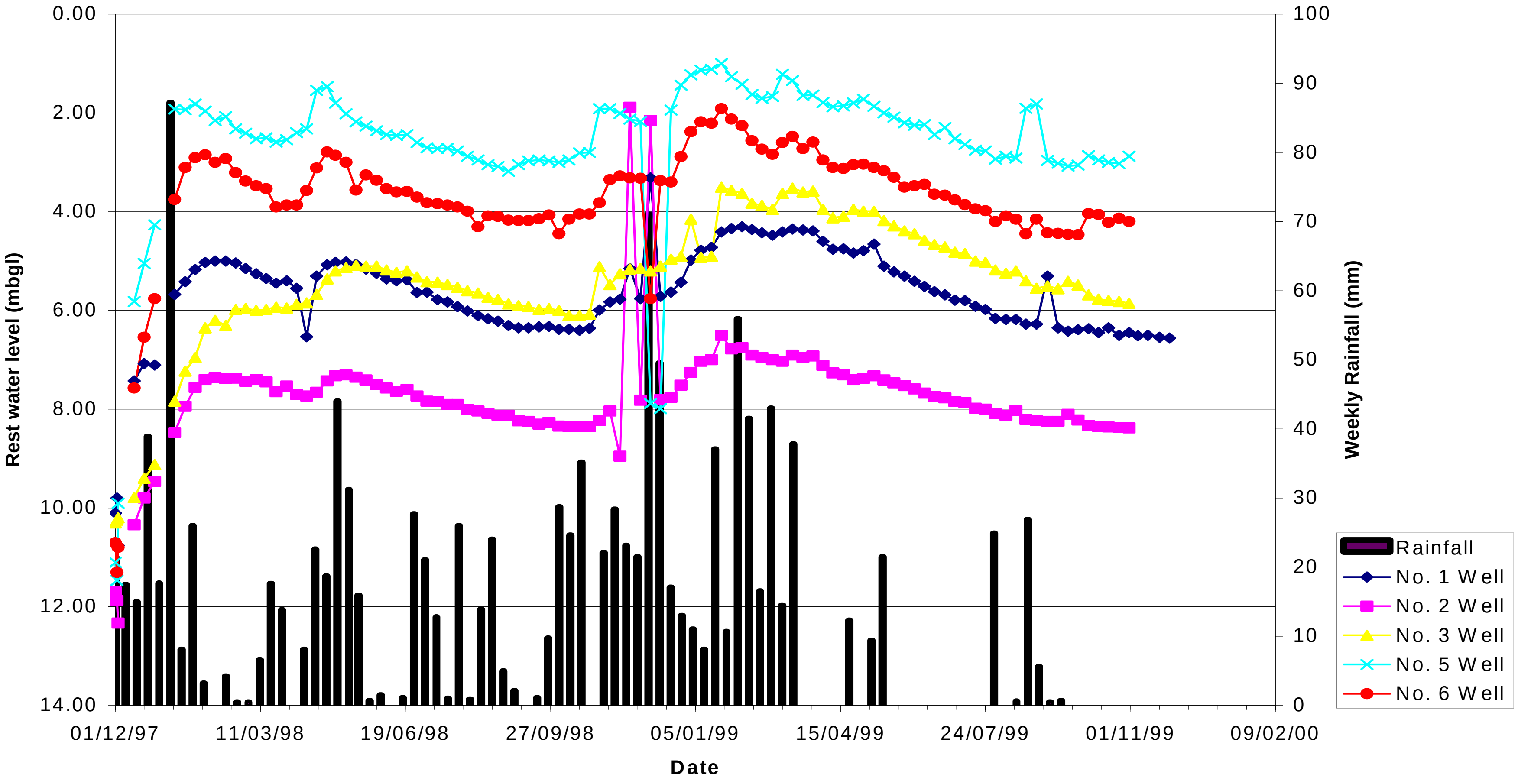

Figure 4 Rest water level fluctuations for the States of Guernsey Water Board Wells

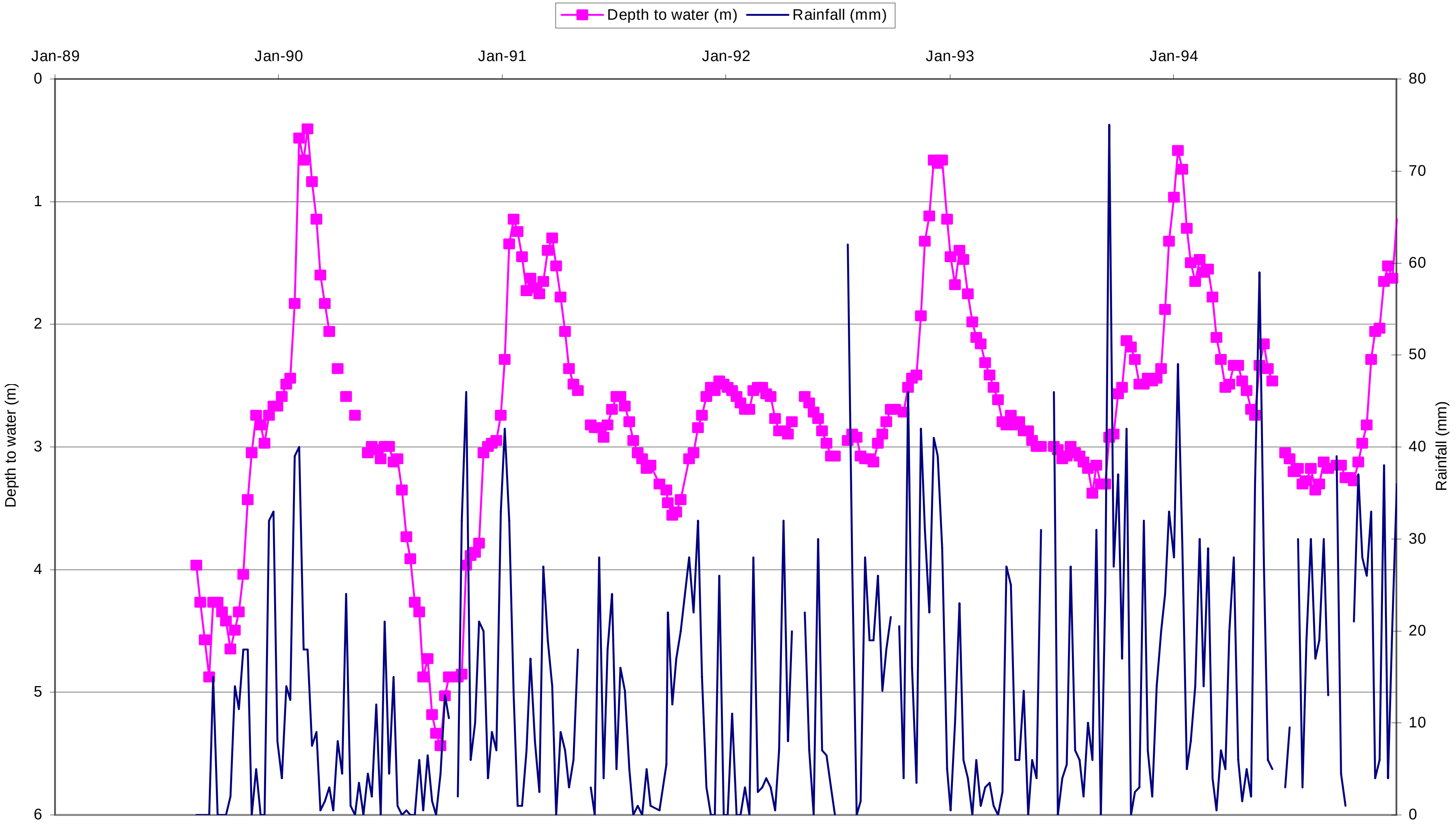

Figure 5 **La Houguette 1989-1999**

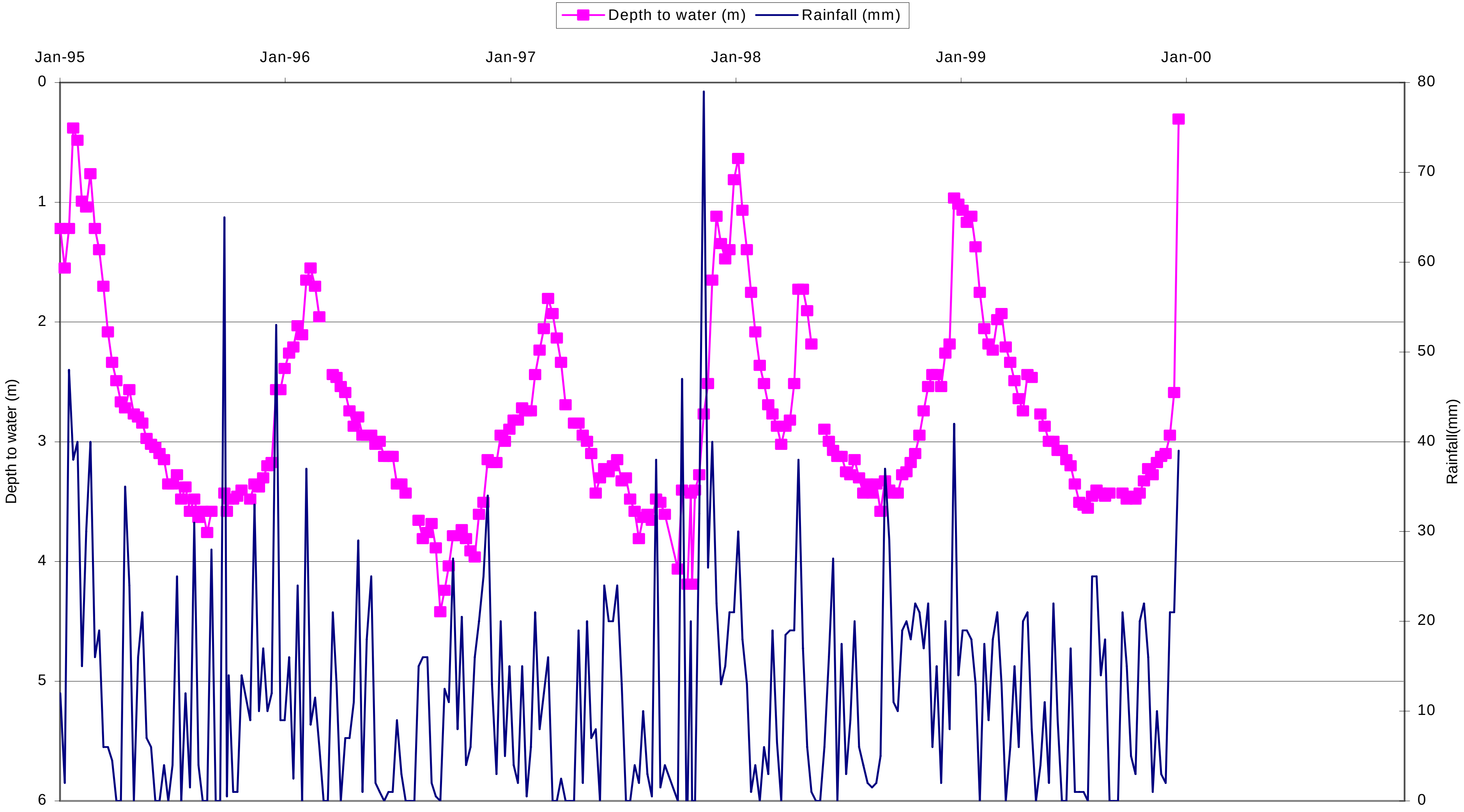

Figure 5 (continued)

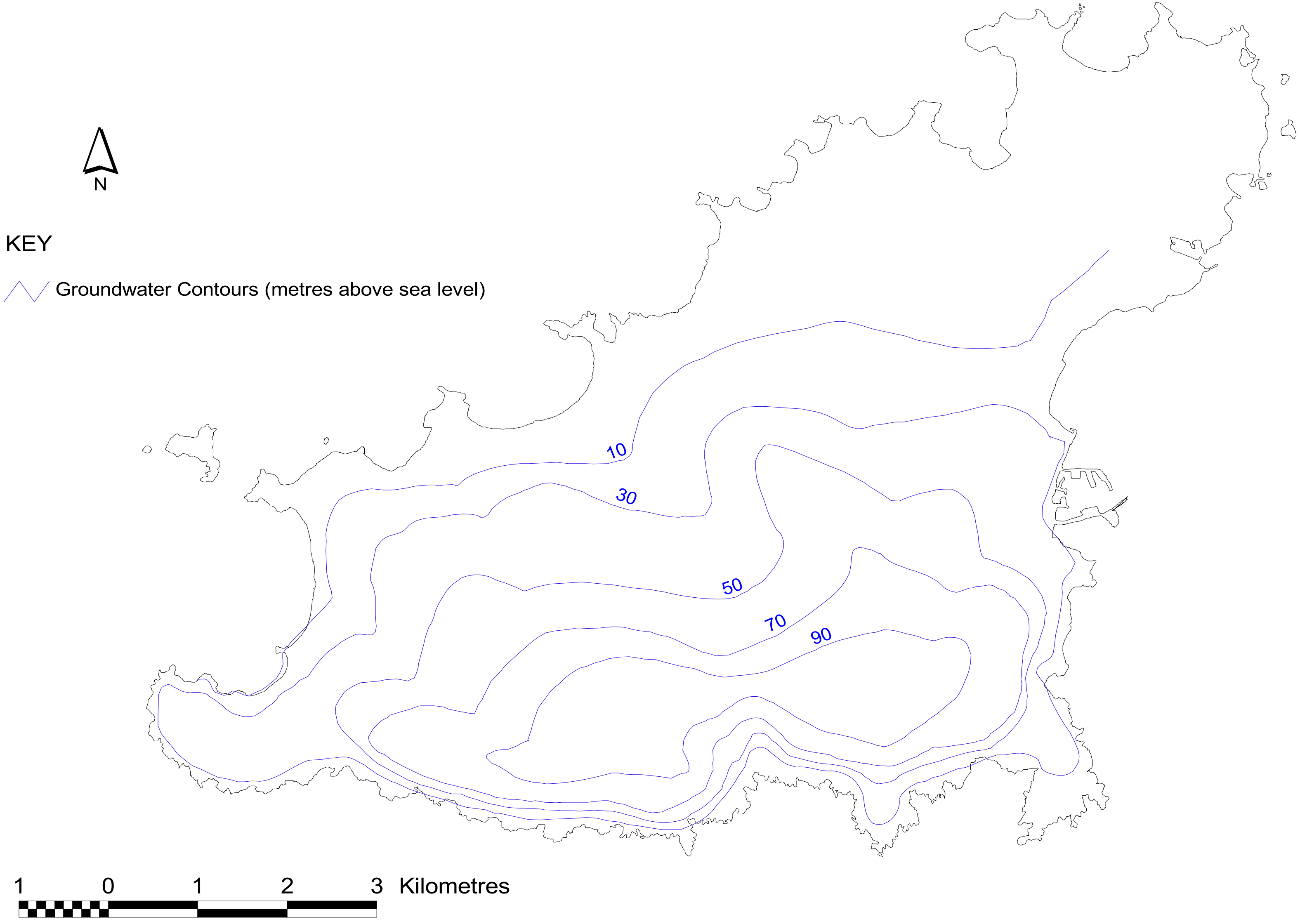

Figure 6 Groundwater level contours

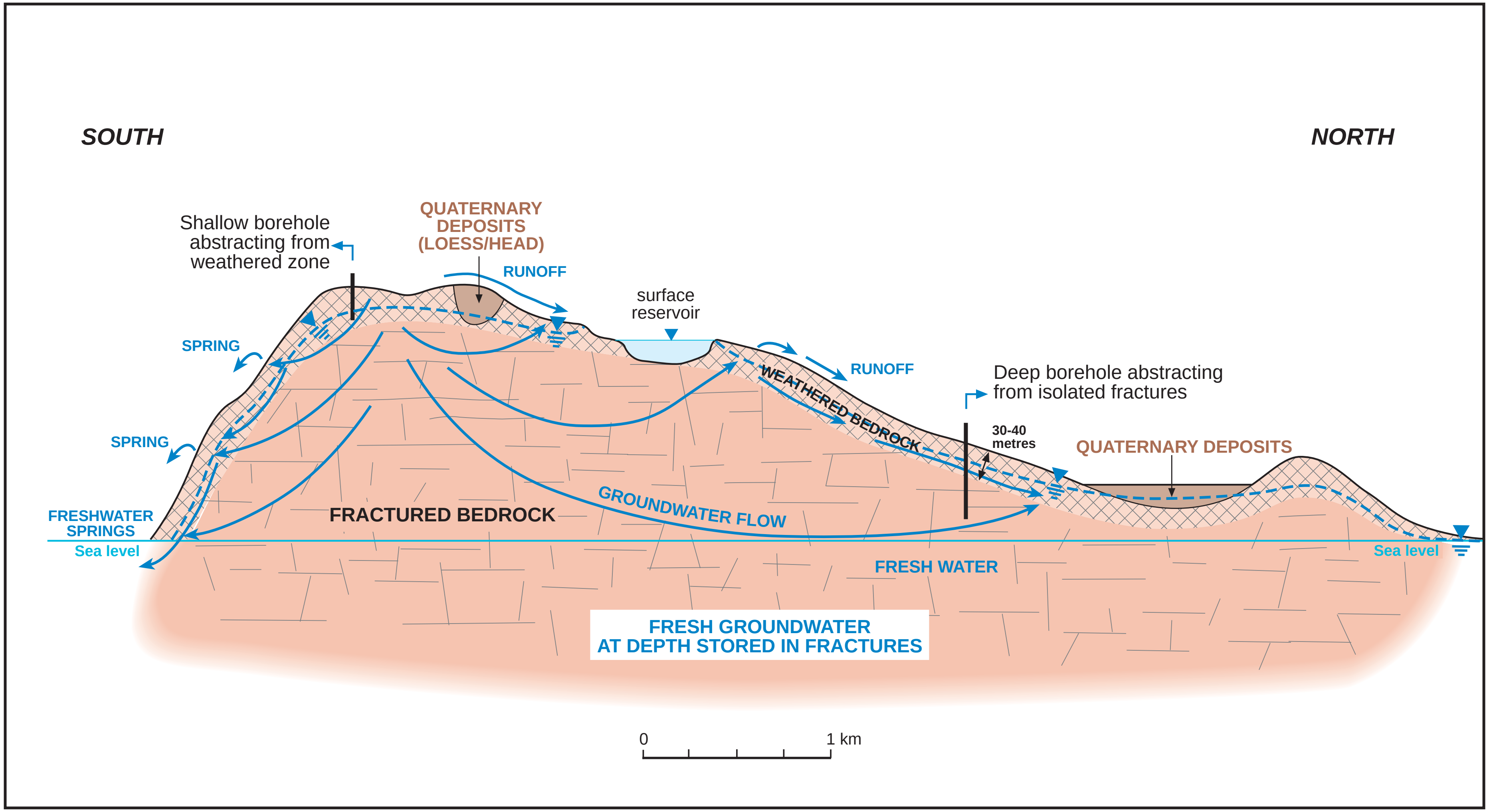

Figure 7 **Schematic groundwater flow systems**

water levels in this area are generally about 9 or 10 m above mean sea level, i.e. within a metre or two of the ground surface.

A conceptual groundwater flow model for Guernsey is illustrated in Figure 7. This shows two groundwater flow systems, a dominant shallow flow circulation typically up to 25 m below the water table in which the majority of groundwater transport takes place, and a deeper flow system controlled by fractures and fissures in which preferred but relatively small flow paths exist. In coastal areas, the fresh groundwater sits on top of a saline wedge of sea water, although the effective hydraulic base of the shallow aquifer is above sea level in many parts of the island.

2.5 Groundwater Demand

Although groundwater abstraction has declined as the horticultural industry demand has reduced and water use efficiency has improved, there has been an increase in the number of operational sources. As a result of loss of confidence in the public supply in the mid-1970s, many domestic water users developed their own small sources to maintain gardens, swimming pools and other amenities. In addition, a number of industries developed water sources, not least hotels, leisure centres and some golf courses.

Traditional groundwater users, the breweries and the vineries which now produce flowers, have continued to use groundwater. These users tend to require the larger groundwater abstractions.

The present survey is insufficient to quantify total demand. However, it shows that private groundwater use is widespread. The two main drilling contractors report that between 12 and 15 new boreholes are being drilled each year. Some of these will be replacement sources, but the majority are new sources, many for garden use. Many of these new sources are only needed when the States of Guernsey Water Board have restrictions in supply.

3. GROUNDWATER CHEMISTRY

3.1 Data Collection and Field Sampling

Samples were collected from 21 sources distributed across the island. The sources included both shallow wells and deep boreholes. Sources in regular use with well head sampling points were preferred, although some samples were collected from discharge outlets, usually above a storage tank. It is important to note that most boreholes on Guernsey are open hole except for a few metres of casing at the surface Therefore although it assumed that the groundwater sample is from depth, near the level of the pump, it is likely that shallower fractures will also be contributing. Thus the sample could be a mixture of different depth waters rather that representative of one distinct horizon. At those sites where taps or outlets were available, well-head measurement of redox potential (Eh), dissolved oxygen (DO) and pH were made in an anaerobic cell as the sample flowed gently to waste through the cell. If on-line sampling was not possible, pH was measured directly in a standing sample, but Eh and DO could not be measured. Groundwater temperature, specific electrical conductance (SEC) and alkalinity were also measured at the well head. Alkalinity was determined with a Hach titration kit and the result converted to bicarbonate ion concentration.

Three samples were taken for later laboratory analysis. Two samples were passed through a 0.45 μm filter, and one was stabilised by acidification with concentrated nitric acid (1% HNO_3). The third sample was unfiltered and placed in a glass bottle for stable isotope analysis. If the source was not in regular use prior to sampling, water was pumped to waste for approximately three borehole volumes or until such time as stable readings were recorded for SEC. In addition, four samples were collected for analysis of chlorofluorocarbon (CFC) species.

Major cations, SO_4 and trace metals were analysed on filtered and acidified samples by inductively-coupled-plasma atomic emission spectrometry (ICP-AES). Analysis of total oxidised nitrogen (TON), and Cl was by automated colourimetry on filtered but unacidified samples. Br was determined by ion chromatography. Stable isotope analysis was by mass spectrometry, and the CFC analysis by gas chromatography. The analytical work was carried out at BGS Wallingford apart from the CFC analyses which were made by Spurenstofflabor, in Wachenheim, Germany.

3.2 Regional Groundwater Chemistry

The results of the field and laboratory chemical analyses are presented in Appendix 2.

SEC ranges from 427 to 1578 μS cm^{-1} (Figure 8) with an average of 809 μS cm^{-1}. SEC is highest (i.e. the water is more mineralised) in the north-eastern part of the island. The pH of the groundwater varies from 5.6 to 7.0 with an average value of 6.4, i.e. they are generally slightly acidic. The pH is highest, although not exclusively, in the northern and north-eastern part of the island, with other high values in the High Parishes. There is a wide range of DO from 0.4 to 10.2 mg l^{-1}, with a mean of 5.0 mg l^{-1}. Chloride concentrations vary from 50.3 to 178.0 mg l^{-1}, with an average of 92.0 mg l^{-1}. Highest recorded values are again in the northern part of the island.

These distributions may not be significant considering the few sample points and the scale of the island, but they reflect the conceptual groundwater flow model described in Section 4.1. Groundwater recharge in the High Parishes flows south and north-west, whereas the flat lowlands in the north offer no groundwater flux as there is little potentiometric head. In the recharge area young and weakly mineralised waters are expected whereas beneath the flat lands, older and more mineralised waters should occur. This is the case for SEC and Cl, and the pH is also greatest in the flat lands of the Vale area where water-rock reaction has taken place. However, DO remains elevated suggesting that even though the groundwater is not moving it remains in contact with the atmosphere in this shallow groundwater system. There will also be some direct recharge to this area which would necessarily have an elevated DO content. Very few Guernsey groundwaters are depleted in oxygen and redox potential (Eh) is always positive (Appendix 2).

The distribution of other major ions reflects this same pattern. There is a strong marine influence on all the groundwaters. Figure 9 shows a Piper trilinear plot (Hem, 1959) for the groundwaters which all plot with a strong Na and Cl bias, whereas a typical continental groundwater would show a bias towards Ca and HCO_3. This reflects the maritime influence on the rainfall plus input from sea spray carried over the island, but there is little evidence of any direct contamination of groundwater by marine invasion. Cl concentrations range from 50.3 to 178.0 mg l^{-1} and the mean is 92.0 mg l^{-1}, the higher concentrations tending to be clustered in the northern part of the island on, and near, the reclaimed land.

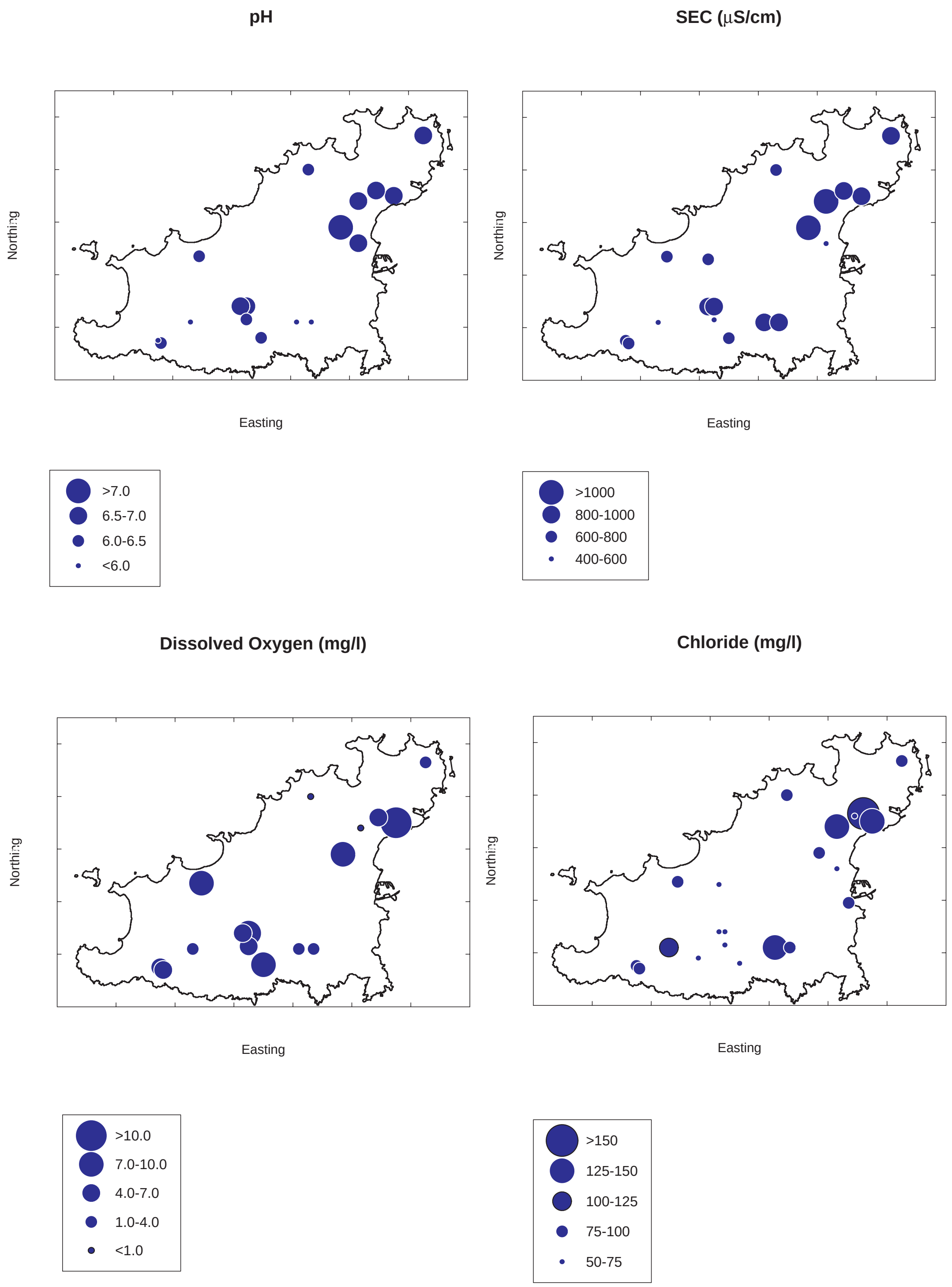

Figure 8 **Island-wide distribution of pH, SEC, DO and Cl**

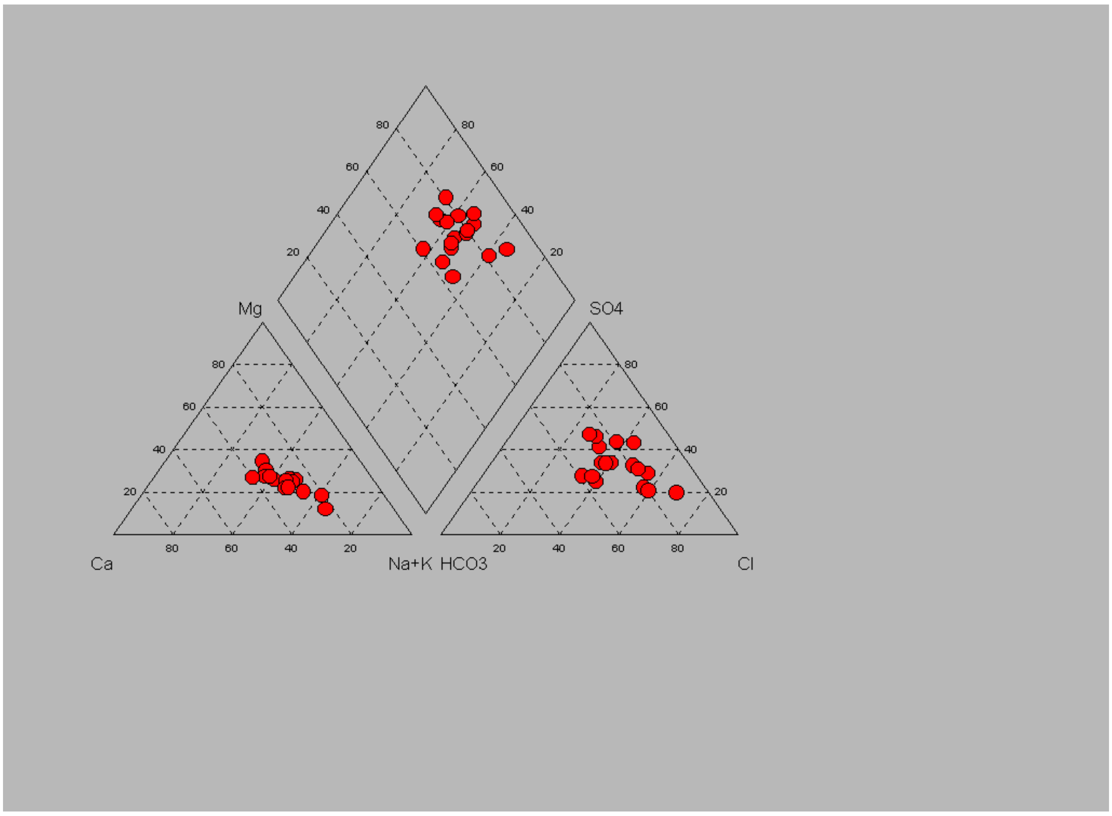

Figure 9 **Piper diagram showing major ions**

The marine influence is illustrated in Figure 10 which shows the trend line between rainfall chemistry (measured at Jersey in the early 1990s) and sea water for four major ions plotted against Cl. They show that Na is slightly elevated, Ca and Mg are considerably elevated and K is partly depleted with respect to seawater. This means that uptake of Ca and Mg, and a small amount of Na has occurred as part of the water-rock interaction during the chemical maturation of the groundwaters, whereas some K appears to have been lost to plant uptake and cation exchange within the soil and bedrock. The Ca derives principally from minerals such as calcite, gypsum, calcium-rich feldspar minerals. Ca is not abundant in Guernsey bedrock, although marine derived superficial strata contain abundant shelly material as a source of these alkaline minerals.

3.3 Pollution and Potability

A histogram of nitrate occurrence is shown in Figure 11. This indicates a grossly polluted groundwater body in which 10 out of the 21 samples exceeded the EU maximum admissible concentration (mac) of 11.3mg N l^{-1}, and the mean for the sample set also exceeded the EC mac at 14.1 mg l^{-1}. The nitrate sources are likely to be nitrogen fertilizer leached from the soil horizon and leakage from cess pits. The higher NO_3 concentrations do not generally coincide with higher Cl concentrations suggesting that sewage is not the main source of NO_3. Analysis of nitrogen isotopes could identify the relative contributions from the two sources, but analyses of Jersey groundwater samples found nitrogen derived from fertilizer to be dominant.

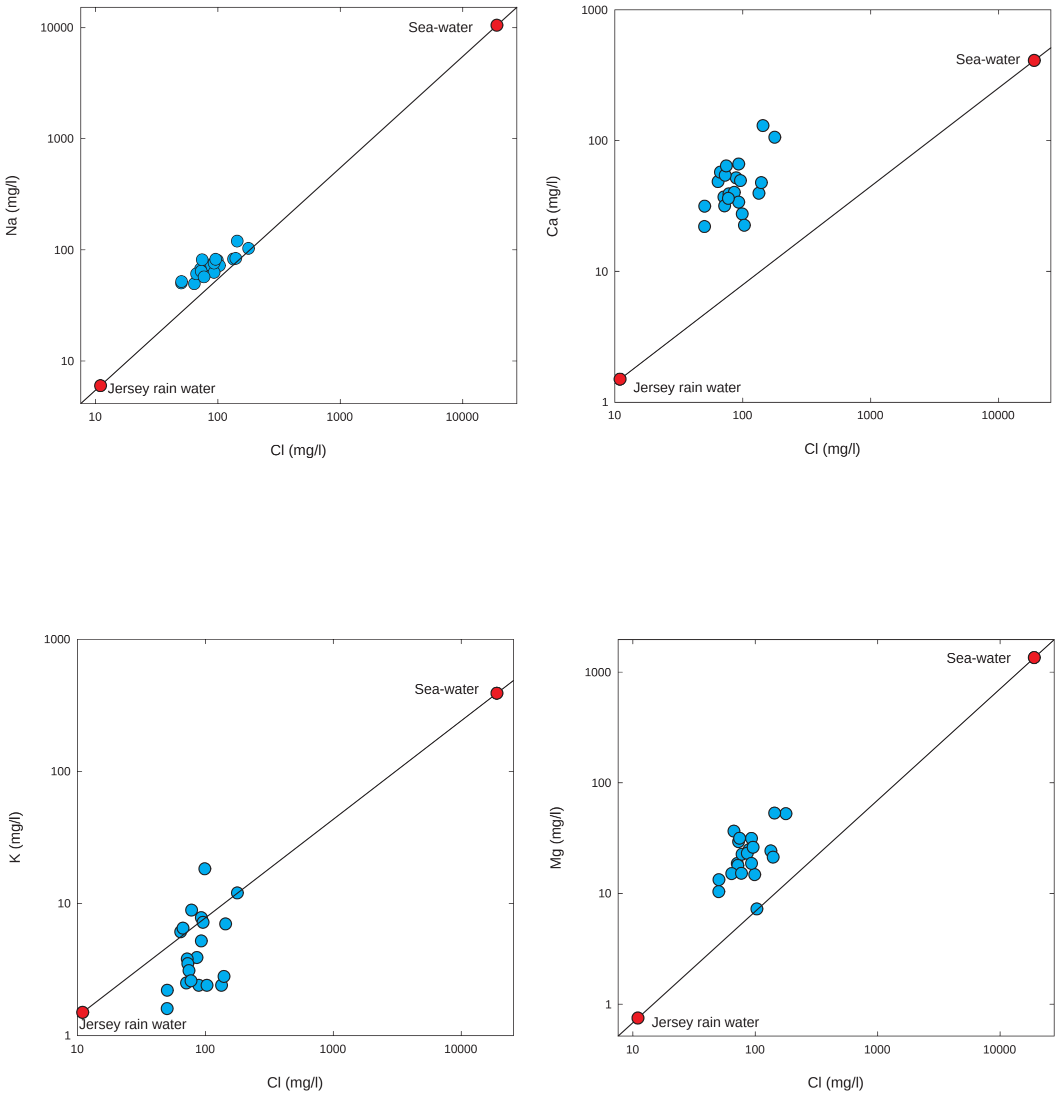

Figure 10 Na, Ca, K and Mg plotted against rain-water sea-water trend line

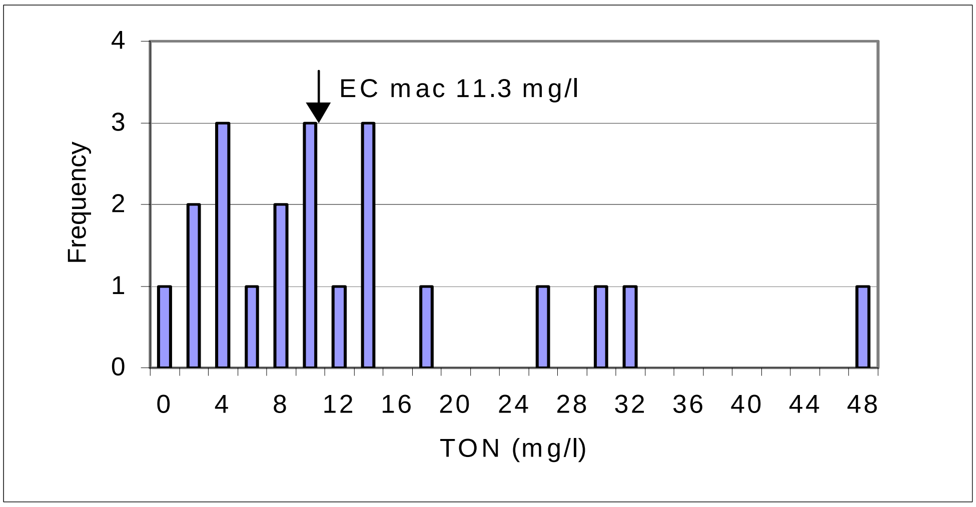

Figure 11 **Occurrence of total organic nitrogen**

Although the occurrence of nitrate in drinking water poses some risk to health, high nitrate concentrations also suggest that other less desirable species may also be present in some groundwaters. These could include pesticides derived from horticultural and agricultural use.

Analysis of other inorganic and organic pollutants was not included within the scope of this study.

3.4 Stable Isotopes

The stable isotope data are given in Table 4. They are all fairly similar with the exception of the sample from site 10b at the northeastern tip of the island. The plot in Figure 12 (a) shows the data in relation to the meteoric water line (MWL) and a freshwater-seawater mixing line. The size of the data symbols approximates the precision of measurement; while most of the samples are quite tightly clustered, there is evidence of a slight evolutionary trend. The most obvious cause would be the presence of small quantities of seawater, and the δ^{18}O-Cl plot in Figure 12(b) shows that this is probably the case with most samples on or near the freshwater-seawater mixing line (curved because of the Cl log scale). Minor evaporation before recharge would explain the slight scatter in δ^{18}O values.

Site No	Parish	Grid Ref	δ^{18}O	δ^{2}H
			‰	
12	Vale	316 820	-5.18	-31.8
24	Forest	317 762	-5.94	-31.4
21	St Saviour	295 768	-5.78	-32.1
22	St Saviour	293 768	-5.60	-32.2
30	St Peter’s	276 762	-5.61	-30.2
16	Castel	279 787	-5.25	-29.4
10b	Vale	355 833	-3.19	-24.3
11	St Sampson	333 808	-5.25	-31.8
18	St Peter Port	333 792	-5.76	-35.9
33	St Peter Port	337 779	-5.30	-31.0

Table 4 **Stable isotope analyses in permil with respect to Vienna Standard Mean Ocean Water (VSMOW)**

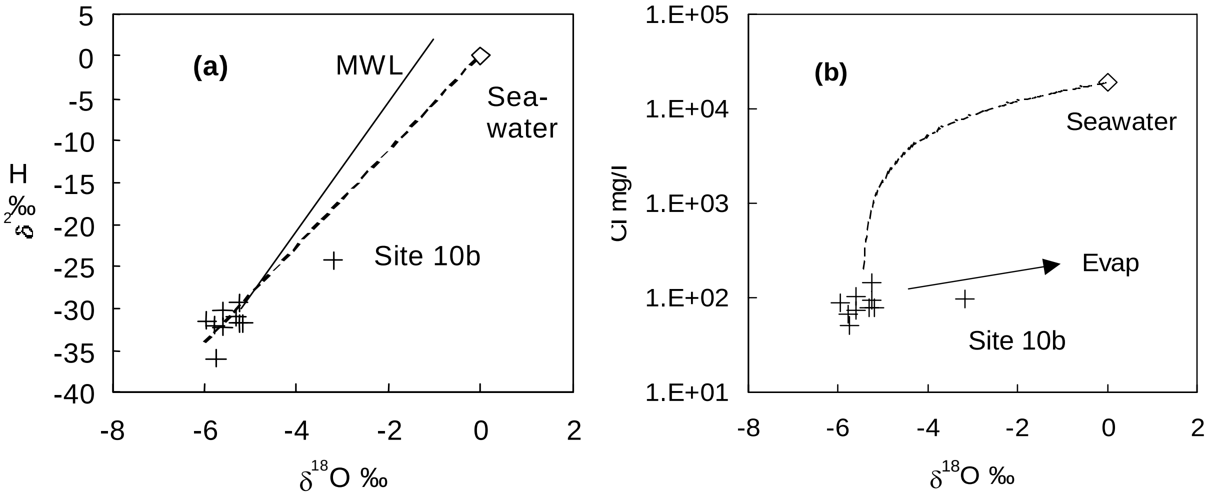

Figure 12 (a) δ-plot with meteoric water line (WML) and seawater mixing line, (b) δ^{18}O-Cl plot with seawater mixing line.

While the position of the site 10b sample on Figure 12 (a) suggests that seawater mixing may be a factor, its position on Figure 12 (b) shows that Cl is much too low for this to be the case. Instead, this indicates that the water must have undergone quite significant evaporation before recharge, i.e. it must have spent some time at the surface in a lake or reservoir. There is a small lake some 0.4 km away, but its isotopic composition is unknown.

3.5 Chlorofluorocarbons

CFC results are contained in Table 5. Given that peak modern values for recharge at 11ºC are about 5.3 (CFC-11), 2.8 (CFC-12) and 0.5 (CFC-113) pmol l^{-1} it is apparent that three of the sites show at least some evidence of contamination. While obviously this raises groundwater CFC concentrations, they can be lowered by degradation under low-oxygen conditions. Generally this is not serious above about 0.5 mg l^{-1} O_2, so none of the sites appears likely to have suffered from this in their overall CFC balance.

Sample	Temp	DO_2	CFC-11		CFC-12		CFC-113	
	ºC	Mg l^{-1}	Value	±	Value	±	Value	±
25	12.4	3.5	15	2	8.6	0.9	0.50	0.1
30	12.8	3.1	8.4	0.9	8.3	0.9	0.40	0.1
10b	13.6	2.1	2.9	0.2	1.5	0.1	0.21	0.1
32	11.2	10.2	8.4	0.9	2.9	0.2	0.55	0.1

Table 5 CFC values for Guernsey groundwaters. Concentrations in pmol/l.

The two most contaminated sites, 25 and 30, are situated respectively east and west of the airport. It may be that the observed contamination is due to the use of solvents at or near the airport resulting in some leakage to groundwater, but the most likely species to show such behaviour (CFC-113) is actually present at natural concentrations. Although the actual concentrations of CFCs are exceedingly low, they may be the precursors of more serious forms of pollution. At site 32, there appears to be contamination of CFC-11, CFC-12 (which is generally the most reliable of the species) and CFC-113 which are all present within measurement error of their mid-90s peak. Water from site 10b has consistent results suggesting an age of 15-25 years old. However, the nature of the Guernsey aquifer is unlikely to promote simple intergranular flow and it is, therefore, probably best to interpret the CFCs at all sites in terms of the mixing of young water from the 1990s with a small component of older pre-CFC (beyond 1940) water.

For sites 25 and 30 it is not possible to put a figure on the percentage of young water because of the contamination of CFC-11 and CFC-12, but the concentrations of CFC-113 suggest around 95-100% young recharge at site 25 and 75-80% at site 30. For site 32, the CFC-12 concentration can be interpreted as indicating that the water is 95-100% young recharge. All CFC species at site 10b are consistent with a 40-50 % contribution. The anomalous stable isotopic composition at site 10b (see above) indicated a surface water input but the CFCs can offer no evidence about this one way or the other because whatever the mode of recharge, the dissolved concentrations should be governed by equilibrium with the atmosphere at the average air temperature. In other words, although stable isotope ratios are altered by evaporation, there is no reason why CFC concentrations should be so affected. It seems most likely that the evaporated water is the young component, the recharge of which may have been promoted by abstraction from the borehole.

4. THE RENEWABLE RESOURCE

4.1 The Single Water Body

The shallow and deeper groundwater systems are contiguous (Figure 7). Although most of the groundwater flow takes place within the uppermost shallow weathered zone, there is a small component of deeper groundwater flow within selected fractures which remain dilated despite the pressure exerted by the overlying strata. It had been expected that the deeper groundwaters would have an older chemical signature than the shallow waters reflecting the longer flowpath containing them. The degree of contamination of some of the groundwaters selected for dating by CFCs has prevented precise relative dating of the shallow and deeper waters, but the fact that the deeper waters are contaminated suggests in itself a relatively young age. This demonstrates that the two groundwater flow systems are part of a single groundwater body originating from direct rainfall over the island but may, in part, reflect sampling problems associated with boreholes open throughout their length, i.e. the sample may be a mixture of shallow and deep waters.

Intersection of the water table with the ground surface sustains the surface water areas and wetlands. Although the Water Board collects much of the surface run-off in the valleys just before it gets to the sea, some may discharge underground through gravels and other permeable deposits beneath the valley floors. The underground flows are unlikely to be of significant quantity because the cross sectional area of the deposits is small and the gradients are insufficient to maintain worthwhile flows. However, fresh water discharge to beaches at low tide indicates that groundwater baseflow discharges to the sea. Although it is possible to engineer recovery of this water, it would not be economically viable.

Surface water flow derives from runoff during and after rainfall events, shallow interflow through the soil horizon and groundwater baseflow. Baseflow is significant in periods of low flow which arise in dry weather, when there is no run-off and little if any interflow feeding the streams. During low flow, almost all of the stream is fed by groundwater, either from discrete discharge along the valley floor or as springs and seepages along the valley sides. As the water table slowly recedes in response to continued discharge of baseflow the springs and later the baseflow discharge along the valley bottoms begins to dry up and the streams cease to flow altogether until the onset of the next significant rains. The groundwater body is, therefore, contiguous also with the surface water system and the whole should be viewed as a single water resource system. Abstraction of groundwater from boreholes affects discharge of groundwater as baseflow to surface water, and withdrawal of surface water from streams will have an adverse effect on the adjacent groundwater body as the stream flow declines and hydraulic contact to the water table is lost.

The deeper groundwater is tapped by those boreholes which have been drilled to depths up to 100 m. Just to the north of the airport, for example, are two boreholes which were drilled less than 50 metres apart. One of them is 18 m deep with an estimated yield of 60 m^3 d^{-1}, or more, whereas the second had to be drilled to a greater depth of 55 m in order to obtain a supply of only 17 m^3 d^{-1}. The favourable water bearing fractures intersected at shallow depths by the first borehole were not penetrated by the second borehole which intersected deeper but tighter and lower yielding fractures at depth.

Anecdotal evidence suggests that artesian conditions have, on occasion, been encountered during drilling, most notably in the vicinity of the airport but also in the King's Mill and Pleinmont areas. Some of these boreholes and wells are relatively shallow and may relate to a perched water table, others relate to the confining pressure of water contained in a fractured aquifer but recharged from some point of higher ground elevation.

4.2 Origin of the Water Resource

There is a commonly held belief that some of the water resources of Guernsey (and for that matter Jersey and also Essex) are sourced underground from rain falling on the Pyrenees. This unlikely scenario requires some direct conduit connection beneath the sea allowing water to be transported from the elevated head of the Pyrenees to the lower elevations of Guernsey. However, transport over such distances requires many thousands of years and the water would take up salts in solution from the rocks containing it before it finally re-emerged at surface. There is no evidence of ancient waters or of brines on Guernsey, on the contrary there is ample evidence to suggest that the waters are young and fell as rain over the last two or three decades. All the water resources of the island, must derive from direct rainfall over Guernsey.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The water resources of Guernsey comprise a single water system. This consists of a deep groundwater flow system within available dilated fractures in bedrock, a shallow aquifer in the weathered bedrock in which most of the groundwater flow takes place, shallow groundwater contained within granular superficial deposits and the surface waters of streams, ponds and reservoirs. The water system is sourced by rainfall over the island and is not connected to any off-island water system. Analysis of the island-wide water budget, using data derived for Jersey as an analogue, suggests that average runoff is equivalent to an annual depth of 226 mm and groundwater recharge of 129 mm.

The conceptual groundwater flow pattern for the island indicates flow from the High Parishes north-west and south to the coast, and little transport of groundwater beneath the flat land to the north. Most of this flow takes place in the uppermost saturated zone from the water table to a depth of about 25 m beneath the water table. Groundwater flow paths are short, typically less than a few kilometres, although some groundwater reaches deeper fractures and may flow over longer distances to reach shoreline discharge zones. There is no fresh water to sea water interface beneath much of the island except in some areas where the water table is less than 25 m above mean sea level.

There remains scope for additional groundwater development from the shallow weathered aquifer in selected places. Elsewhere, the aquifer is under stress and there may be interference between adjacent sources. The occurrence of the deeper aquifer is not predictable because of the irregular distribution of deep fractures, and it does not warrant systematic development. Besides, the volumes available from the deeper fractures are limited.

Much of the groundwater is contaminated as a result of intensive horticultural and agricultural activity and possibly also leaking cess pits. Over half of the sources that were sampled had a nitrate concentration exceeding the EC mac limit of 11.3 mg N l^{-1}. The groundwater chemistry is influenced by the maritime climate and by sea spray, but there is little evidence of any direct marine invasion of the groundwater body. The groundwaters show small uptake of Ca and HCO_3 from contact and chemical reaction with the host rock, but are in general moderately mineralised and oxygenated.

Stable isotope analyses do not contradict the idea that slight variations in groundwater chloride value reflect small contributions from seawater. However, there is evidence from the extreme north-east of the island that evaporated surface water may have recharged the aquifer, presumably in response to abstraction. Chlorofluorocarbon concentrations suggest that much of the pumped groundwater is of recent age, with the possibility that the high levels near the airport are precursors of pollution by other contaminants.

5.2 Recommendations

Monitoring to enable predictions on the physical status of the water resource is currently inadequate. A full meteorological station should be installed which will enable accurate determination of actual evapotranspiration. A distributed network of four or five rain gauges needs to be established to determine areal variation in rainfall. Measurement of groundwater levels needs to commence at a network of observation sites across the island in order to forewarn of stress on the groundwater body during periods of low rainfall. The present network of observation wells needs to be expanded to one of about 15 sites, including deeper boreholes, shallow wells and also one or two of the more important spring discharges. In addition stream gauging of the perennial water courses should be carried out at quarterly or monthly intervals.

Groundwater chemical sampling should be routinely undertaken on a twice yearly frequency at a further 15 sources which are in regular use. Analyses should include the eight major ions plus Fe, Mn and Al. In addition a campaign to identify likely organic contaminants in groundwater should be made so that the levels of pesticide contamination can be monitored. In view of the presence of CFC contamination from waste water and other sources, SF_6 (ideally sampled from individual flow horizons) could usefully be employed as a residence time indicator for groundwater.

Given that the whole of the island acts a capture zone for groundwater and surface water, all the land area of Guernsey should be considered as a Source Protection Zone (Environment Agency, 1992). To this end an inventory of point sources of pollution should be carried out and the nature of the risk that each one poses to the water body recorded. Thus a petrol station would pose a risk, but so would a domestic oil fuel tank. Similarly a photo processing laboratory or a dry cleaners would also pose a risk even though these activities are subject to stringent codes of practice. These data are valuable both to the water resource manager and to the planner.

Finally, consideration should be given to carrying out a detailed hydrogeological investigation of Guernsey, much along the lines of the investigation recently completed in Jersey. The margin between long-term renewable water resource and consumption may seem adequate today but the prospects of climate change may soon compromise that margin, and could have an effect also on water quality.

ACKNOWLEDGEMENTS

We thank the many people of Guernsey who welcomed us, gave us access to borehole and well sites, and shared information regarding their groundwater sources with us. We are particularly grateful to Nigel Jee for permission to reproduce hydrograph data, Dave Jehan at Stan Brouard Limited and to the staff of the Guernsey Airport Meteorological Office. The authors are grateful to the Chief Executive, Public Services Department, St Helier, for permission to use the Jersey recharge model.

REFERENCES

Collenette A 1916. The Pleistocene Period in Guernsey. Report and Transactions Guernsey Society of Natural Science and Local Research, **7**, 337-408.

Environment Agency 1998. Policy and practice for the protection of groundwater. Environment Agency, Bristol.

Guernsey Airport Meteorological Office 1998. Climatological Report for 1997. Report Guernsey Airport Meteorological Office, La Villiaze.

Hawksley 1977 Report on water resources in the south and west. Report T&C Hawksley, Aldershot.

Hem J D 1959. Study and interpretation of the chemical characteristics of natural water. US Geological Survey Water Supply Paper, No. 1473.

Hill E and Bonney T G 1884. The Rocks of Guernsey. Quarterly Journal of the Geological Society, **40**, 404-430.

Jehan N D 1993. Groundwater in Guernsey, a geochemical pollution study. BSc Dissertation, University of Leicester.

Keen D H 1978. The Pleistocene deposits of the Channel Islands. Institute of Geological Sciences Report 78/26.

Keen D H 1981. The Holocene deposits of the Channel Islands. Institute of Geological Sciences Report 81/10.

Meteorological Department 1991. Jersey Weather 1990. Report States of Jersey Airports and Harbours Committee, St Helier.

Mourant A E 1933. The raised beaches and other terraces of the Channel Islands. Geological Magazine, **70**, 58-66.

Roach R A 1966. Outline and Guide to the geology of Guernsey. Report and Transactions of the Société Guernesiaise, **17**, 751-776.

Roach R A, Topley C G, Brown M, Bland A M and D’Lemos R S 1991. Outline and guide to the geology of Guernsey. Guernsey Museum Monograph, **3**.

Robins N S & Smedley P L 1998. The Jersey groundwater study. British Geological Survey Research Report RR/98/5.

APPENDIX 1 Physical Characteristics of Wells, Boreholes and Springs

Parish	Grid Ref.	Estimated Elevation (m amsl)	Type	Depth (m)	RWL (m amsl)	Use	Quantity ($m^3 d^{-1}$)	Land use in surrounding area
St. Martin	323 755	93	bh	24	80.65	H	36 (seasonal)	H
St. Martin	309 762	102	bh	27	95.71	H	545 (seasonal)	H/A
St. Martin	308 762	102	bh	27	96.35	H		H/A
St. Martin	308 763	102	well	9	95.25	H/A	<1	H/A
Forest	300 756	100	bh	27	91.2	D		H/R
St. Peter Port	327 798	17	bh	30	15.1	H	130	H
St. Sampson	328 803	10	well	unknown	unknown	unused		H
St. Sampson	339 813	10	bh	unknown	8.95	H		H
St. Sampson	339 812	10	bh	15	9.39	H		H
St. Sampson	339 812	10	well	unknown	unknown	H		H
Vale	343 827	12	bh	30	8.35	H		H
Vale	355 834	10	bh	30	7.2	H		H/R
Vale	355 833	10	bh	55	2.27	H	18 (but up to 75)	H
St. Sampson	333 808	10	bh	50	8.55	H		H
Vale	316 820	20	bh	30	unknown	H	27	H, A and R
Vale	310 808	10	bh	6	9.25	H	98	H/A
Castel	294 791	30	well	24	unknown	D/A		R
Torteval	273 764	75	bh	unknown	60	H		R/H
Castel	279 787	15	bh	55	5.65	A/D	65+	A/H/R
St. Peter Port	335 788	40	well	21	unknown	I	14	U
St. Peter Port	333 792	60	bh	unknown	unknown	Rec		U
Torteval	266 754	83	bh	unknown	80.9	H		H
St. Saviour	295 768	88	bh	18	81.65	H	65+	H
St. Saviour	293 768	90	bh	55	69.5	H	13	H
Forest	317 762	100	well		93.5	SWB, rarely used		R
Forest	312 762	102	well		93.55	SWB, rarely used		Nr. Airport
St. Andrew	295 763	102	well		96	SWB, rarely used		Nr. Airport
Forest	285 755	100	well		97.05	SWB, rarely used		G
Forest	286 758	94	well		89.87	SWB, rarely used		G

Parish	Grid Ref.	Estimated Elevation (m amsl)	Type	Depth (m)	RWL (m amsl)	Use	Quantity ($m^3 d^{-1}$)	Land use in surrounding area
Castel	293 786	25	well			SWB		R
St. Peters	276 762	86	bh	100		D		R
St. Sampson	342 813	19	bh	18	14.3	D	<0.1	A
St. Sampson	345 810	32	bh	unknown		Rec		Rec
St. Peter Port	337 779	10	spr			I		U

Uses: D = domestic (including gardens and swimming pools), A = agricultural, Rec = recreational, I = industrial, H = horticultural, SWB = denotes States of Guernsey Water Board Well.
Land uses: R = residential, U = urban, G = grassland, Rec = recreation ground.

APPENDIX 2 Inorganic Groundwater Chemistry (mg l^{-1})

Major elements

Parish	Grid ref	Temp ^{o}C	PH	SEC µS cm^{-1}	Na	K	Ca	Mg	Cl	SO$_4$	HCO$_3$ (field)	TON
Forest	300 756	14.3	6.15	607	61.1	2.5	37.0	18.6	71.3	81.3	78.0	11.5
Vale	316 820	13.4	6.43	718	69.5	8.9	39.2	22.6	78.0	97.3	106	10.6
Forest	317 762	12.1	5.68	825	72.0	2.4	51.9	24.8	89.0	81.9	61.0	30.5
Forest	312 762	12.4	5.62	805	82.7	2.4	39.6	24.2	134	95.3	67.1	5.2
St. Saviour	295 763	11.6	6.11	427	50.4	1.6	22.0	10.4	50.3	43.4	77.2	1.4
St. Saviour	265 755	12.1	5.94	728	73.3	3.9	40.2	23.1	86.0	117	45.7	15.5
St. Saviour	286 758	-	-	-	67.3	3.8	31.7	17.9	72.1	106	-	8.7
King's Mills	293 786	11.1	-	611	49.6	6.1	48.5	15.1	64.2	44.6	-	5.6
St. Peters	266 754	11.2	6.33	745	80.9	18.3	27.5	14.8	99.0	81.5	60.4	8.1
St. Saviour	295 768	13.2	6.51	877	60.8	6.5	57.3	36.6	66.9	106	58.5	48.6
St. Saviour	293 768	13.3	6.55	800	64.2	3.5	54.3	29.4	73.0	125	100	18.9
St. Peters	276 762	12.8	5.87	559	72.3	2.4	22.5	7.2	103	40.2	27.4	3.2
Castel	279 787	10.0	6.41	650	62.8	7.8	33.8	18.7	93.0	49.4	57.9	15.5
St. Sampson	342 813	-	-	-	103	12.0	106	52.6	178	301	-	2.2
St. Peter Port	327 798	13.8	7.00	1387	76.0	5.2	66.2	31.4	93.0	104	184.1	32.8
St. Sampson	339 812	14.3	6.65	978	81.6	3.1	64.0	31.5	74.4	161	108.5	27.3
Vale	355 833	13.6	6.78	858	82.3	7.2	49.4	26.1	96.0	114	119.5	14.3
St. Sampson	333 808	11.8	6.68	1578	120	7.0	130	53.3	144	350	246.7	8.0
St. Peter Port	333 792	12.0	6.95	548	51.9	2.2	31.5	13.3	50.5	51.0	82.9	12.3
St. Sampson	345 810	11.2	6.55	869	83.7	2.8	47.7	21.3	140	66.7	79.9	11.8
St. Peter Port	337 779	-	-	-	57.2	2.6	36.2	15.2	77.2	53.2	-	4.8

APPENDIX 2 Inorganic Groundwater Chemistry (mg l^{-1}) Continued

Trace elements

Parish	Grid ref.	Br	F	Total I	P	Si	Ba	B	Li	Fe	Mn	Sr	Al
Forest	300 756	0.43	0.11	0.0264	0.07	10.9	0.028	<0.2	<0.009	0.03	0.003	0.19	0.045
Vale	316 820	0.46	0.14	0.541	<0.02	7.62	0.049	0.2	0.011	0.02	0.17	0.24	0.046
Forest	317 762	0.48	0.08	0.0195	0.05	9.91	0.064	<0.2	<0.009	0.03	0.004	0.25	0.057
Forest	312 762	0.60	0.09	0.0225	0.04	9.67	0.053	<0.2	<0.009	0.03	0.001	0.23	0.046
St. Saviour	295 763	0.14	0.15	0.0166	0.07	12.2	0.024	<0.2	<0.009	0.04	0.002	0.12	0.03
St. Saviour	265 755	1.09	0.12	0.0348	0.07	10.7	0.032	0.2	0.01	0.05	0.01	0.23	0.05
St. Saviour	286 758	0.49	0.13	0.0354	0.04	10.9	0.027	0.3	0.01	0.03	0.011	0.16	0.043
King's Mills	293 786	0.32	0.17	0.0518	0.06	8.97	0.048	<0.2	<0.009	0.35	0.13	0.19	0.071
St. Peters	266 754	0.58	0.12	0.0765	0.3	7.58	0.033	0.3	<0.009	0.14	0.004	0.19	0.047
St. Saviour	295 768	1.16	0.11	0.0683	0.05	10.4	0.071	<0.2	<0.009	0.05	<0.001	0.29	0.06
St. Saviour	293 768	1.65	0.15	0.0601	<0.02	11.4	0.023	<0.2	0.01	0.02	0.004	0.19	0.059
St. Peters	276 762	0.25	0.14	0.0320	0.18	12.7	0.033	<0.2	<0.009	0.11	0.02	0.083	0.035
Castel	279 787	0.44	0.20	0.578	0.03	7.98	0.031	<0.2	<0.009	0.02	0.02	0.35	0.06
St. Sampson	342 813	0.64	0.12	0.0749	<0.02	9.27	0.07	<0.2	0.031	1.44	1.42	0.39	0.089
St. Peter Port	327 798	0.45	0.03	0.159	0.03	11	0.063	0.2	<0.009	0.03	0.003	0.41	0.068
St. Sampson	339 812	0.52	0.04	0.0863	<0.02	12.1	0.022	0.2	0.013	0.03	<0.001	0.36	0.066
Vale	355 833	0.48	0.12	0.310	0.04	6.98	0.034	0.2	0.009	0.03	0.054	0.35	0.061
St. Sampson	333 808	1.18	0.09	0.186	1.07	8.02	0.047	<0.2	0.019	0.04	0.51	0.77	0.11
St. Peter Port	333 792	0.25	0.15	0.0167	0.03	16.9	0.043	<0.2	<0.009	0.03	0.005	0.3	0.041
St. Sampson	345 810	0.49	0.07	0.0507	0.02	14	0.023	<0.2	<0.009	0.08	0.002	0.43	0.069
St. Peter Port	337 779	0.31	0.15	0.0205	<0.02	11.3	0.043	<0.2	0.01	<0.02	<0.001	0.16	0.044

APPENDIX 2 Inorganic Groundwater Chemistry (mg l^{-1})

Trace elements continued

Parish	Grid ref.	Zn	La	Be	Cd	Cu	Co	Cr	Ni	Mo	Pb	As	Se
Forest	5475600	0.041	0.0003	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	0.02	<0.02
Vale	5482000	0.02	0.0012	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
Forest	5476200	0.04	0.0005	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
Forest	5476200	0.11	0.0006	<0.009	<0.001	0.06	<0.003	<0.001	<0.008	<0.005	<0.01	0.02	<0.02
St. Saviour	5476300	0.02	0.0003	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
St. Saviour	5475500	0.054	0.0003	<0.009	<0.001	0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
St. Saviour	5475800	0.013	0.0006	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
King's Mills	5478600	0.033	0.0006	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
St. Peters	5475400	0.046	0.0015	<0.009	<0.001	<0.02	<0.003	<0.001	0.008	<0.005	<0.01	<0.02	<0.02
St. Saviour	5476800	0.016	0.0006	<0.009	0.001	<0.02	<0.003	0.001	0.066	<0.005	<0.01	0.02	<0.02
St. Saviour	5476800	0.34	0.0005	<0.009	0.001	0.03	<0.003	<0.001	0.012	<0.005	<0.01	0.02	<0.02
St. Peters	5476200	0.013	0.0004	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
Castel	5478700	0.013	0.0012	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
St. Sampson	5481300	0.057	0.0008	<0.009	<0.001	<0.02	<0.003	<0.001	0.009	<0.005	<0.01	0.03	<0.02
St. Peter Port	5479800	0.028	0.001	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	0.02	<0.02
St. Sampson	5481200	0.014	0.001	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	0.02	<0.02
Vale	5483300	0.011	0.0007	<0.009	<0.001	<0.02	0.004	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
St. Sampson	5480800	0.022	0.0008	<0.009	0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	0.03	<0.02
St. Peter Port	5479200	0.092	0.0005	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
St. Sampson	5481000	0.032	0.0007	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02
St. Peter Port	5477900	0.01	0.0006	<0.009	<0.001	<0.02	<0.003	<0.001	<0.008	<0.005	<0.01	<0.02	<0.02