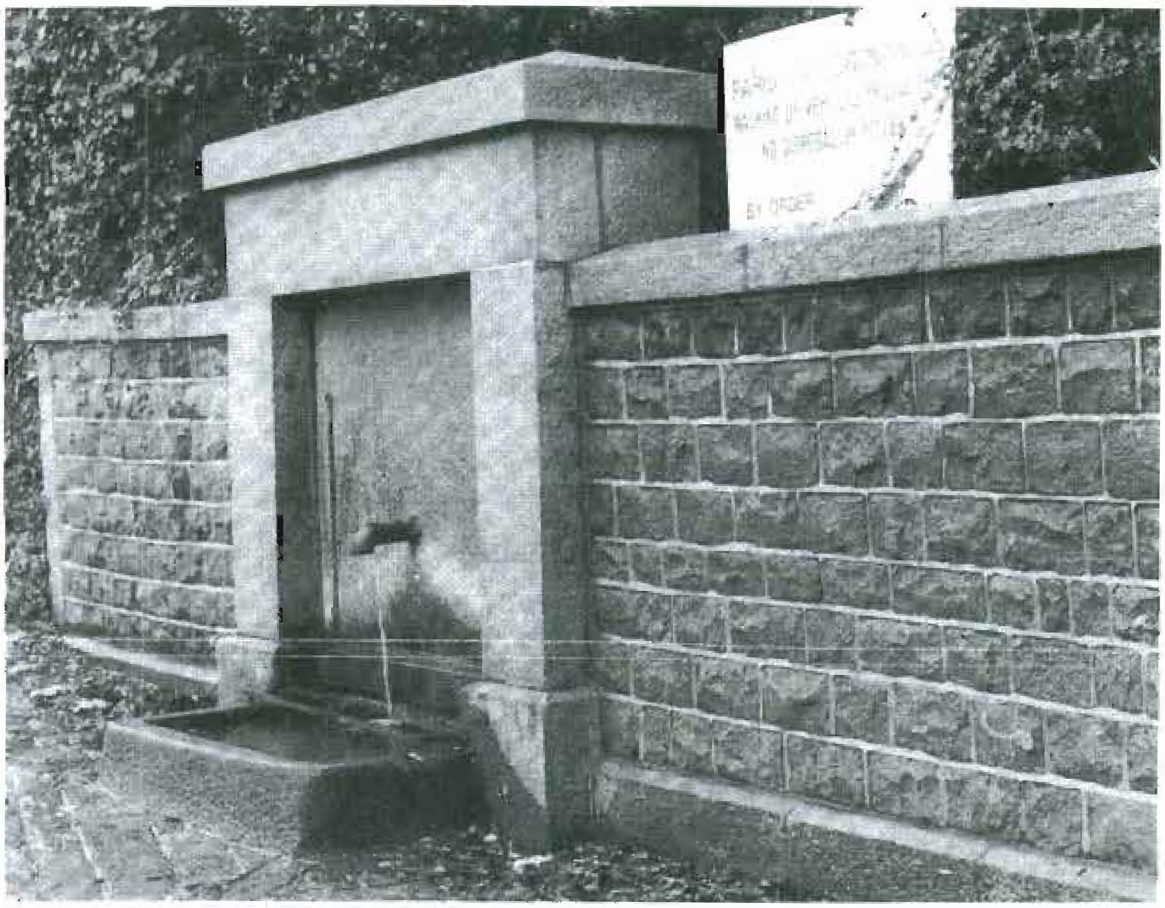
TECHNICAL REPORT WD/91/15

Hydrogeological and hydrogeochemical survey of Jersey

N S Robins and P L Smedley



Frontispiece - The Grouville Spring

BRITISH GEOLOGICAL SURVEY

TECHNICAL REPORT WD/91/15
Hydrogeology Series

Hydrogeological and hydrogeochemical survey of Jersey

N S Robins and P L Smedley

Cover photo
Corbière, South-west Granite, Jersey. (*Joe Bates*)

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BRITISH GEOLOGICAL SURVEY

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EXECUTIVE SUMMARY

Jersey is a heavily populated island with intensive agriculture. It has limited water resources which are at risk from pollution. The island is some 117 square kilometres in area and comprises in the main a plateau of 60 to 120 m elevation. Rivers drain generally from higher ground in the north to lower ground in the south. Mean annual average rainfall is 877 mm.

Bedrock is of Precambrian to Cambro-Ordovician age. The oldest rocks belong to the Jersey Shale Formation which underlies much of the west-central part of the island. The Jersey Volcanic Formation occupies much of the east of the island. There are a number of plutonic complexes principally of granite but including diorite and gabbro. The Rozel Conglomerate Formation crops out in the north-east corner of the island. None of the rocks have any significant intergranular porosity and groundwater storage and transport depends on the occurrence of secondary features such as dilated cracks and joints.

Superficial deposits include wind-blown sand, loess and alluvium. The sand forms small coastal aquifers notably at St Ouen's Bay and St Helier.

There is widespread use of fertilisers and organic compounds. Soakaways are commonplace. There is no law pertaining to underground water.

A survey of 109 groundwater sources was carried out. Measurements include: hydraulic character of the source, inorganic and selected organic chemistry as well as microbiology of the groundwater. The sample locations represent approximately one per square kilometre and are evenly distributed. Other data include selected metering of boreholes, water level hydrographs, and meteorology. There is no comprehensive database relating to groundwater previous to this survey.

Soil moisture deficit analysis suggests that the island's theoretical renewable resource is approximately 5.5 x 10^6 m^3/a. Estimated total abstraction is about 70% of this figure at 3.7 x 10^6 m^3/a. This high percentage indicates that overpumping is already occurring and eroding baseflow to streams and the coast because of declining water levels in the aquifer above. The water table is declining permanently in some areas as full recovery cannot occur during the winter rains. The figure of 70% compares unfavourably with data available for other similar islands (cf 20% on St Helena, 10% on St Kitts or 8% on Nevis).

In the bedrock the hydraulic performance of the volcanic rocks and the conglomerate is more favourable than that of the granite. The Jersey Shale Formation is, in general, only half as productive as the volcanic rocks or the conglomerate.

St Ouen's sand aquifer is a thin aquifer capable of supporting considerable abstraction. A computer model of the Mont a la Brune area indicates that abstraction around the existing public supply wellfield could be increased by 600 m^3/d. Overpumping will not occur because the head of fresh water will sustain the saline interface beneath the beach.

The bedrock groundwaters are largely of Na-Ca-Cl or Na-Ca-HCO_3 type with subsidiary SO_4. Repeat sampling between summer and autumn 1990 indicates chemical stability of sources. Many groundwaters are acidic, 80% have pH values less than 7. Most are oxidising with redox potentials greater than 250 mV but a small proportion are reducing particularly in St Helier,

St Clement and Grouville. These reducing waters have high Fe (total Fe and Fe^{2+}) and Mn concentrations but they are low in nitrate because of bacterial and chemical denitrification.

There is some saline intrusion in certain coastal areas. All waters are Cl enriched due to the marine environment. There are few noticeable chemical variations of groundwater with lithology, although water in the Jersey Shale Formation has slightly higher pH values than elsewhere due to reaction with clay minerals and carbonate.

Stable isotopes (δ^2H and $\delta^{18}O$) indicate that Jersey groundwaters largely represent recently recharged water, having equilibrated in contemporary climatic conditions. There may be a minor influence of marine water mixing.

Agricultural and domestic pollution has had a significant impact on the shallow fissured aquifers particularly with respect to NO_3-N. Over 60% of samples had concentrations greater than 11.3 mg/l, the EEC maximum admissible concentration. Pollution is also observed in K and P concentrations, but pollution by persistent weedkillers and other herbicides is not generally a problem. The high concentration of Simazine in the Grouville Spring is however, cause for concern.

The major processes affecting Jersey groundwater quality appear to be geochemically rather than microbiologically motivated, although some redox processes may be aided by microbial activity. The geochemistry of groundwater is strongly influenced by agricultural pollution, redox, water rock interaction and saline infiltration. Each process affects certain determinands to different extents, and the processes cannot be ranked in importance. A potential rise in sea level of 1 m as a response to possible global warming will threaten groundwater in the south-east of the island but would have little impact on water quality elsewhere.

The bedrock aquifers are under threat from overpumping and disperse pollution. If this is allowed to continue, the groundwater resources will decline in quality and availability. Continued monitoring will enable the situation to be evaluated. In the meantime a series of legislative measures is recommended.

1. INTRODUCTION

1.1 Groundwater - a social asset

Jersey sustains a demanding consumer society. Given offshore economic status, a strong tourist industry and the traditional early supply of horticultural produce to the English market, Jersey is able to maintain a thriving economy. The island has a resident population of 82,000 and beds for an additional 50,000 visitors. Jersey is roughly rectangular some 16 km east-west by 6 to 10 km north-south, and much of the population is concentrated in the southern half of the island.

Approximately 80% of the resident population receive mains reticulated water from the Jersey New Waterworks Company. The remainder, largely but not entirely situated in rural locations, rely on private water supplies. The public water supply is 96% derived from impounded surface catchment storage whereas the private supplies are almost all groundwater. The balance of the public water derives from groundwater and desalinated sea water.

Private groundwater supplies sustain individual and community domestic requirements, hotels, hospitals, light industry, agriculture and some recreational needs. Potable supplies may be supplemented by rainwater cisterns. There are many perennial and seasonal springs on the island and these along with hand-dug wells were the traditional water sources of the island. More recently as demand has increased, these supplies have been supplemented by narrow-diameter drilled boreholes with electrically driven pumps.

Groundwater demand has now increased to such an extent that it has probably already exceeded the available replenishable resource. When this happens more water is taken out of the aquifer or flows from it as baseflow, than is put into the aquifer as recharge. As a result, groundwater levels will fall and seasonal replenishment is incomplete; springs, shallow wells and deeper boreholes each cease to produce, baseflow to surface waters diminishes and stream flows to surface reservoirs decline both in quantity and quality.

Increased water use has not universally been matched by increased mains sewerage and other sanitary protection. Many farm wells are situated between the soakaway and the silage clamp in such a position that surface runoff from the farmyard may enter the well. Increased use of agricultural chemicals provides a more diffuse source of pollution to groundwater. Other hazards include leaking storage tanks and waste disposal sites. A further threat to water quality is posed by overabstraction of groundwater in low-lying areas which allows marine water to invade the aquifer.

Jersey's groundwater resources are replenished by direct rainfall over the island; none derives from underground flow from recharge elsewhere. The resources are limited and they are vulnerable to pollution; the resources are, however, a most valuable asset which must now be safeguarded and properly managed.

1.2 Physiography and climate

The land area of Jersey above high-tide mark is some 117 square kilometres. The island comprises a plateau standing at an elevation of between 60 and 120 m above datum (mean sea level; Figure 1.1). The plateau is divided by a series of valleys orientated north-south draining from higher ground in the

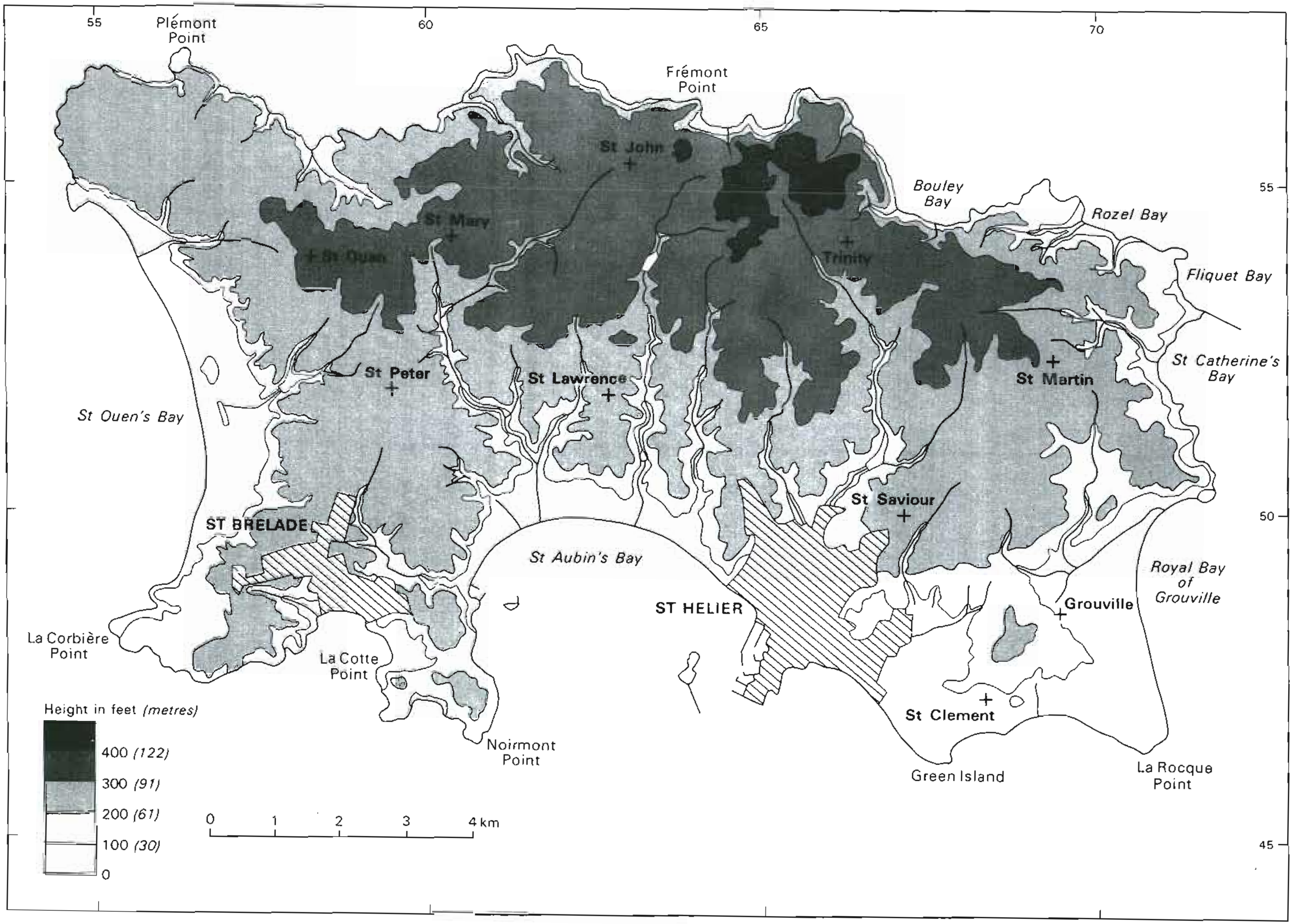


Figure 1.1 Topography and place names

northern part of the island to the south coast. From west to east the major valleys are: St Peters Valley, St Lawrence (Water Works) Valley, Les Grandes Vaux and Queens Valley.

The northern coastline is adjacent to the highest ground, and is rocky and generally cliff-bound with small sandy coves. The west coast comprises the broad sands of St Ouen's Bay whereas the east coast is divided between St Catherines Bay north of Gorey and the Royal Bay of Grouville to the south where the adjacent land is low lying. The south coast is dominated by St Aubin's Bay which is overlooked by the main town of St Helier. To the east the foreshore is rocky and low tide exposes distinctive erosional features in rock outcrops across the wide foreshore. Rocky headlands to the west enclose St Brelade's Bay. Spring tides may attain up to 12 m range, and at a low spring tide a total foreshore of some 44 square kilometres is exposed.

Relatively flat low lying land occurs behind St Ouen's Bay, the Royal Bay at Grouville, in the extreme south-east corner of the island, and behind parts of St Aubin's Bay. Elsewhere elevations rise steeply away from the coast to provide a varied inland topography with the steepest slopes along the main valleys and adjacent to fossil shorelines. The topography is otherwise gentle and rises to maximum elevations in excess of 130 m above datum between Trinity and St John in the northern part of the island.

Jersey enjoys a temperate maritime climate. Prevailing wind directions are from the west and south-west with minor incidence of north-easterlies. Mean average annual rainfall is some 877 mm (1951-1980). Rainfall is least in the west and south-west of the island with only 747 mm recorded at La Sergente in 1986, and highest in the north-east where 983 mm were recorded at Trinity in 1988 (Figure 1.2). The average annual period of rainfall is 23 days and 7 hours (Jersey Airport).

The mean annual air temperature is 11.5°C and ranges from 8.6°C to 14.3°C. Mean daily temperatures in July and August are 20.7°C to 20.8°C respectively, but maximum temperatures in the low 30's °C are not uncommon. The average incidence of ground frost is sixty per annum and air frost some twelve per annum. Average sea temperature is 12.3°C and ranges from 7.3°C in February to 17.5°C in August. Relative humidity varies from 75% in early summer to 85% in mid-winter. The incidence of fog is some 15 days per year.

1.3 Geological setting

The oldest rocks on Jersey are those of the Jersey Shale Formation (Figure 1.3) which has been correlated with the Brioverian Supergroup of Normandy and Brittany (Table 1). These sedimentary rocks were succeeded by the deposition of volcanics (also Brioverian) which show a change from andesitic to rhyolitic composition as volcanism proceeded. These rocks were then folded and metamorphosed during the Cadomian Orogeny and intruded by both acid and basic igneous rocks, principally granite, granophyre, diorite and gabbro. Subsequent uplift and erosion produced the Rozel Conglomerate Formation, of Cambro-Ordovician age.

The only other lithologies exposed on the island are of Quaternary age. Interglacial raised beach deposits, head and loess were laid down during the Pleistocene, and more recently (Holocene) peat, alluvium and blown sand have been deposited. The Quaternary deposits have a strong influence on soil type: loess deposits give rise to loamy brick earth, whereas sandy (and peaty) soils are developed elsewhere.

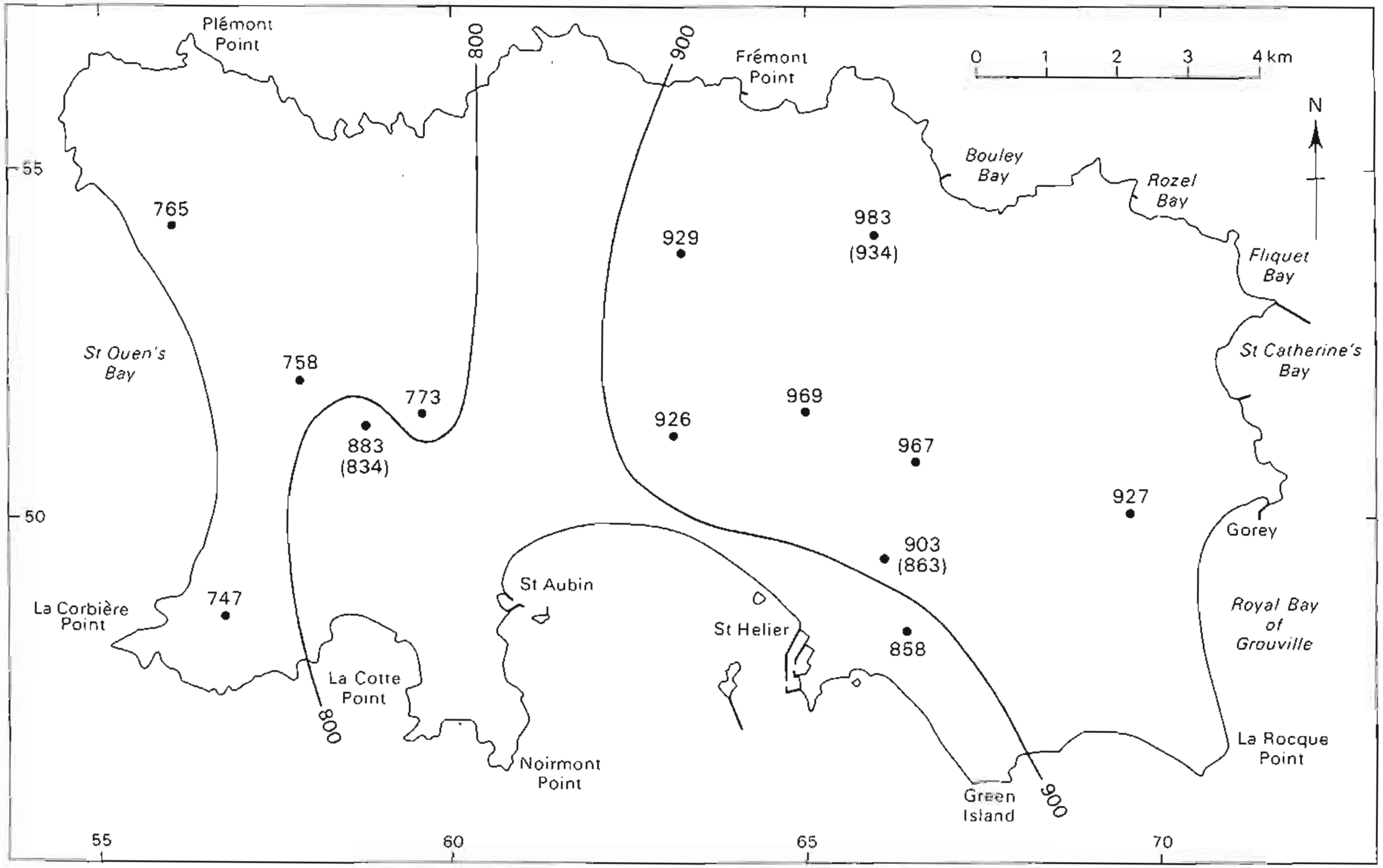


Figure 1.2 Average annual rainfall (mm, 1951-1980)

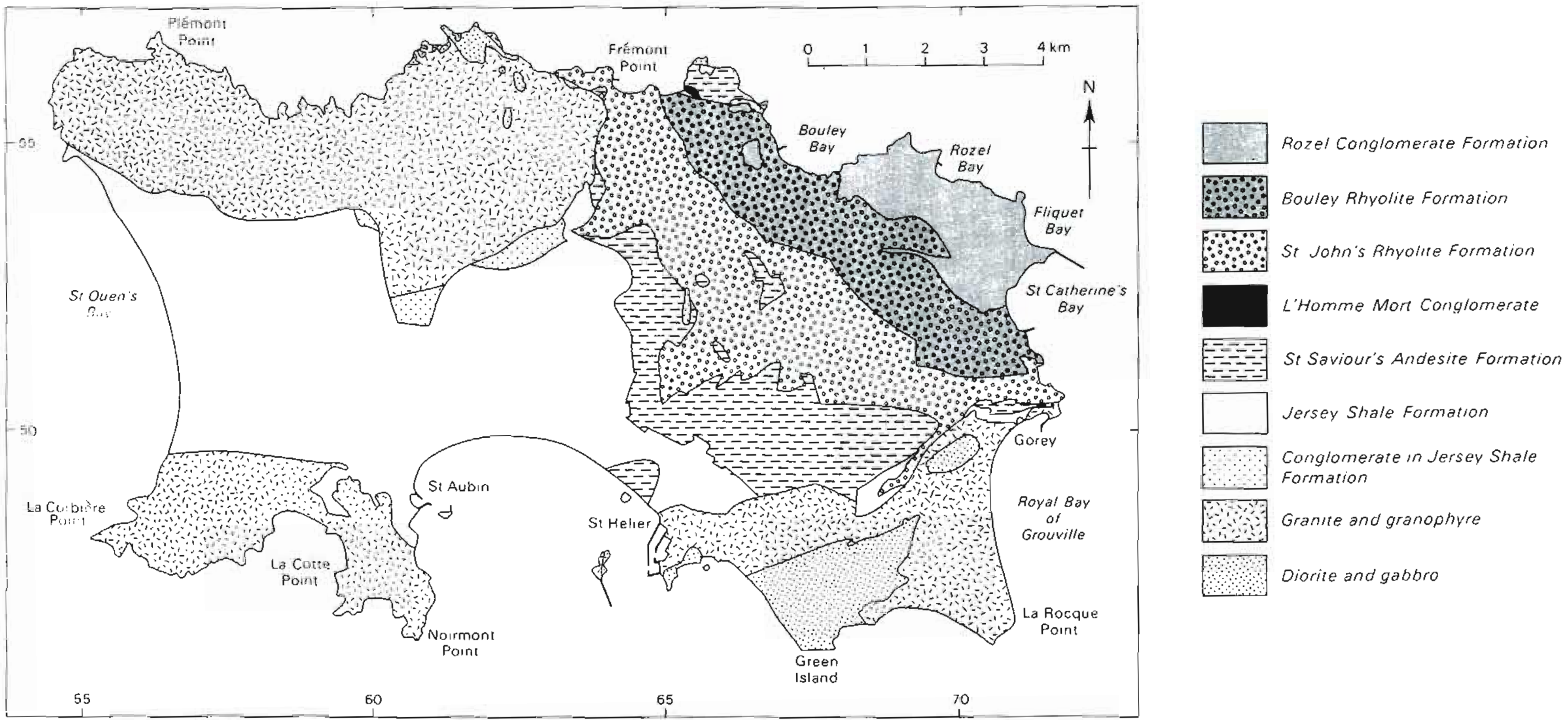


Figure 1.3 Solid geology

The Jersey Shale Formation crops out over a large part of the western half of the island. It consists of cleaved mudstone, siltstone and greywacke (fine-to medium-grained sandstone and subordinate conglomerate).

Table 1. Stratigraphic succession (after Helm, 1983; 1984).

Era/Eon	Supergroup	Formation/group with thickness (m)	Orogeny
Cambro-Ordovician		Rozel Conglomerate Formation (100-600)	Cadomian (700-500 Ma) with plutonism
Proterozoic	Brioverian	Volcanic Group (2300) Jersey Shale Formation (2500)	1100-900 Ma
	Pentevrian		

Six discrete facies have been identified: silt and mud; very fine sandstone both of which have sheet-like bedding in units 1 to 10 cm thick; fine to medium-grained sandstone in units 10 to 50 cm thick; cross bedded medium-grained sandstone in units 10 to 30 cm thick; lenticular bedded conglomerate usually thicker than 100 cm; chaotic beds some 10 to 50 cm thick. These sedimentary facies are generally related to deposition by turbidity currents on a submarine fan. Mudstone and fine-grained sandstone are the principal facies. The matrix of greywacke is approximately 70% quartz and 10 to 15% feldspar (Helm and Pickering, 1985). Diagenetic calcite is also present. The sediments have been metamorphosed to low greenschist facies so that clay minerals have been replaced by chlorite. Contact metamorphism has only occurred at L'Etaq.

Four phases of deformation can be identified in the strata (Helm, 1983). These have resulted in north-south periclines and singly plunging folds. A later phase induced an easterly plunging anticline with conjugate faults and associate folds. Superimposed on these is an array of radial fractures. Bedding planes are commonly at right angles to cleavage. At outcrop, principally in coastal sections, many of the tectonic and sedimentary discontinuities weather to open cracks and fissures. More recent exposures of the Jersey Shale Formation (e.g. in and around some of the German tunnels) suggest that the dilation does not persist far from outcrop or with depth other than in rare and major discontinuities.

The overlying Volcanic Group crops out to the east of the Jersey Shale Formation and occupies a large part of eastern Jersey. The following sequence has been defined on the basis of work reported by Bishop and Bisson (1989):

Bouley Rhyolite Formation	430 m
St John's Rhyolite Formation	950 m
St Saviour's Andesite Formation	850 m

The contact between the St Saviour's Andesite and the underlying Jersey Shale Formation is largely faulted, but a thin conglomerate has been observed in places. Petrographically the volcanic rocks are very variable, but a detailed report was presented by Casimir and Henson (1955) for the Giffard Bay area.

The St Saviour's Andesite Formation comprises volcanic flank deposits of subaerially deposited lava, tuff and agglomerate. They are andesitic to basaltic in composition. The andesites possess a keratophyric mineralogy, and most of the lavas contain an abundance of plagioclase phenocrysts.

The St John's Rhyolite Formation can be divided into five major cooling units each containing numerous individual flows. They are largely ignimbrites rather than rhyolites and include erosional features between flows. Texture may vary from tuffaceous to brecciated or eutaxitic.

The base of the Bouley Rhyolite Formation is marked by rhyolite flows. There are thin andesites within the rhyolites, and there is evidence of periodic erosion within the sequence. There are some ignimbrites with associated airfall tuffs, particularly along the east coast.

Various fold structures have been identified in the Volcanic Group with axial trends to the west, south-west and south. These include the so called Trinity Syncline and the St Helier Syncline, the latter forming an inlier to the west of St Helier. There are three cleavage trends, north-west, north and north-east (Helm, 1984). There are numerous minor faults and other such features of brittle fracture.

Reddish-brown conglomerate with subordinate sandstone and mudstone form the Rozel Conglomerate Formation which crops out in the north-eastern corner of the island. It has a continental alluvial fan origin derived from a source area to the north. Some of the coarser material is graded. The conglomerate comprises both poorly stratified and unstratified pebble and cobble conglomerates with a sand and granule size matrix. Very rare mudstone and sandstone intercalations occur at a few localities. The cement is hematitic oxidising to limonite near surface. The strata are disposed in a west-north-westerly trending syncline.

The principal plutonic rocks, notably granite, diorite and gabbro were emplaced after the low-grade metamorphism and folding of the older strata had occurred. The granites are younger than the gabbro and diorite. There are three granite complexes: North west Granite, South west Granite and South east Granite.

The North west Granite is the largest and the youngest. It has a sharp contact with the country rock with little brecciation. The granite is generally coarse-grained with tabular crystals of orthoclase or orthoclase-perthite, with subordinate and smaller plagioclase, abundant quartz and biotite and hornblende; accessory minerals include zircon and apatite. Enclaves of gabbro and diorite occur in the northeast of the complex.

The South west Granite was intruded into the Jersey Shale Formation but there is no evidence of an aureole. There are three granite types: coarse-grained Corbiere Granite with megacrysts of potassic feldspar set in a fine-grained matrix, the La Moye Granite, and an aplogranite, the Beau Port Granite. The Corbiere granite contains crystals of orthoclase perthite, plagioclase, quartz mica and hornblende with accessory minerals - zircon, apatite, iron oxide, fluorite and allanite. Average grain size is 4 mm. The Beau Port Granite has an average grain size of 1 mm. The main minerals are: quartz, perthite, plagioclase with subordinate biotite, iron oxide and hornblende. The La Moye microgranite has an average grain size less than 1 mm and comprises perthitic alkali feldspar, oligoclase quartz and minor amounts of biotite and ilmenite with accessory chlorite, zircon, apatite, fluorite and muscovite phases (Bland, 1984).

The South east Granite complex includes gabbro and diorite massesas well as granite. The gabbro principally contains clinopyroxene and calcic plagioclase with subordinate apatite and titanomagnetite. Typical chemical analyses for the gabbro and diorite are shown in Table 2.

Table 2. Typical chemical analyses in weight per cent for South east Gabbro and Diorite (after Bishop and Key, 1983).

	Gabbro	Diorite
SiO_2	48	46
TiO_2	0.7	1
Al_2O_3	17	16
Fe_2O_3	0.5	3
FeO	6	9
MnO	0.1	0.2
MgO	9	6
CaO	13	10
Na_2O	2	3
K_2O	0.9	0.9
P_2O_5	tr	0.1
H_2O	3	2

There are numerous minor intrusions, principally basic, acid and lamprophyre dykes. The main trend is west-east but there is also a west-south-west trend. Dykes may be less than 1 m wide but some of the basic intrusions may be up to 10 m wide. The basic dykes are principally of dolerite containing pyroxene with or without amphibole. The acid dykes are porphyritic microgranite and flow-bonded rhyolite from 4 to 10 m in width. The lamprophyres may be hornblende -or mica-lamprophyres.

Dislocations may occur at some dyke margins, and some dykes were intruded along faults. Principal faults trend east-south-east and are dominantly subvertical wrench faults. The location of the faults is shown on the 1:25,000 geological map of Jersey (IGS, 1982). Folding within the Jersey Volcanic Group and the Rozel Conglomerate Formation has produced jointing and occasional shear zones. However few records of joint spacing or joint density have been made and few observations on joint dilation or infill material are available. Nevertheless, the volcanic rocks appear to be well jointed in outcrop and even have an element of slaty cleavage in places.

Further details on the solid geology of Jersey are available in the geological sheet description of Jersey (Bishop and Bisson, 1989) and the 1:25,000 scale geological map (IGS, 1982).

The superficial deposits of Jersey were described by Keen (1981). The aerial distribution of the drift deposits is shown in Figure 1.4, and the probable succession with estimated maximum thicknesses is given in Table 3.

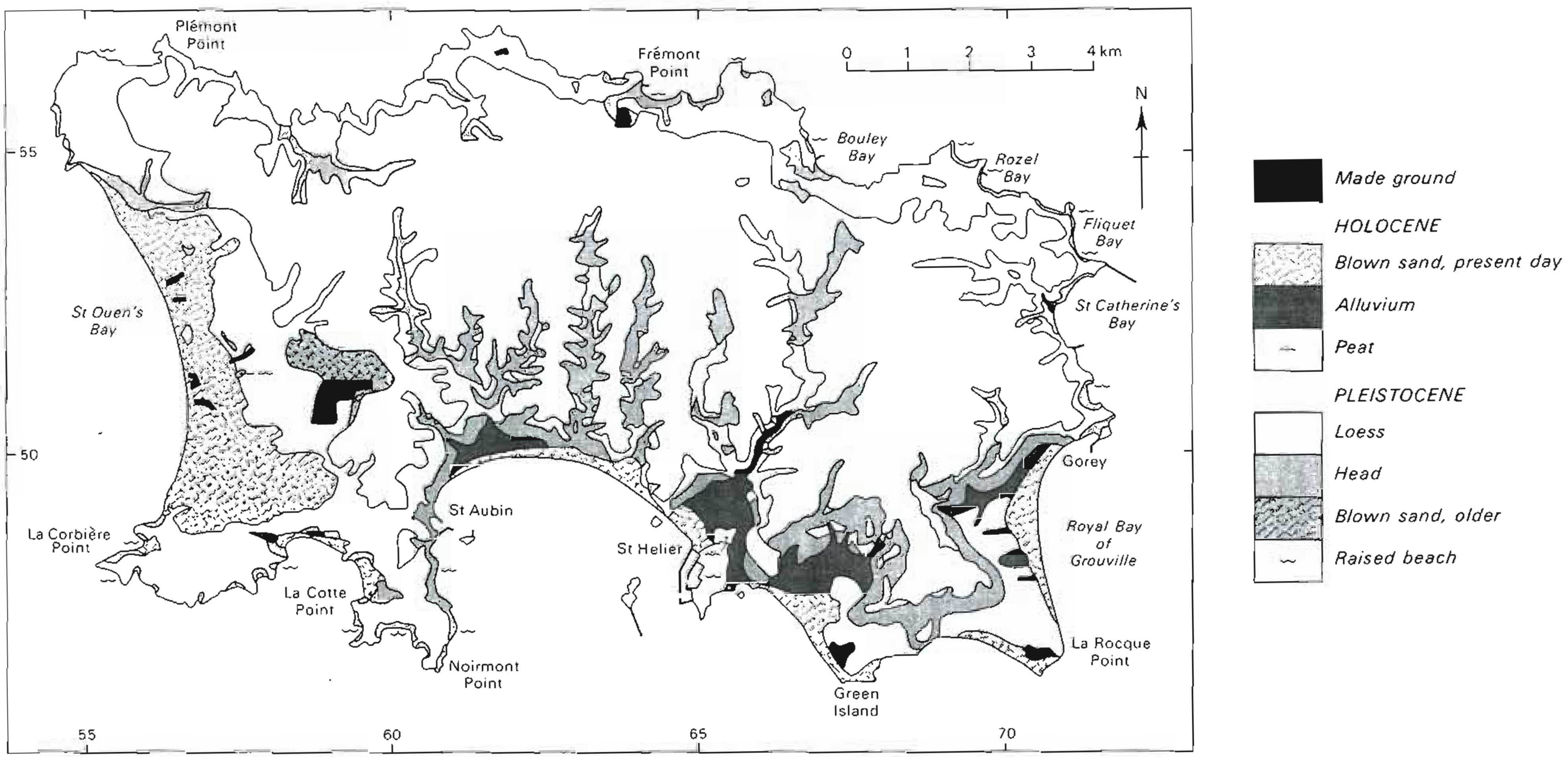


Figure 1.4 Drift geology

Table 3. Quaternary sequence and maximum thickness (m).

Holocene	Blown sand	20
	Peat and alluvium	10
Pleistocene	Loess	5
	Head	30
	St Peters Sand	5
	8 m Raised Beach	3
	Head	2
	18 m Raised Beach	2
	30 m Raised Beach	2

The 30 m and 18 m raised beaches are of very limited distribution and comprise mainly gravels. The 8 m raised beach is more widespread (Figure 1.4). It ranges from cobble grade down to fine-sand, mainly of local origin. St Peters Sand is a well-sorted quartz and feldspar sand with an iron cement. It occurs only in a small area to the north and east of the airport and is probably of blown sand origin.

Head occurs along valley sides and at the foot of cliffs. It is generally weakly sorted and comprises reworked weathered remnants of local material. At higher elevations the interior plateau of the island is covered in a mantle of loess - wind blown detritus derived from the exposed floor of the sea bed. It comprises quartz and feldspar of which 80% is of silt grade.

Recent deposits include peat and alluvium which occur at the bottom of the major valleys along the south and east coast, and peat also occurs in the northern part of St Ouen's Bay. The alluvium is largely silt grade material. The largest deposit of Recent blown sand is at St Ouen's Bay, but it is also present in St Aubin's Bay, St Clement's Bay and the Royal Bay of Grouville. The St Ouen's Bay sand attains a maximum thickness of 27 m and spreads from 1.5 to 3 km inland (Thurrell, 1972). Elsewhere the sand may occur up to 500 m from the shore but is generally only up to 15 m thick.

The distribution of soil types on the island (Figure 1.5) is strongly influenced by the drift geology. The Plateau area is covered in loam or brickearth which derives from the loess. Elsewhere sand and sandy soils predominate. The valleys tend to support a stony soil which relates to head deposits, and some of the steeper cliffs have little soil cover and are merely rocky slopes.

1.4 Land use and water administration

Horticulture is carried out over a large part of the island. The production of vegetables and flowers is widespread and specialist glasshouse cultivation is common. Fruit is grown mainly in Trinity. Elsewhere grassland predominates and dairying is most intense in the Maufant area. Large areas of grassland are also developed for recreational purposes. Urban development covers large areas along the south coast.

The effect land use has on hydrogeology may either be physical or chemical. Urbanisation tends to increase runoff as mains drainage from hard standing areas prevents infiltration. Soakaway drains and domestic soakaways tend to increase infiltration.

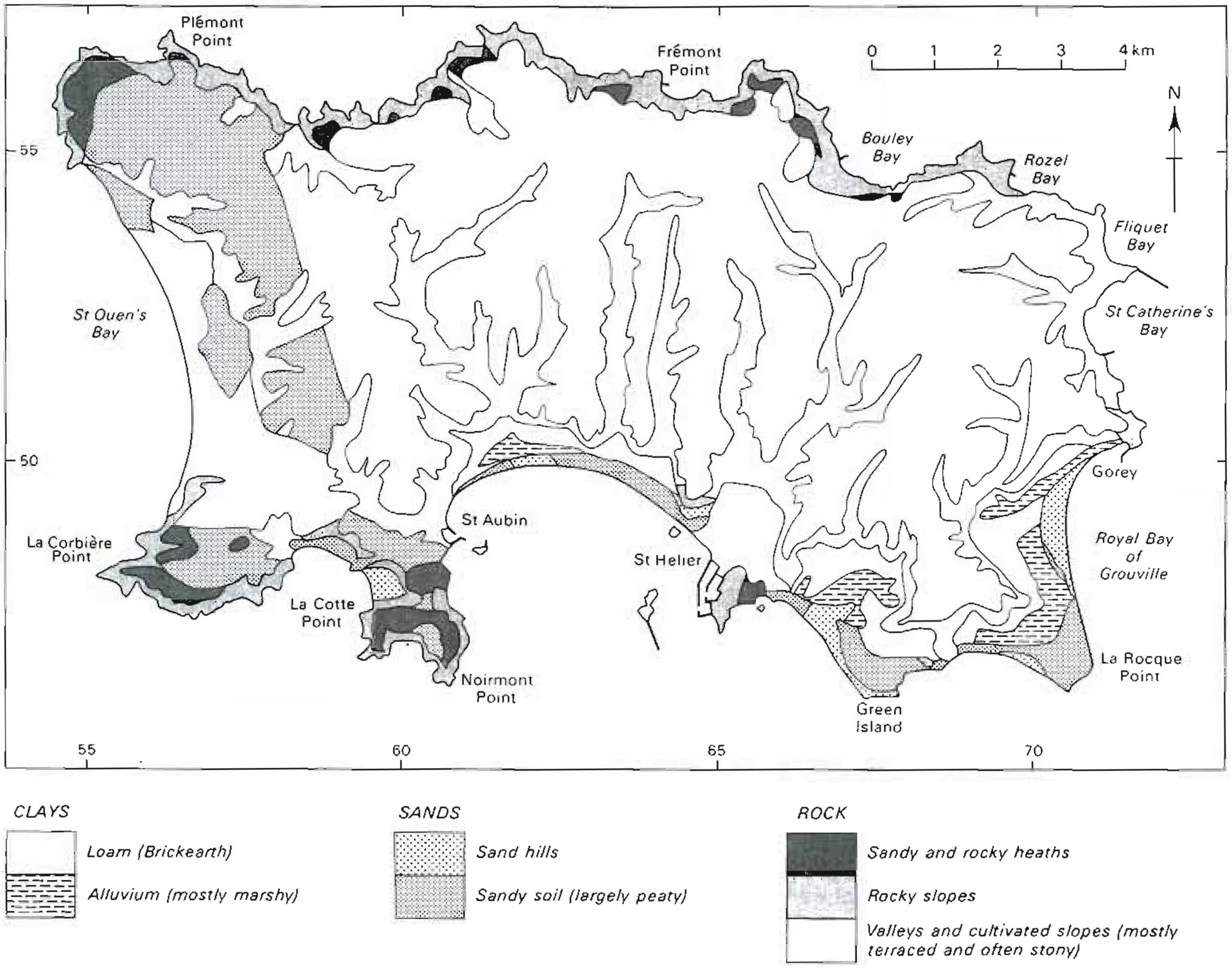


Figure 1.5 Soil types

The influence of land use on groundwater quality is important on Jersey. Intense and often specialised crop growing has promoted the addition of nutrients to the soil and more recently the use of organic compounds principally for weed and pest control. Some of these compounds may leach through the soil profile into the shallow aquifers of Jersey, others may bypass the soil zone via soakaways and so arrive at the water table. Bacterial pollution may also occur near domestic soakaways and leaking sewers.

With these influences in mind, a simple five category land use map has been devised (Figure 1.6). The categories are as follows:

(1) Glasshouses - intense cultivation accompanied by nutrient application, use of organic compounds and irrigation.

(2) Urban - enhanced runoff, pollution risk to groundwater from sewers, storage tanks, etc. and weedkillers.

(3) Grassland - nutrient application, selective irrigation (e.g. golf courses).

(4) Arable - varied cultivation, nutrient application, use of organic compounds, selective irrigation.

(5) Woodland (and scrub) - little pollution risk, promotes retention of soil moisture.

Given the demands of the agricultural community for water resources and the demands of the remainder of the population for wholesome water supplies, it is significant that the island has no water law pertaining to groundwater. There are no licenses of right as in the Water Act 1989 of England and Wales, not even Water Orders to protect public water supplies as in the Water (Scotland) Act 1980. Unlike mainland UK there is no statutory obligation to register boreholes, wells or springs.

The Water (Jersey) Law 1972 lays a statutory duty on the Jersey New Waterworks Company to provide wholesome water for public consumption. Subsequent bye laws, notably the Water (Prevention of Pollution) (Jersey) Bye Laws 1975 prevent certain activities taking place in a defined area of selected surface water catchments. However, none of the statutes have regard to groundwater and its role as baseflow to surface water courses and public supply reservoirs. There are no restricted areas for nitrate application or for the use of persistent weedkillers. Neither are there restrictions on groundwater abstraction and derogation of supply, not least derogation of baseflow to public supply catchments.

The absence of any recognised island-wide water policy needs attention. This report demonstrates that the groundwater resources of the island are finite and under threat from pollution, and that the continued development of new sources cannot proceed indefinitely without damage to existing water users. In the mean time the public supply utility competes for its water supply with "all and sundry" (James, 1989) and the land owner claims ownership of the water on and under his land.

Acknowledgement of maximum admissible concentrations (mac) of certain ions and organic compounds in public and private supplies is desirable. Although some of the EEC limits are difficult to maintain on Jersey (e.g. mac 11.3 mg/l NO_3-N), a set of rules must be identified and upheld so that arbitrary limits are not defined to suit local pollution levels. Guidance can be obtained from

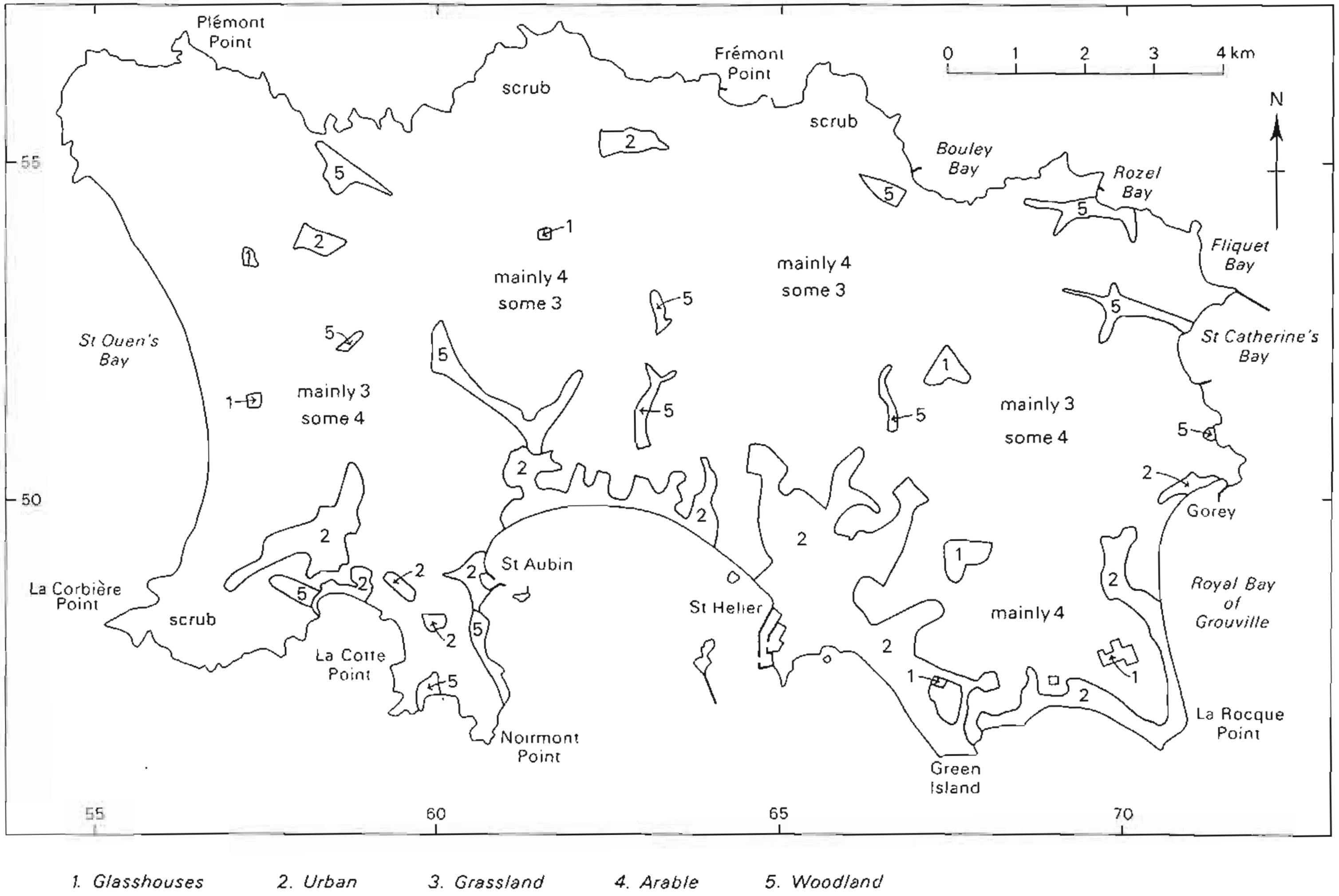


Figure 1.6 Land use

other authorities such as the EEC, American EPA (who are less strict with organic compounds than the EEC) or the World Health Organisation.

1.5 The existing groundwater database and the present survey

In a review of the existing databases Robins (1989) concluded that the available information pertaining to groundwater resources and processes was inadequate, and that groundwater management could not, therefore, be carried out rationally. The first well inventory for the island was compiled by Dr Klupfel, who was with the German occupying forces during the war. This work was expanded by T & C Hawksley (1976). Other databases include the records of the two local drilling companies and those held by Jersey New Waterworks Company. Together these data are insufficient for resource estimate work.

Early records maintained by a Mr J Green provide some historical insight into groundwater development. There are many off-island consultancy reports but there is a basic lack of hydrogeological information. For this reason the present survey sets out to collect data appropriate for a reconnaissance evaluation of the available groundwater resources and of their vulnerability to pollution. These data are the foundation of the Jersey groundwater database.

The survey was established and carried out under the guidance and help of the Groundwater Review Group (GRG). Periodic meetings took place in St Helier throughout the project between BGS and the GRG. Membership of the GRG is described in the Preface. The GRG was charged by the Public Services Department (then Public Buildings and Works) to carry out the following:

(1) Provide advice to the Public Building and Works officers on the adequacy of the BGS brief, prior to commissioning their study.

(2) Provide BGS with any geological information which it may find of assistance with the initiation and progression of the hydrogeological survey.

(3) Provide the Public Building and Works officers with advice when requested, with regard to the BGS hydrogeological survey of the island.

(4) Provide the Public Building and Works officers with continuing advice on the interpretation of hydrogeological and geological matters with regard to the island's water resources.

The brief for BGS was as follows:

(1) Establish a hydrogeological database for the island to determine location and quantification of available groundwater resources together with yield and response to abstraction, rainfall and drought, including risks of marine invasion.

(2) The quantification of the relationship between ground and surface water, including the effect of agricultural irrigation on recharge.

(3) To evaluate groundwater chemistry and to determine vulnerability of water supplies to pollution from commercial, agricultural and domestic sources and to recommend possible remedial measures.

This groundwater source database will be based on a survey of existing wells and boreholes at a density of one per km grid square. BGS to be responsible for all arrangements including identification, monitoring and sampling of boreholes.

(4) To evaluate the potential groundwater resource and the reaction of the St Ouen's Bay Sand Aquifer to rainfall, drought and abstraction, by means of a computer model.

(5) To supply monitoring equipment for a minimum period of 12 months for a longer term groundwater monitoring process. Public Building and Works Department to identify locations of possible boreholes, and BGS to comment on suitability and monitoring requirements. The results of this survey would be used for possible further refinements to the groundwater survey at a later date.

Fieldwork was carried out between 30 April and 15 June 1990, and between 28 October and 30 October 1990. Six autographic borehole level recorders had previously been installed during February 1990. The main field programme was carried out by two people at any time. Their task was to compile a well inventory from field measurements and to collect water samples for later analysis. A total of 109 sites were visited and these are distributed as evenly as was practical over the whole of the island despite geology, land use, topography or other potential influences. This sample density is equivalent to one site per 1070 ha or just less than one site per square kilometre. There are two dual sites where measurements were made from adjacent shallow wells and deeper boreholes.

The main site criterion was that boreholes or wells should be in regular use with either their own pump which could deliver water to the well-head, or room for a test pump to be inserted for the same purpose. This ensured that the sources were well flushed, and if pumped for 20 to 30 minutes were most likely to produce representative samples of the local groundwater. One spring source was also sampled. Boreholes and wells which pumped directly to remote storage tanks or those which had on-line pH adjustment equipment were not sampled unless wellhead, or near wellhead access could be arranged.

Secondary selection criteria were even distribution of sample sites, access and water use. In the latter case, public supply boreholes were a high priority, and private supplies for public consumption (e.g. hotels and hospitals) were a second priority.

Site measurements and sampling procedure are described in detail in Sections 2.1 and 3.1. Additional observations such as water use, local land use, proximity of soakaway/silage clamp and use of slurry were also recorded. The physical site measurements enabled the hydraulic performance of the source to be quantified, and the wellhead chemistry and subsequent laboratory analysis of samples enabled the inorganic chemistry of the groundwater to be described.

Initial interpretation of this basic field data set allowed fifteen of the 109 sites to be identified either as of special interest or typical of a standard water type. These selected sites were revisited during October (there had been no significant winter recharge by this time) and resampled for inorganic chemical analysis. In addition samples were also collected for analysis of selected organic compounds and bacteriological assay (not pathogens) at these same sites.

Other data collection included the metering of bulk water take at 76 sources for periods up to 12 months and the collection of water level hydrographs. Selected rainwater samples were also analysed for inorganic constituents, notably the chloride ion. These activities were all carried out in the field by local agencies on behalf of BGS (see Preface).

Throughout the fieldwork, opportunity was taken to contact all authorities on the island who might have data to contribute. Contributions included inorganic chemistry of groundwater, meteorology, agriculture and land use, geology, groundwater and health, public and private demand for water, sewerage, waste disposal, and drilling. The full list of contacts is acknowledged in the Preface.

The data and information so collected have been analysed and interpreted to provide a series of generic statements about the hydrogeology of Jersey. These are described in the concluding section of this report and are featured graphically on the 1:25,000 scale Hydrogeological Map of Jersey (BGS, in prep).

One specific study was also carried out in the present survey. The southern part of the superficial deposits at St Ouen's Bay comprise the St Ouen's Bay sand aquifer. This is heavily exploited for public supply and private irrigation purposes. Detailed information was collected separately on this aquifer and this was used to create a mathematical model on which a number of predictive sequences were run (Williams, 1990). This work is summarised in Section 2.4.

2. GROUNDWATER RESOURCES

2.1 Field collection of physical data

Physical data were measured and collected at each sample station. The volume of data returned is summarised in Table 4, and the data are listed in Appendix 1.

Table 4. Return of physical data from field inspection.

	Number of Data Points
Sample stations	109
Well/borehole diameter	100
depth	101
static water level	70
Pumping rate and for how long	78
Pumping equipment, water use Land use Slurry disposal, soakaway, silage clamp proximity	109
Specific capacity test*	40

* see text

Well/borehole diameter was measured by tape, depth by plumb line, and static water level (and dynamic water level) by electric dipper. Pumping rate was measured by timing a known volume wherever possible. Elsewhere estimates were made or advice taken from the borehole owner. Specific capacity is the yield from a pump divided by the drawdown (static water level minus dynamic water level, or water level during pumping) over a fixed period of time, often 24 hours. Time available during sampling was limited, and pumping times range from only 20 to 40 minutes; specific capacity values quoted in Appendix 1 are, therefore, short time approximations. Some more detailed tests were carried out in the form of brief constant discharge tests. During these tests the pumping water level was measured at regular time intervals after pumping began and again after pumping ceased.

2.2 The water balance

Only a small part of the rain falling on the ground percolates down to the water table and becomes groundwater. Most of the rainwater, particularly in the summer months, is returned to the atmosphere by evaporation and plant transpiration. The remainder flows over the ground surface or through the topsoil directly to streams or rivers and back to the sea. Evaporation from the sea completes the water cycle with the formation of new rain clouds.

Long term rainfall statistics are available for Jersey Airport, St Louis Observatory and States Farm (Meteorological Department, 1989). The composite mean monthly and annual data derived from these sites are listed in Table 5. The rainfall must balance the sum of evapotranspiration, infiltration to groundwater and runoff to streams and the sea.

Table 5. Groundwater recharge.

Month	Mean rainfall (mm)	Potential evaporation (mm)	Rainfall-pot. evap. (mm)	Runoff + infiltration (mm)	Runoff (mm)	Infiltration (mm)
J	100.1	2.2	97.9	97.9		
F	78.9	12.5	66.4	66.4		
M	67.7	33.8	33.9	33.9		
A	50.6	55.8	-5.2	0		
M	54.8	76.0	-21.2	0		
J	43.5	84.9	-41.4	0		
J	43.5	88.1	-44.6	0		
A	58.7	76.5	-17.8	0		
S	72.3	54.7	17.6	0		
O	79.4	35.0	44.4	0		
N	115.9	13.0	102.9	56.6		
D	111.7	2.0	109.7	109.7		
Total	877.0	534.4		364.5	317.8	46.7

Daily pan evaporation measurements are made only at States Farm but it is not known how representative these are of the island as a whole. An alternative model for potential evaporation is described by Calder et al. (1983). This provides a sinusoidal variation of potential evaporation with a summer maximum, and this mean climatological model has been used to generate the monthly and annual means shown in Table 5. The fourth column in Table 5 is the difference between monthly rainfall and monthly potential evaporation, or "effective rainfall". This figure is negative during the summer months. In order that runoff and infiltration to groundwater can occur the soil has to be at field capacity (nearly saturated) otherwise the soil has a moisture deficit (SMD). Autumn rains first have to satisfy this accumulated SMD before runoff or recharge can take place. Various models for calculating SMD have been devised (Lerner et al., 1990) and different route constants for different vegetation types have been accepted. One such model is used here (for grassland) to generate column 5 in Table 5, which is the monthly value for runoff plus infiltration.

Evaluation of historical rainfall and runoff records for 1962 to 1971 was carried out by the Water Research Association (1972). The average runoff was 306.3 mm given an average annual rainfall of 845.3 mm; pro rata for an average rainfall of 877.0 mm (Table 5) the runoff becomes 317.8 mm (column 6, Table 5) leaving an estimate of annual infiltration of 46.7 mm (column 7, Table 5). (Runoff need not always be in strict proportion to rainfall). This is equivalent to 46,700 $m^3/a/km^2$ groundwater recharge or 5,500,000 m^3/a estimated theoretical total recharge to an island of 117 square kilometres.

An alternative means of deriving groundwater infiltration (plus runoff) is the technique known as chloride mass balance. This technique assumes that the mean value of annual runoff plus infiltration (R+I) is equal to the mean annual precipitation (P) distributed according to the mean chloride concentration in rainfall (C_p) and the mean chloride level in ground and surface water (C_s):

$$R + I = C_p/C_s\ (P)$$

The assumption is based on the fact that chloride cannot be removed by evaporation and that the chloride level is the same in surface water as it is in groundwater. The range of chloride concentrations in groundwater, surface water and rain water prevent the sensible application of this technique on Jersey. Needless to say a value of infiltration can be derived using selected data, to support the 50 mm value derived by the soil moisture deficit method.

2.3 The aquifers - recharge, storage and groundwater transport

The bedrock beneath Jersey is not conducive to groundwater storage or to groundwater flow. Specific yield of an aquifer depends on the interconnected pore space within the rock that can be drained to yield water out of store. The hydraulic conductivity of an aquifer is a measure of the energy required to transmit groundwater through the rock. The rocks of Jersey have little if any interconnected pore space except where severe weathering has occurred in some areas of granite. Most of the porosity is secondary and derives from the presence of fissures, joints, bedding planes, cleavage and faults. These features may only be dilated sufficiently for groundwater flow to take place near surface because of the pressure of overburden. All the main water bearing strata in Jersey are, therefore, shallow, generally within the uppermost 10 to 40m.

Storage in bedrock is dependent on joints and other porosity fractures and is restricted by the shallow thickness of the aquifer. Hydraulic conductivity is equally dependent on secondary features and is best developed in the tectonically more broken areas, notably in the volcanics and the conglomerates. Values of these parameters can be determined by test pumping a borehole. As part of the survey, tests were conducted at three volcanic sites as follows (the data were analysed using the Jacob Approximation):

Table 6. Hydraulic properties of volcanic boreholes.

Borehole No.	Borehole Depth (m)	Hydraulic Conductivity (m/d)	Specific Yield
J76	15	1	nd
J86	20	0.2	nd
J87	40	13	10^{-2}

In the migmatites in Queens Valley, exploratory work prior to the construction of the new dam demonstrated a fissure interval of 20/m and values for hydraulic conductivity ranging from 10^{-3} to 1 m/d for individual fissures. In comparison, the hydraulic conductivity of fissured limestone (e.g. Chalk in Southern England) might be as high as 100 m/d and that for a cemented non-fissured sandstone (e.g. Permo-Triassic of England) is 10 m/d.

The Jersey values are not meaningful in isolation. They merely indicate that bedrock for the most part relies on fissure flow and hydraulic conductivity is normally of the orders 10^{-1} to 1 m/d exceptionally rising to 10 m/d. Storativity is likely to be of the order of 10^{-2} throughout.

The sands and gravels within the superficial deposits offer more favourable hydraulic properties than the bedrock. However, these deposits are of limited areal extent and thickness. They occur behind St Ouen's Bay (the St Ouen's Sand Aquifer) within St Helier and behind the Royal Bay of Grouville.

The St Ouen's Sand Aquifer is best developed in the south. Here the aquifer stretches up to 3 km inland and is deep enough to support abstraction for private and public supply boreholes. It principally comprises blown sand. In the northern part of the aquifer the sand thins and includes peat horizons which reduce its hydraulic potential. Sufficient fresh water recharge is available naturally to sustain throughflow and to withhold the marine interface beneath the beach, leaving a considerable surplus of freshwater for abstraction (Section 2.4). The average hydraulic conductivity for the sand aquifer is 10 m/d and the specific yield is 0.1 (Watson Hawksley, 1986). This specific yield value indicates that a decline in water level in the aquifer of 1 m would yield 0.1 m^3 groundwater from storage for every cubic metre of dewatered sand.

The St Helier alluvial aquifer is principally silt and clay grade material with thin layers of sand and gravel. It is of much smaller potential than the St Ouen's Bay aquifer but Littlejohn et al. (1989) demonstrated that the more permeable horizons may have a hydraulic conductivity up to 20 m/d. These strata are thin and occur only near the base of the alluvium.

The blown sand deposits along the Royal Bay of Grouville are relatively thin. They offer little groundwater potential.

The annual infiltration over the island is just under 50 mm or 5.5 M m^3 for the whole island (Section 2.2). This is equivalent to 500 mm depth in the sand aquifer (storativity 0.1) or 50 mm in the volcanics. Groundwater transport limits actual fluctuations in water level to only a few metres and is a very important component of the groundwater system. The recharging water moves through cracks and joints down gradient to discharge as baseflow or to be intercepted as borehole or well abstraction.

Long term borehole water level hydrographs are not available for the bedrock. Autographic recorders were placed on four boreholes during February/March 1990. These all showed a continuous slow decline in levels following the dry weather which commenced in March through the period of record. The recorder stations were selected because they were remote from pumping effects in nearby boreholes. A borehole in granite showed a decline in water level from 3.0 m below ground level (bgl) to 3.9 m bgl from 14 March through to 18 October; a well at La Hougue Bie in volcanic rock showed a decline from 13.7 m bgl to 16.8 m bgl between 4 April and 16 October; water level in a borehole in shale at St Ouen's village dropped from 4.6 m bgl on 29 March to 4.9 m bgl on 18 October, and in the volcanics it dropped from 12.0 to 12.1 m bgl between 20 February and 17 April. These figures represent a decline of between 0.04 and 0.5 m/month during dry weather.

This decline represents loss of storage to baseflow and abstraction. If an average figure of 0.1 m/month is assumed, and storativity is 10^{-2} then each square metre of ground yields 0.1×10^{-3} m^3 water per month. Given a total area of 117 square kilometres, this represents over 100,000 m^3 water for the whole island or about 20% of the estimated available infiltration per month.

Hydrograph data are not available as yet for recharge events.

2.4 St Ouen's Sand Aquifer - a special case

The hydraulic conductivity and specific yield of the sand aquifer at St Ouen's Bay are one to two orders of magnitude greater than those in the bedrock. There is no runoff from the sand, and infiltration to groundwater is thus potentially some 8 times greater than for bedrock. The St Ouen's sand aquifer, therefore, merits special consideration as a water resource.

Freshwater in the sand aquifer derives entirely from direct rainwater infiltration and runoff from the surface water catchment behind the aquifer. A small additional component may derive from seepage of groundwater from bedrock. Groundwater storage within the sand aquifer is sufficient to maintain both groundwater abstraction and throughflow to the sea during long periods of dry weather.

The St Ouen's Bay sand aquifer extends inland from the coast for up to 3 km. The sand is well sorted with a mean grain size of 2.5 mm and is up to 10 m thick. The aquifer is widest and best developed in the vicinity of Mont a la Brune and it is here that a wellfield has been constructed for public water supply. The wellfield comprises five production and six monitoring boreholes, each screened throughout the saturated part of the aquifer. The sustainable yields of the production boreholes range from 160 to 550 m^3/d. Drawdown is limited by aquifer thickness, and ranges from 6.1 to 7.4 m. Average daily take from the wellfield is 1500 m^3/d.

The aquifer is too thin to allow a conventional saline wedge to develop along the coast. A zone of diffusion between salt and fresh water occurs somewhere between high and low water under the beach. A stagnation point is maintained between the sea and the wellfield by a balance between groundwater throughflow, abstraction, and the sea. Provided the balance is not upset (e.g. by over abstraction) the sea cannot intrude into the aquifer.

Natural groundwater flow paths are essentially perpendicular to the coast (Figure 2.1). Abstraction boreholes placed along any one flow path would therefore have a cumulative effect on that stream of groundwater whereas abstraction or proposed abstraction boreholes (e.g. new golf course) drawing from different flow paths are not likely to interfere unless their capture zones intersect.

In order to quantify the relationship between recharge, throughput, abstraction and the saline interface, Williams (1990) prepared a digital model of the Mont a la Brune area incorporating the whole of the public supply wellfield. The purpose of the model was to determine the optimum abstraction rate possible from the aquifer near the wellfield, and the effect prolonged dry weather would have on the aquifer.

The water balance (as described for the island in Section 2.2) is modified for the slightly lower rainfall at this end of the island and the fact that there is no runoff over the sand. Values for hydraulic conductivity and specific yield are assigned from grain size measurements and pumping tests, catchment boundaries are fixed as no-flow boundaries, and historical water levels, abstraction and climatological data are matched to model simulations.

Potential derogation from groundwater users (present and proposed) elsewhere in the sand aquifer cannot be modelled at this scale because historical data are sufficient only to model the Mont a la Brune area. However, provided

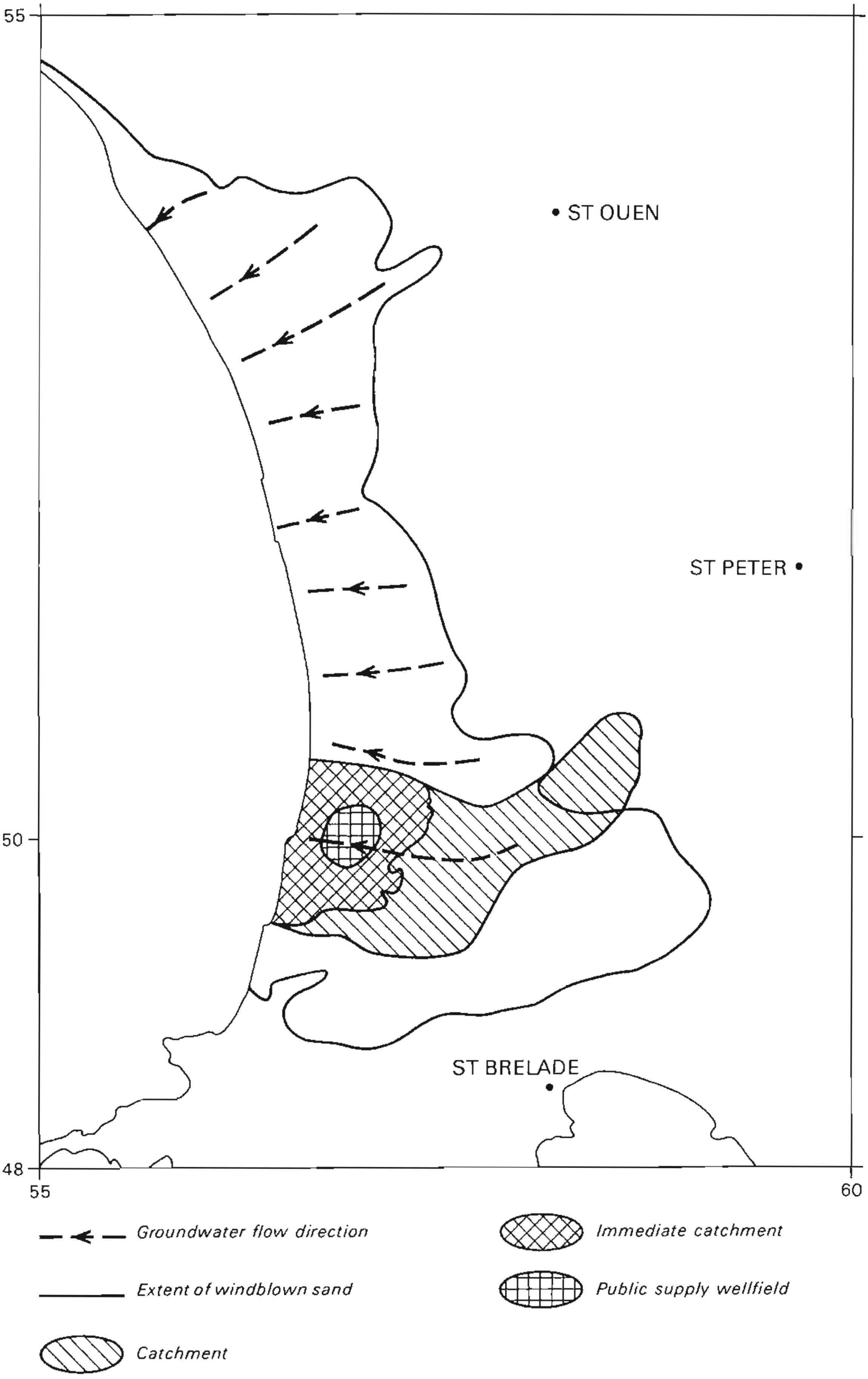


Figure 2.1 St Ouen's Sand Aquifer

these users draw from flow paths to the north or south of the modelled area, little influence is anticipated.

The computer model was based on the USGS MODFLOW package (McDonald and Harbaugh, 1984). An initial steady-state model was devised leading to a more comprehensive transient model which considered historical water level data, pumping records, climate and changes in storage. The model provides excellent correlation with historical data within the period 1982-1984.

Predictive modelling for the 1982-1984 period was carried out to investigate hypothetical stresses. These include increased abstraction from existing or new boreholes in the sand aquifer or within the catchment to the sand aquifer, and the effect of reduced rainfall.

The model demonstrates that an additional 600 m^3/d can be abstracted within the areal limits of the model, representing at least a 30% increase over present day pumping rates. It also shows that two dry winters would lead to reduced abstraction in the third year, but given normal winter rains thereafter, full abstraction could resume and near total recovery would occur by year four (Figure 2.2). The scale of the model does not allow small (c. 1 m) changes in mean sea level or the effect of the nearby open water sand pit to be incorporated.

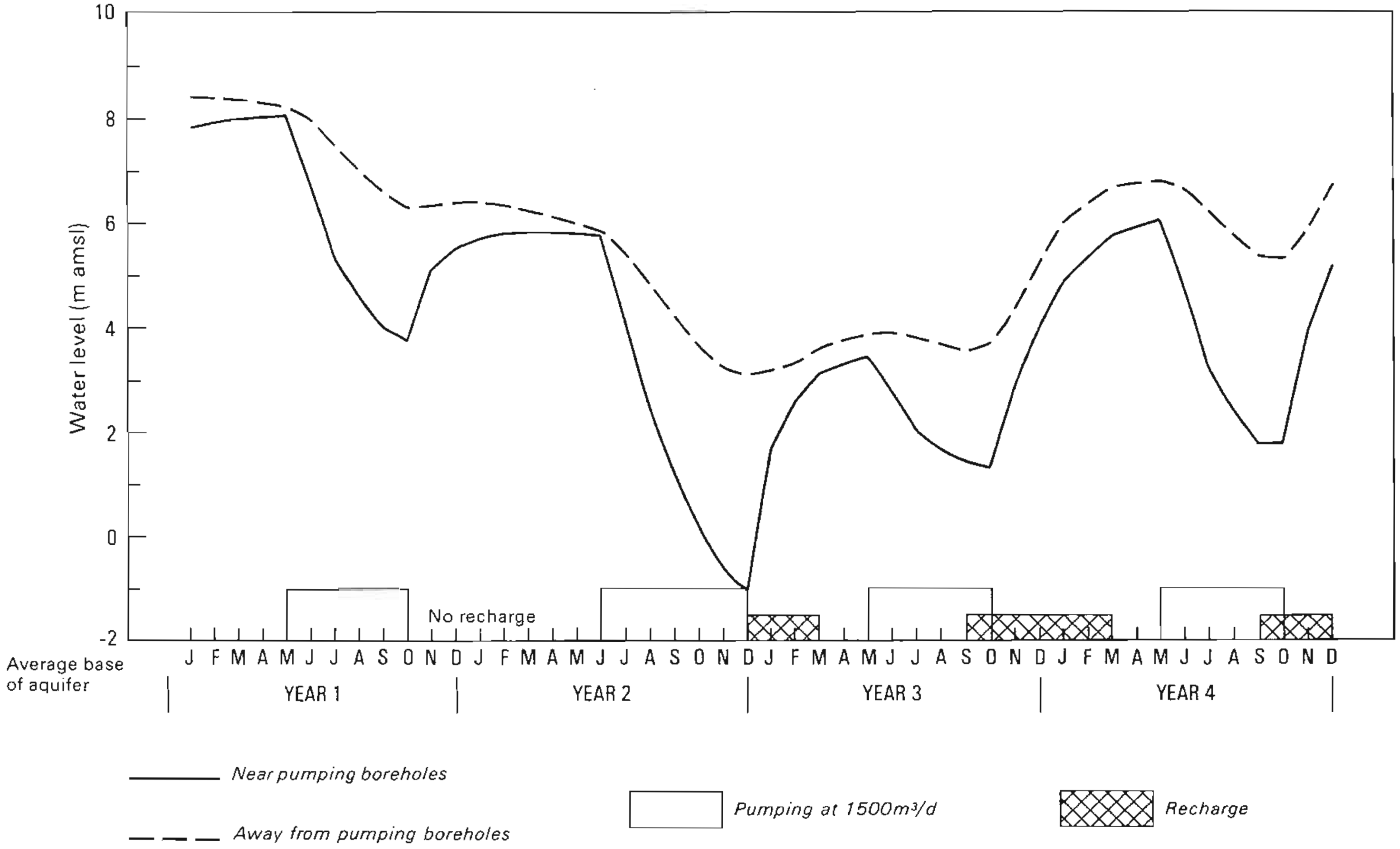
The sand aquifer is clearly very forgiving. Its limited thickness promotes self regulation at any borehole, and this prohibits damage occurring to the aquifer unless a large number of new boreholes are used.

2.5 Total demand - extrapolation from the field data

The observed groundwater recession in dry weather amounts to some 100,000 m^3/month groundwater from the bedrock aquifers of the whole island (or 0.1 m/month decline in water level). This represents a total annual recession of 1,500,000 m^3/a which represents baseflow plus abstraction. Average annual recharge amounts to a further 5,500,000 m^3/a and this sustains the basic level of recession between recharge events and replenishes the groundwater lost in the interim from storage.

The resource estimate derived from recession depends on a single value of specific yield. Although it is of the same order as that derived by conventional soil moisture deficit analysis it will be assumed that the latter higher value is most representative of the real situation. In fact recession is known to be much greater in certain parts of the island where even deep boreholes were reported to be non yielding by June and July. A much wider spread of recession data are therefore required to validate this calculation.

During the period between Summer 1989 and Autumn 1990, 76 boreholes and wells were metered for bulk abstraction. These sources have been categorised according to water use and the data converted to mean consumption and in turn, total consumption from the sample set (Table 7). The standard deviations are large and this coupled with the small data sets suggests that the derived values should be treated as first estimates only.



Base of aquifer is +0.3 to -5.5m relative to Datum (mean sea level), average -2.0m relative to Datum

Figure 2.2 St Ouen's Sand Aquifer - modified levels after no winter recharge and poor winter recharge

Table 7. Groundwater consumption measurements.

Water Use	Sample size	Mean consumption (m^3/d)	Standard deviation	Total consumption (m^3/d)
Irrigation	24	7.5	8.2	178
Golf and playing fields	9	58.8	43.0	529
Industry (inc. laundry)	10	10.7	6.1	107
Hotels and hospitals	20	5.1	3.5	102
Domestic	6	0.6	0.4	3
Total (inc. uncategorised)	76	12.3	23.0	935

The following arguments are used to justify extrapolation of these data island-wide in order to derive a preliminary estimate of total groundwater abstraction (Table 8):

(1) Irrigation - assume average of 4 pumped irrigation sources per square kilometre or 500 in total amounting to an average total demand of 3750 m^3/d. Demand is largely between April and September - this dry season demand accentuates this value.

(2) Golf and playing fields - the sample includes La Moye and Royal Jersey but there are other major users in St Ouen's Bay and St Helier areas. Assume sample represents 20% of total take then average total demand is 2646 m^3/d. Demand is largely between April and September - this dry season demand accentuates this value.

(3) Industry (including laundry) - major users included in sample set. Say sample set represents half of total then 20 boreholes demand average daily consumption of 214 m^3/d.

(4) Hotels and hospitals - let sample represent 20% of total. Then 100 boreholes demand average daily consumption of 510 m^3/d.

(5) Domestic - if 80% of the population is on the mains water supply, 16,000 people are on private supplies or rainwater cisterns. If each supply provides an average 4 people there may be 4,000 private domestic supplies of which most will be groundwater. The total domestic demand is therefore estimated as 2400 m^3/d.

Table 8. **Estimated total groundwater consumption.**

Water Use	Est. no. of sources	Mean consumption (m^3/d)	Total consumption (m^3/d)	Annual take ($m^3 \times 10^3/a$)
Irrigation	500	7.5	3750	1369
Golf and playing fields	45	58.8	2646	966
Domestic	4000	0.6	2400	876
Public supply*	5	149	747	273
Hotels and hospitals	100	5.1	510	186
Industry	20	10.7	214	78
Total	4670		10 991	3748

* JNWWCo figures

The estimated total groundwater take of 3.7×10^6 m^3/a compares with Jersey New Waterworks Company total supply of 6.0×10^6 m^3/a (1985 figure).

Given annual theoretical estimate of recharge of 5.5×10^6 m^3/a the difference between abstraction and recharge must be baseflow and loss (or gain) to storage. That difference is some 1.8×10^6 m^3/a and it is this water that maintains spring flows and seepage to streams, rivers and the coast. The estimated annual take represents approximately 70% of the available resource, a percentage which leaves little scope for weaker supplies in dry years and one which seriously erodes the baseflow component to surface waters and surface reservoirs. It is also a very high value when compared to other similar islands (Table 9). It reflects the high density of population on Jersey and the comparatively modest rainfall. It is also significant that the 70% represents average abstraction in an average rainfall year and takes no account of dry or successively dry years.

Careful consideration must be given to the way in which the bulk take from groundwater has been estimated. There is clearly scope for this calculation to be refined and it may be that the figure is an under-estimate. The sand aquifer at St Ouen's Bay is capable of additional withdrawal, however, as described in Section 2.4.

Table 10 summarises the specific capacity values for the different lithologies derived from pumping rate and drawdown measurements made during the field survey. It shows that the highest values were obtained on average from the volcanic rocks and the conglomerate. The shale performed on average only half as well as the volcanics and the conglomerate; and that the granite was of intermediate ability. The range within the data is reflected by the high values of standard deviation, and rock type is not therefore critical to hydraulic performance within the bedrock. The standard deviation for the sand aquifer is comparatively low.

Table 9. Percentage abstraction of theoretical renewable resource, examples.

Island	Area (sq km)	Mean average annual rainfall (mm)	Estimated annual infiltration (mm)	%age abstraction of theoretical renewable resource	Dominant geology
Jersey	117	880	50	70	Fissured basement
St Helena(1) (S. Atlantic)	121	660	145	20	Fissured volcanic
Nevis(2) (E. Caribbean)	90	1000	200	8	Fissured volcanic
St Kitts(2) (E. Caribbean)	163	1600	230	1	Fissured volcanic

(1) Lawrence (1983)
(2) Robins et al (1990)

Table 10. Specific capacity and rock type.

Rock Type	Sample population	Mean specific capacity (l/s/m)	Standard deviation
Volcanic	15	1.16	1.5
Conglomerate	4	1.16	1.1
Granite	11	0.76	0.8
Shale	7	0.63	0.9
Sand	4	1.1*	0.3

* value limited by thickness of aquifer

3. HYDROGEOCHEMISTRY

3.1 Field sampling methods

Hydrogeochemical investigation is a necessary part of the groundwater resource assessment of the region since the size of the resource is defined by quality as well as quantity. Water quality is important from the potability point of view, but can also be of value for determination of processes such as water-rock interaction and hence flow paths and residence times in the aquifer, as well as pollution risk. Better understanding of the hydrochemical processes governing water quality can aid the management of the resource and the assessment of its limits. For these reasons, the reconnaissance hydrogeological survey of Jersey has included chemical analysis of the groundwater samples and determinands include pH, redox potential (Eh), specific electrical conductance (SEC), dissolved oxygen, major ions, a wide range of trace elements, stable isotopes (δ^2H and δ^{18}O) and selected organic compounds.

The two sampling programmes during summer and autumn 1990 have already been described in Section 1. During the summer survey, attempts were made to obtain flowing samples by pumping from as many survey sites as possible so that Eh and dissolved oxygen could be reliably measured. During the autumn survey, these parameters were not determined and so flowing samples were not required.

At the sampling sites where pumping of groundwater was undertaken, continuous monitoring of the field-determined parameters pH, Eh, dissolved oxygen, SEC and temperature was carried out, the first three parameters in anaerobic flow-through cells attached directly to the discharge pipe from the sample source. Monitoring was carried out until stable readings were obtained, usually at least 20 minutes. At sites where it was not possible to obtain a flowing sample, Eh and dissolved oxygen could not be reliably measured and so were not attempted. In all cases, pH was determined by combination glass electrode calibrated at sample temperature by pH buffers. Eh was measured by platinum electrode and dissolved oxygen by membrane electrode. SEC (corrected to 25°C) was monitored by conductivity meter and temperature by mercury-in-glass thermometer. Total alkalinity (HCO_3) was determined on-site by volumetric titration.

At all sites, samples were collected after filtering through 0.45 μm membrane filters and one aliquot was subsequently acidified with pure nitric acid to a concentration of 1% by volume in order to reduce the sample pH to c. 2 and preserve its chemical integrity.

At selected sites, samples were collected for ferrous iron (Fe^{2+}) determination by the 2,2' bipyridyl method (Moss and Mellon, 1952). This is a colorimetric method in which bipyridyl forms a pink complex with dissolved Fe^{2+} in the sample, the intensity of the colour being proportional to the Fe^{2+} concentration. Since Fe^{2+} oxidises readily on contact with the atmosphere, samples were filtered and complexed as rapidly as possible in order to minimise this effect.

At 14 selected sites sampled during the summer 1990 survey, unfiltered water samples were collected in glass bottles for subsequent stable isotopic analysis. Seven selected organic compounds were analysed by the Water Quality Centre for samples collected in the autumn 1990 survey.

3.2 Analytical methods

Acidified aliquots were analysed for major cations, SO_4 and selected trace elements by inductively-coupled plasma optical emission spectrometry (ICP-OES) and Cl, NO_3-N, NO_2-N and NH_4-N concentrations (nitrate, nitrite and ammonium respectively, all expressed as nitrogen) were determined by automated colorimetry. Cation-anion charge imbalances are generally less than 3%.

Dissolved Fe^{2+} in samples collected during the summer survey was analysed within a few days of collection by portable colorimeter at a wavelength of 525 nm using Fe standards in the range 0.2 to 4.0 mg/l. Those collected during the autumn survey were analysed spectrophotometrically at 522 nm in the laboratory using standards in the range 0.1 to 4.0 mg/l.

Stable isotopic analysis (δ^2H and $\delta^{18}O$) was carried out by mass spectrometry and results are quoted as per mil deviations relative to standard mean ocean water (SMOW). Precision for $\delta^{18}O$ analysis approximates to ± 0.2‰ and that for δ^2H to ± 1‰.

3.3 Results and discussion

Results of the chemical analysis of groundwater samples from both the summer and autumn surveys are presented in Appendices II, III and IV.

3.3.1 pH

The acidity of a water sample is governed by the concentration of H^+ ions in solution. H^+ concentration (or strictly activity) in water may be measured in moles/litre but tends to be very small in all but very acidic samples. It is therefore conventional to define acidity as pH which is $-\log_{10}\{H^+\}$. The pH of most natural waters calculated in this way generally varies between 4 and 9, values less than about 7 being acidic and those greater than 7 being alkaline (although pH varies with temperature). Values of pH outside this range are relatively rare but not unknown. Water pH is influenced by many different types of chemical reactions, but is most strongly controlled by the carbonate system. The dissolved CO_2 species H_2CO_3, HCO_3^- and CO_3^{2-} govern pH by the reactions:

$$CO_2 + H_2O = H_2CO_3 \qquad [1]$$

$$H_2CO_3 = H^+ + HCO_3^- \qquad [2]$$

and $$HCO_3^- = H^+ + CO_3^{2-} \qquad [3]$$

Since dissociation of carbonic acid (H_2CO_3) and bicarbonate (HCO_3^-) both produce H^+ ions (equations [2] and [3]), these species clearly influence pH. Carbonate-rich waters effectively buffer pH (i.e. do not allow large shifts in pH for small additions of acid or base) and most natural waters in equilibrium with carbonate (e.g. limestone) have pH values which are alkaline (> 7).

Other reactions also affect pH. Examples are hydrolysis reactions which involve alteration of water:

$$2NaAlSi_3O_8(s) + 2H^+ + 9H_2O \;=\; Al_2Si_2O_5(OH)_4(s) + 4H_4SiO_{4(aq)} + 2Na^+ \qquad [4]$$

and $$Fe^{3+} + 3H_2O \;=\; Fe(OH)_3(s) + 3H^+ \qquad [5]$$

In the example in equation [4], H^+ ions are consumed in the hydrolysis of Na-feldspar (albite: $NaAlSi_3O_8$) and clay minerals ($Al_2Si_2O_5(OH)_4$), and silicic acid (H_4SiO_4) and Na^+ ions are produced. In equation [5], ferric iron (Fe^{3+}) is hydrolysed and ferric hydroxide ($Fe(OH)_3$) and H^+ ions are produced (Hem, 1985).

Redox reactions can also influence pH significantly (Section 3.3.3). An example is:

$$FeS_2 + 7/2\ O_2 + H_2O \;=\; Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad [6]$$

The pH of rainwater in equilibrium with atmospheric CO_2 is about 5.5 unless acid-rain-producing species such as sulphur dioxide and nitrous oxides are present. Once rainwater infiltrates soil, its pH may decrease significantly due to high microbially-generated pCO_2 values, but is rapidly modified by water-rock interactions once it has infiltrated into an aquifer, particularly if the aquifer has a high carbonate and/or clay mineral content.

Table 11 gives the range of pH values observed in groundwater samples collected during the summer 1990 survey and ranges observed in the much smaller autumn 1990 survey are presented in Table 12. The pH is not quoted for some of the samples collected during the autumn survey because of meter and/or electrode malfunction. Median values from the two sampling expeditions are pH 6.25 and 6.15 respectively. The maximum range extends from pH 4.95 to 7.62 and indicates that some Jersey groundwaters are quite acidic.

3.3.2 SEC

Electrical conductivity is the ability of a solution to conduct an electric current. Charged ionic species in solution render the substance conductive and hence conductivity is a useful guide to total ionic concentration. Conductivity increases dramatically with increasing temperature and for this reason, the parameter is usually corrected to a standard temperature of 25°C and the term specific electrical conductance (SEC) is adopted.

SEC is a useful indication of the total dissolved solids (TDS) content of water. Edmunds and Kinniburgh (1988) for example found in a study of groundwater from south-west England that:

$$TDS = 0.7\ SEC \quad (TDS\ in\ mg/l\ and\ SEC\ in\ \mu S/cm)$$

However SEC is not affected by dissolved constituents which are uncharged such as Si, and so cannot be used as a direct substitute for TDS. Nonetheless, the parameter can be a useful and easily measured field guide to solute concentration in water samples.

Table 11. Variations in groundwater quality for samples collected during the Summer 1990 Survey.

Determinand	Units	Min	Max	Median	Number of analyses
pH		4.95	7.62	6.25	109
Eh	mV	58	539	416	87
O_2	mg/l	<0.1	10	3.0	87
SEC	μS/cm at 25°C	282	1800	674	109
Na	mg/l	17.7	166.7	57.5	109
K	"	1.5	92.6	5.73	"
Ca	"	6.14	201.4	52.6	"
Mg	"	5.48	57.0	17.6	"
HCO_3	"	3	494	61	"
SO_4	"	18.4	401.4	103.2	"
Cl	"	19.6	238	79.3	"
NO_3-N	"	<1	63	13.5	"
Sr	"	0.088	2.0	0.26	"
Ba	"	0.003	0.23	0.043	"
B	"	0.02	0.50	0.09	"
Si	"	3.1	19.3	8.1	"
P	"	<0.3	3.35	0.114	"
Fe_T	"	<0.015	8.5	0.023	"
Fe^{2+}	"	<0.06	6.6	0.03	71
Mn	"	<0.003	1.85	0.03	109

Fe_T: Total Fe

Table 12. Variations in groundwater quality for samples collected during the Autumn 1990 Survey.

Determinand	Units	Min	Max	Median	Number of analyses
pH		5.80	6.65	6.15	8
SEC	μS/cm at 25°C	420	1450	785	15
Na	mg/l	24.3	99.3	56.1	"
K	"	1.6	9.5	3.2	"
Ca	"	17.8	113.0	70.9	"
Mg	"	7.2	45.9	16.1	"
HCO_3	"	20	266	112	"
SO_4	"	39.5	257.0	97.5	"
Cl	"	42.5	143.0	74.5	"
NO_3-N	"	<0.2	44.8	10.6	"
NO_2-N	"	<0.005	0.036	<0.005	"
Sr	"	0.107	0.465	0.270	"
Ba	"	<0.004	0.197	0.046	"
Si	"	6.2	12.6	9.9	"
P	"	<0.3	2.0	<0.3	"
Fe_T	"	<0.015	2.47	<0.015	"
Fe^{2+}	"	<0.06	2.54	0.095	13
Mn	"	<0.003	0.781	0.176	15

Fe_T: Total Fe

SEC in the Jersey samples ranges between 282 and 1800 μS/cm with median values in the summer and autumn surveys of 674 and 785 μS/cm (Tables 11 and 12). This is a broad range from relatively unmineralised to quite strongly mineralised concentrations, values greater than 1000 μS/cm being particularly high. For example, shallow groundwaters from granitic and metasedimentary aquifers in Cornwall reported by Smedley et al. (1989) all had SEC values less than 800 μS/cm. The high SEC values observed in Jersey samples are believed to be related largely to marine influences and are discussed further in Section 3.6.

3.3.3 Eh

Just as pH is affected by the transfer and movement of protons (H^+ ions) in aqueous solutions, redox is a process affected by the behaviour of electrons. Oxidation occurs by loss of electrons from an element or species and reduction involves electron gain. Oxidation for example of ferrous to ferric iron may be described by the half reaction:

$$Fe^{2+} \quad = \quad Fe^{3+} + e^-$$

where e^- represents one electron. In nature, electrical balance demands that no free electrons can remain in solution and redox reactions involve coupled oxidation and reduction half reactions. One example is given by equation [6] where pyrite (FeS_2) is oxidised and molecular O_2 is reduced.

Eh (redox potential, usually measured in millivolts) is not directly equivalent to dissolved oxygen concentration, but is generally related since oxygen is a strong oxidising agent. The Eh measured in pumped groundwaters in fact generally represents a mixed potential which is determined by the various redox couples present in solution. Principal influencing couples include Fe^{2+}/Fe^{3+}, Mn^{2+}/Mn^{4+}, As^{3+}/As^{5+}, HS^-/SO_4^{2-} and CH_4/CO_2. In general, oxidising groundwaters have high Eh values and reducing groundwaters have low Eh, some extremely reducing waters having negative values. Eh varies with pH.

Eh ranges observed in Jersey groundwaters are between 58 and 539 mV with a median value of 416 mV (Table 11). The upper end of the range and the median value represent highly oxidising groundwaters characteristic of shallow unconfined aquifers open to the atmosphere and with ample supply of atmospheric oxygen. Although less common, Jersey also has some reducing groundwaters represented by the lower end of the range. Redox processes have important influences on Jersey groundwater chemistry - particularly in respect to dissolved oxygen, Fe, Mn and nitrogen species and are discussed in more detail in Sections 3.6 and 4.

3.3.4 Dissolved oxygen

The solubility of oxygen in water is inversely proportional to temperature. Solubility in groundwater at an average temperature of 11°C is about 10 mg/l and shallow groundwater open to ready supplies of atmospheric oxygen may have concentrations approaching this solubility limit (i.e. up to 100% saturation). Reducing groundwaters are expected to have low or no oxygen because O_2 acts as an electron acceptor and is consumed in the oxidation of reduced species. In practice, dissolved oxygen concentrations in groundwaters may lie anywhere within the range 0-10 mg/l (depending on temperature) as a result of disequilibrium or mixing of groundwaters with different redox characteristics and kinetic effects.

Jersey groundwaters indeed display a whole range of dissolved oxygen concentrations from <0.1 mg/l to 10 mg/l, with a median value of 3.0 mg/l (Table 11). The compositional range supports the observation that some groundwaters are reducing but that most are relatively oxidising. Some mixing of groundwaters with different oxygen concentrations (possibly from different depths) is doubtless responsible for the large range observed.

3.3.5 Na

Na is a major alkali metal which occurs in aqueous solution as a monovalent cation or less commonly in ionic complexes. It does not participate in redox reactions, but Na speciation may be significantly affected by adsorption onto clay particles involving cation exchange with Ca and Mg ions.

Na is a major component of sodic feldspars ($NaAlSi_3O_8$) which weather readily. It may therefore be a major ion in groundwater in terrains composed of acid volcanic and granitic rocks, as well as feldspar-rich sediments. Na may also be a large component in groundwater in clay-rich sediments as a result of ion-exchange reactions.

Since Na is the major cation constituting seawater (10,000 mg/l; Hem, 1985), groundwater affected by saline intrusion, marine aerosol effects or maritime-influenced recharge may have large concentrations of the Na ion although modification of cation concentrations as a result of ion exchange may occur. Other major components of seawater include Cl (19,000 mg/l), SO_4 (2,700 mg/l) and Mg (1,350 mg/l; Hem, 1985) such that groundwaters affected by marine infiltration or mixing are likely to have elevated concentrations of these ions.

Na in Jersey groundwater ranges between 17.7 and 166.7 mg/l in the summer survey and 24.3 and 99.3 mg/l in the autumn survey, with comparable median values of 57.5 and 56.1 mg/l respectively. Some of the higher values reflect the seawater influences that might be expected in a low-lying (at least in parts) island setting.

3.3.6 K

K is also a major monovalent alkali metal which is generally less abundant than Na in igneous rocks but more common in sediments. Its concentration in groundwater is generally restricted because it forms relatively insoluble K-aluminosilicate mineral phases and readily adsorbs onto clay minerals. K is a major component of K-feldspar ($KAlSi_3O_8$), mica (especially muscovite) as well as illite and other clay minerals. It is also important in the biosphere, being a major plant nutrient. K may be high in groundwater because of agricultural pollution from NPK fertilisers.

The K concentrations of Jersey groundwater vary from relatively low values of 1.5 mg/l to high concentrations up to 92.6 mg/l (Table 11), the higher values probably being related to pollution effects (Section 4).

3.3.7 Ca

Ca is a major constituent of most groundwaters, being derived principally from weathering reactions involving Ca-feldspar ($CaAl_2Si_2O_8$), calcite ($CaCO_3$), gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$). It also participates in ion exchange reactions on clay minerals. Ca-feldspars are more abundant in basic igneous rocks and groundwaters in such terrains usually have Ca as a more important constituent than in acid igneous terrains. Ca is also abundant in carbonate aquifers although its solubility is restricted by the presence of HCO_3^- ions.

Ca is a major cation in the Jersey groundwater samples collected during summer and autumn surveys in 1990, ranging from 6.1 to 201.4 mg/l and from 17.8 to 113.0 mg/l respectively.

3.3.8 Mg

Mg occurs principally as a divalent cation in natural waters and like Ca, its solubility is largely controlled by the carbonate system. Mg is most common in ferromagnesian minerals such as olivine and pyroxene and groundwaters in terrains predominated by ferromagnesian phases should therefore have dissolved Mg as an important component. Mg is also involved in ion-exchange reactions on clays, and is a major component of secondary phases such as chlorite. As mentioned in Section 3.3.5, Mg is also a major constituent of seawater.

The range of Mg concentrations in the 1990 Jersey groundwater samples is between 5.5 and 57.0 mg/l with a median value of 17.6 mg/l (summer survey, Table 11).

3.3.9 HCO_3 (alkalinity)

Alkalinity is defined as the capacity of a solution to react with and neutralise acid. Strictly, the alkalinity determined by volumetric titration is the total alkalinity contributed by all forms of dissolved CO_2 (HCO_3^-, H_2CO_3, CO_3^{2-}) as well as weak acids, but the major anion in most natural waters is HCO_3^- and therefore alkalinity is usually, as here, reported simply as the HCO_3^- ion.

HCO_3 concentrations in groundwater accumulate throughout the hydrologic cycle as a response to water-rock interactions. Concentrations are particularly high in carbonate aquifers and rocks where Ca-Mg carbonates are a constituent of the cement. Carbonate minerals are not usually abundant in igneous rocks unless secondary calcite has replaced primary mineral phases or veining has occurred, but Ca-Mg carbonates are often present in cements of sedimentary and metasedimentary rock types.

Bicarbonate determinations in Jersey groundwaters range from extremely low values (3 mg/l) to quite high values (up to 494 mg/l) with median concentrations in the summer and autumn 1990 surveys of 61 mg/l and 112 mg/l respectively. The lowest values observed are comparable with the concentrations of granite-derived groundwater from the Carnmenellis area in Cornwall (Smedley et al., 1989). They suggest that these groundwaters have had relatively short residence times in carbonate-poor aquifers.

3.3.10 SO_4

Sulphur occurs in oxidation states ranging from S^{2-} to S^{6+} and its chemical behaviour is therefore strongly influenced by redox (Hem, 1985). Redox reactions involving S are however generally slow unless they are microbiologically mediated. Over the pH ranges of most natural waters, dissolved sulphur in oxidising systems occurs as the sulphate ion (SO_4^{2-}). In extremely reducing waters, sulphur occurs as H_2S (in acid systems) or HS^- (in alkaline systems).

Sulphur is widely distributed in reduced form in many rock types as metallic sulphide phases, such as FeS_2 (pyrite). These oxidise readily in oxygenated conditions. Equation [6] is one example where pyrite is oxidised and significant quantities of SO_4 and H^+ ions are produced.

In oxidised form, sulphur is most common in evaporite minerals such as gypsum and anhydrite ($CaSO_4.2H_2O$ and $CaSO_4$ respectively).

Dissolved SO_4 in rainwater is usually low in areas remote from sources of airborne pollution, but may be elevated by SO_2 generated by the burning of fossil fuels (the result being dilute H_2SO_4, or acid rain). SO_4 may also be an important anion in groundwater which contains a seawater component (Section 3.3.5).

SO_4 concentrations in Jersey groundwater samples range between 18.4 and 401.4 mg/l from the summer survey and from 39.5 to 257.0 mg/l in the autumn survey of 1990. Median values in the two surveys are comparable at 103.2 and 97.5 mg/l respectively. Some of the higher concentrations are believed to be related to seawater influences.

3.3.11 Cl

The behaviour of Cl in water is relatively simple compared to most other elements. It occurs predominantly as the monovalent Cl^- ion. It does not participate in redox reactions, does not readily form complexes with other ions unless present in very large quantities and once in solution, tends to behave as a so-called 'conservative' element such that it tends not to participate readily in ion exchange reactions or be incorporated into secondary minerals (Feth, 1981). Unlike most other major ions in groundwater, Cl is not a major constituent of the rocks through which it passes.

It is present in the rare mineral sodalite and as a minor component of the phosphate mineral apatite (Hem, 1985). Billings and Williams (1967) gave an average value for Cl of 1466 ppm for shale although Hem (1985) gave a much lower value of 170 ppm for similar rock types. Edmunds et al. (1987) also suggested that Cl in saline Cornish groundwaters was derived from biotite by exchange with OH^- ions in the crystal lattice of the biotite. In general however, most rock types appear to have rather low concentrations of Cl and accumulations in water by water-rock interaction may be slightly higher in clay-mineral bearing strata than in other terrains.

Cl is also the major constituent of seawater (Section 3.3.5) and therefore seawater-influenced water bodies are expected to have elevated levels (by either saline intrusion, marine spray or Cl-laden rainwater).

Cl concentrations in Jersey groundwater reach high values as a response to marine influences. A maximum value of 238 mg/l was observed in the summer 1990 survey.

3.3.12 Nitrogen species (NO_3-N, NO_2-N and NH_4N)

Nitrogen is the major constituent of the Earth's atmosphere and is of great importance in the biosphere. It is strongly redox-controlled in groundwater, and may be present in oxidised form as nitrate (NO_3^-) or in reduced form as nitrite (NO_2^-) or as the ammonium cation (NH_4^+). In extremely alkaline conditions, ammonium may be present as uncharged NH_4OH but this is not likely to be an important N species in Jersey groundwater.

Nitrate (NO_3-N) is highly mobile in aerated groundwaters (Foster and Crease, 1974). Its major source is thought to be from pollution from NPK fertilisers, septic tanks and soakaways, and farmyard manure. In reducing conditions, the phenomenon known as denitrification, where NO_3 is converted to N_2 gas and lost to the atmosphere, can be important in decreasing groundwater nitrate concentrations significantly (e.g. Champ et al., 1979).

Nitrite (NO_2-N) may be measurable in reducing groundwaters, but is rarely present in high concentrations (Hem, 1985). The NH_4-N cation on the other hand, may be important in reducing groundwaters, particularly in association with clay minerals where NH_4^+ is readily adsorbed onto clay particles (Edmunds et al., 1987).

As discussed earlier, most groundwaters in Jersey are oxidising and hence NO_3-N is the major dissolved anionic species of N present (Appendices II, III; Tables 11 and 12). Data from the summer 1990 survey ranges between <1 and 63 mg/l with a median value of 13.5 mg/l.

Analyses of NH_4-N were carried out for the samples collected during the autumn 1990 survey (Appendix III) and a few from the summer survey (Appendix II). The values are generally low, mostly less than 0.05 mg/l but one sample (Sefton Nursery, 901238) had a concentration as high as 0.93 mg/l (Appendix II).

Analyses of NO_2-N carried out for samples in the autumn survey were generally very low, most being below detection limits of 0.005 mg/l (Table 11).

3.3.13 Si

The dominant form of dissolved Si over the pH range of most natural waters is as uncharged H_4SiO_4. Silicon is the most abundant component of rocks and therefore a ready supply of Si is potentially available for dissolution in water. However, the concentration of Si is limited by the solubility of silicate minerals such as quartz, cristobalite and amorphous Si. The solubility of these three phases at 25°C is 6.0 mg/l, 26 mg/l and 115 mg/l respectively (Hem, 1985). The Jersey groundwaters are generally oversaturated with respect to quartz and cristobalite and dissolved Si concentrations reach a maximum value of 19.3 mg/l (Table 11). The solubility is clearly not being controlled by amorphous Si and some other silicate phase (perhaps halloysite; Hem et al., 1973) appears to be responsible.

3.3.14 Al

The most important influence on Al concentrations in water is pH: Al having generally higher concentrations in acid waters. The total Al concentrations in Jersey groundwaters are rather low, most being below detection limits of 0.1 mg/l. The maximum observed concentration is 0.29 mg/l in a sample with pH 5.0 (901207; Appendices II and III). The Al concentrations of shallow groundwater in Cornwall in similar aquifer types are generally higher, reaching up to 1 mg/l in the most acidic granite-derived waters (Smedley et al., 1989).

3.3.15 Sr and Ba

The trace alkaline earth elements Sr and Ba are generally present in low but measurable concentrations in groundwater. Sr readily substitutes for Ca in most minerals as a trace constituent and Ba frequently substitutes for K. The two elements are therefore predominantly derived from weathering of feldspars and from ion exchange reactions on clays. Sr is also usually a trace component of calcite and Ba is present in the less soluble mineral barite.

Sr is generally present in seawater in concentrations of about 8 mg/l (Hem, 1985). Seawater-influenced groundwater should therefore have elevated levels of Sr. Ba concentrations in seawater are on the other hand lower (c. 0.02 mg/l; Hem, 1985) and therefore marine-influenced groundwater is not expected to have greatly modified Ba values.

3.3.16 Total Fe and Fe^{2+}

The geochemistry of iron is strongly redox-controlled, although pH also exerts a significant influence on its speciation. Under acid conditions (pH < about 3) and at high Eh, Fe may be stable as dissolved Fe^{3+} whilst at low Eh the ferrous species Fe^{2+} is stable. At near-neutral pH however, redox has a much more important control; under reducing conditions (low Eh), dissolved Fe^{2+} is stable whilst in oxidising conditions, red-brown ferric hydroxide ($Fe(OH)_3$) precipitates.

Oxidising groundwaters with near-neutral pH values should therefore have low dissolved Fe concentrations. Acidic waters and waters with low Eh values are expected to have much higher iron concentrations, although the solubility is limited by the presence of other dissolved species such as sulphur and carbonate (e.g. Hem and Cropper, 1959; Gale and Smedley, 1989). Solubility of iron is also increased by presence of organic compounds which form stable complexes with either ferrous or ferric iron (Kraynov and Solomin, 1983). This is however not believed to be important in the Jersey groundwaters since organic loadings are not suspected to be high in a granitic/metasedimentary terrain without thick, organic-rich soil horizons.

In the Jersey groundwaters, dissolved Fe should not be stable in the form of Fe^{3+} as they are insufficiently acid. Total Fe concentrations presented in Appendices II and III show a strong correlation with Fe^{2+} concentrations, most values agreeing within 10%. Most of the total Fe is therefore present as Fe^{2+}. Some discrepancy between total Fe and Fe^{2+} concentrations is expected because of the presence of finely-divided particles of $Fe(OH)_3$ which are not truly in solution but are colloidal forms <0.45 µm in diameter and which can therefore pass through a membrane filter. In some samples (especially some collected during the autumn survey), Fe^{2+} concentrations are apparently greater than total Fe concentrations. This discrepancy is rather hard to explain except that delays of several minutes incurred before filtration of samples whilst open to the atmosphere can lead to some oxidation of Fe^{2+}. Whilst great care was taken during sampling to complex samples with bipyridyl solution for Fe^{2+} analysis before significant oxidation had taken place, this was not always possible for total Fe analysis by ICP-OES. The latter samples may therefore have slightly lower concentrations for this reason. Analyses of Fe^{2+} are therefore probably more accurate, but since most samples agree within about 10%, analyses by both methods are believed to be acceptable.

Total Fe and Fe^{2+} concentrations reach maximum values of 8.5 and 6.6 mg/l respectively in Jersey groundwater samples from the combined data for summer and autumn surveys (Tables 11 and 12). These maximum values are rather high and are discussed further in Section 3.4

3.3.17 Mn

The geochemistry of Mn in aqueous solution is similar to that of Fe, being strongly redox- as well as pH-controlled. The two most stable valencies are as reduced Mn^{2+} or oxidised Mn^{4+}. Reduction of Mn to the 2+ valence state is achieved at higher redox potentials than Fe (Champ et al., 1979). Under oxidising conditions, the element forms an Mn^{4+} oxide which readily encrusts particulate matter. Oxidising waters should therefore have low Mn concentrations. Over the pH range of most natural waters, dissolved Mn should be present as the Mn^{2+} species (Hem, 1985).

Manganese is present as a trace element in most major rock types, and tends to partition with Fe in many ferromagnesian mineral phases. Like Fe therefore, there are usually abundant sources of Mn in the aquifer.

Mn concentrations in Jersey groundwaters range between <0.003 and 1.85 mg/l with median values in summer and autumn surveys of 0.03 mg/l and 0.18 mg/l respectively (Tables 11 and 12). Mn concentrations usually correlate reasonably well with total Fe concentrations.

3.3.18 Cu and Zn

Copper and zinc are present in trace quantities in many rock types, especially in sulphide minerals. Their concentrations in groundwater are usually greater than predicted from aquifer chemistry alone because of their common use in industrial and agricultural processes. Cu is used extensively in agricultural pesticide sprays. The solubility limits of both Cu and Zn are significantly increased in acid water.

Concentrations of Cu in Jersey groundwaters are mostly below detection limits (0.01 mg/l) but reach up to 0.19 mg/l (Appendix II). Concentrations of Zn range between <0.019 mg/l and 2.85 mg/l, this higher value being from the Portelet Hotel (901154; Appendix III).

3.4 Potability

Many of the well and borehole sources sampled during the two 1990 surveys provide water supplies for domestic and private use. The ranges of water quality currently being used for potable supply are therefore worthy of note. No information is available for the distribution of pathogens in the water sources as these were not sampled during the two surveys: only inorganic water quality can be assessed.

Table 13 gives the ranges of concentrations of most inorganic determinands analysed for private borehole/well supply sources from all parts of Jersey. EEC recommended guide levels and maximum admissible concentrations (mac) are also given for comparison.

Some pH values are less than the recommended EEC minimum value of 6.5. Whilst this is not in itself greatly detrimental, potential increases in other elements such as Fe, Mn and Al and reduced alkalinity as a result may be of greater concern. Most owners of private supplies are apparently aware of the problem and many use treatment methods such as addition of calcium carbonate to water storage tanks, although some are apparently less well-informed and others replenish the treatment materials too infrequently to be of optimum benefit. HCO_3 concentrations less than the EEC recommended minimum of 30 mg/l are observed in several Jersey private supply sources, the lowest being 4 mg/l (Table 13). Addition of $CaCO_3$ to header tanks would also help to increase these concentrations.

No EEC recommended guidelines are given for Eh or dissolved oxygen. As with pH, it is the consequences of diminished O_2 concentrations and low Eh on determinands such as Fe, Mn and N species which is more important than the ranges of Eh and O_2 themselves.

SEC values in private supplies reach maximum values of 1200 μS/cm and even median values are higher than EEC guide levels (c. 440 μS/cm at 25°C; Table 13). Some samples are therefore more saline than EEC directives consider desirable. Two of the major contributions to high SEC are the Na and Cl ions, both of which are high because of the influence of mixing with saline water in at least some of the Jersey groundwaters. Maximum Na and Cl concentrations are 123 and 238 mg/l respectively (Table 13). EEC directives suggest that health may be affected at Cl concentrations greater than c. 200 mg/l.

Table 13. Groundwater quality ranges for samples from private supply sources. Samples were collected during the summer 1990 survey.

Determinand	Units	Min	Max	Median	Number of analyses	EEC guidelevel	EEC MAC
pH		5.02	7.55	6.07	63	6.5-8.5	
Eh	mV	58	518	434	46		
O_2	mg/l	<0.1	9.7	2.8	45		
SEC	μS/cm at 25°C	320	1200	635	63	400*	
Na	mg/l	22.7	123	53	"	20	175
K	"	1.5	92.6	5.3	"	10	12
Ca	"	6.1	100	47.9	"	100	
Mg	"	5.5	57.0	17.2	"	30	
HCO_3	"	4	241	51.5	"	30**	
SO_4	"	19.8	214	95.3	"	25	250
Cl	"	21	238	78	"	25	(~200)
NO_3-N	"	<1	47.4	13.7	"	5.7	11.3
NH_4-N	"	<0.01	0.06	0.03	4	0.04	0.39
Sr	"	0.09	1.18	0.26	63		
Ba	"	0.003	0.168	0.050	"	0.1	
B	"	0.02	0.37	0.08	"	1.0	
Si	"	3.3	18.8	8.1	"		
P	"	0.02	1.34	0.11	"	0.4	5
Fe	"	0.001	2.59	0.03	"	0.05	0.2
Mn	"	<0.005	1.55	0.028	"	0.02	0.05

* SEC EEC guideline in μS/cm at 20°C (corresponds to approx. 440 μS.cm at 25°C)

** Recommended minimum value

Potassium concentrations reach values far higher than the EEC mac of 12 mg/l largely as a result of agricultural pollution (the maximum observed concentration being 93 mg/l; Table 13).

Nitrate concentrations in Jersey groundwater are known to be high as a result of diffuse agricultural and domestic pollution. Table 13 shows that the maximum concentration observed in private supply boreholes is 47.4 mg/l. The EEC mac is 11.3 mg/l and even the Jersey median value (13.7 mg/l) exceeds this limit. Nitrate has long been linked with the occurrence of methemoglobinemia in young children (WHO, 1972) and it is therefore recommended that high-NO_3 water is not given to infants. The high nitrate content of most Jersey groundwaters is a considerable cause for concern and its presence demonstrates the severity of the pollution problem in the shallow hard-rock aquifer. The presence of nitrate is doubtless a pathfinder for organic pollutants not analysed for in this survey.

Also of major concern is the abundance of groundwater with high Fe and Mn concentrations. Quoted EEC mac values for these elements are 0.2 mg/l and 0.05 mg/l respectively. Whilst neither is known to be directly detrimental to human health (although it is often recommended that high-Fe water is not given to babies), the presence of both causes aesthetic problems. Oxidised Fe imparts a red-brown stain to water which effectively stains food, laundry and plumbing, clogs pumps, well screens and pipework and produces a nasty metallic taste (and often smell). Mn in high concentrations produces troublesome black staining. The highest concentrations observed in Jersey private supply sources were 2.6 mg/l for Fe and 1.6 mg/l for Mn (Table 13). Treatment for high Fe and Mn concentrations in groundwater can however be easily carried out by aeration.

No major water quality problems are observed for Mg, Ca, SO_4, NH_4-N or P and EEC directives do not give mac values for the trace elements Sr, Ba, B or Si.

3.5 Regional water quality

Chemical analyses of water samples from both the summer and autumn 1990 surveys show good overall agreement. Figure 3.1 shows the correlations between determinands analysed in both surveys and 1:1 correlation curves are also indicated. Most parameters lie close to the correlation curves and only Cl shows a small systematic bias towards higher concentrations in one of the surveys (i.e. the summer survey). Chemical analyses are therefore generally believed to be representative of water quality in the sources sampled. This is supported by the similarity of chemical compositions with samples from domestic sources analysed previously by the States Analyst (Public Health Department, pers. comm., 1990).

The shallow groundwaters sampled in Jersey are dominated by the Na and Ca cations and by the Cl (and NO_3-N) and HCO_3 anions (Figure 3.2). Some samples are also relatively SO_4-rich. The dominance of Na-Ca-Cl waters demonstrates the importance of mixing between saline water and groundwaters since the predominant source of the Cl ion is more likely to be marine- than aquifer-derived (Section 3.3.11). Mixing with saline water can be achieved in a number of ways:

(a) by recharge of marine-derived rainwater laden with Cl (and other elements enriched in seawater),

(b) by marine aerosols (ocean spray),

(c) by saline intrusion.

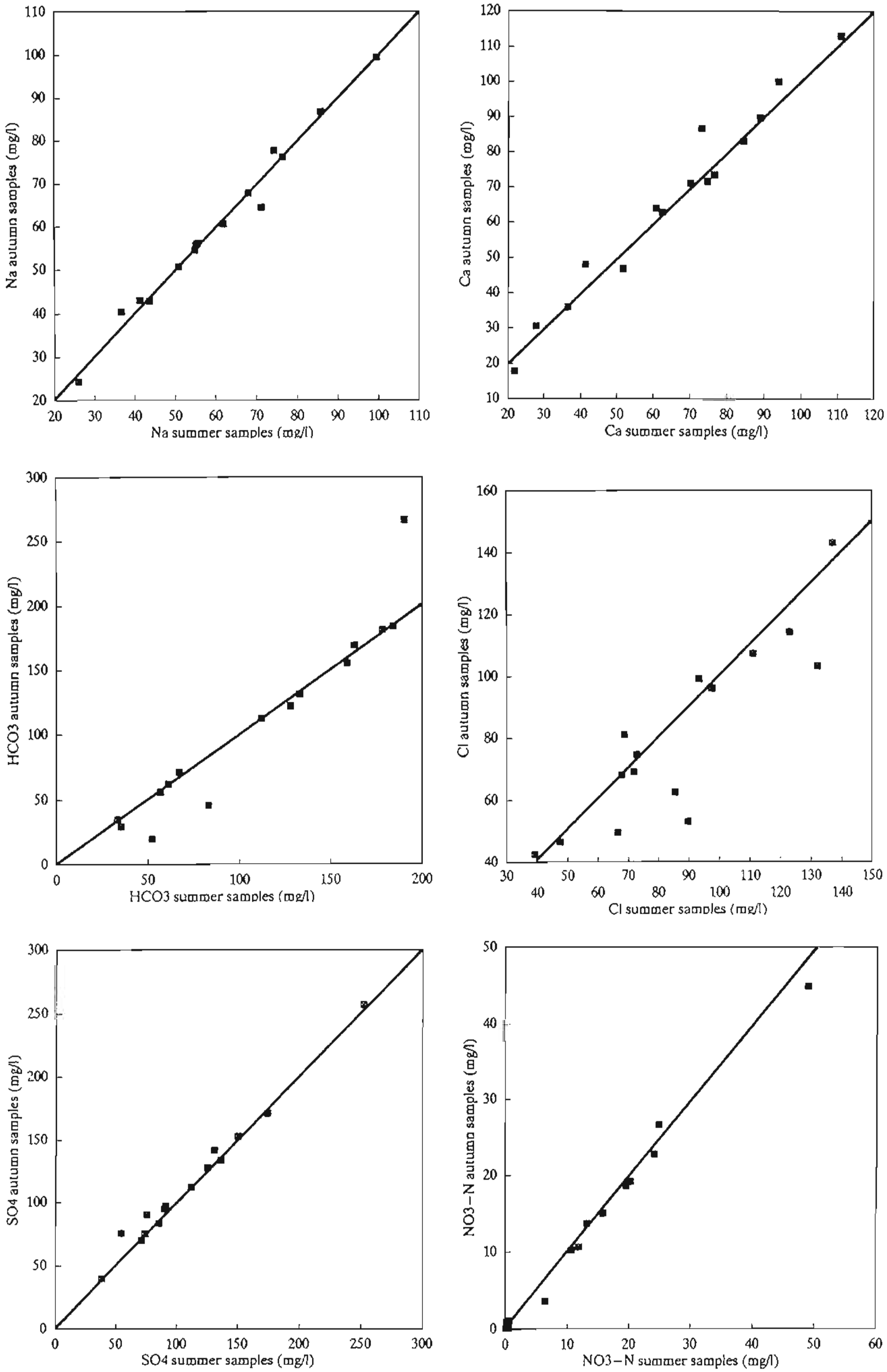
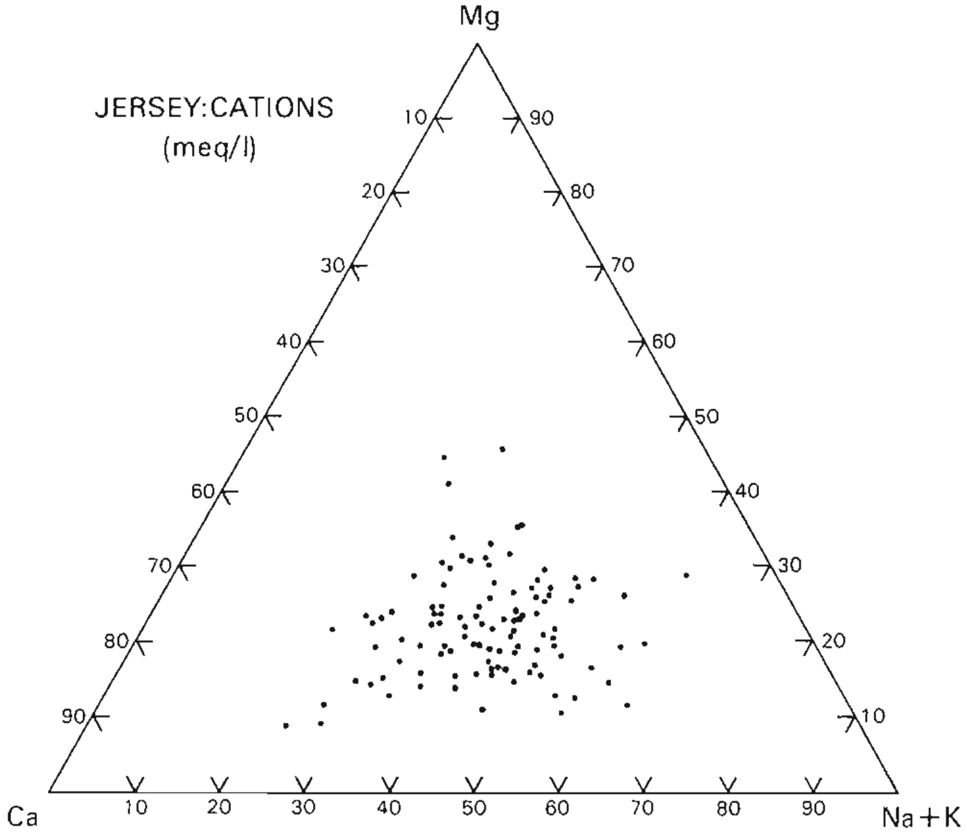


Figure 3.1 Correlation of selected parameters between summer and autumn surveys, 1990. Curves indicate 1:1 correlations



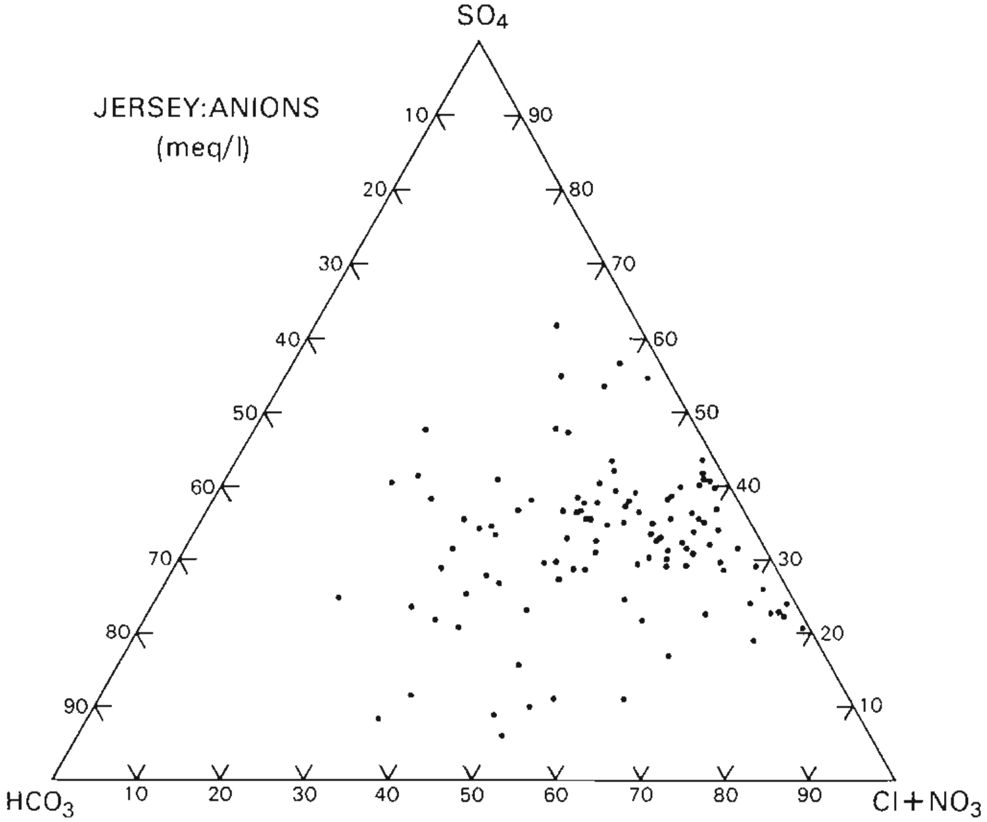


Figure 3.2 Triangular diagrams of major cations (Ca-Mg-Na+K) and anions (HCO_3-Cl+NO_3-N-SO_4) in the Jersey groundwaters taken from the summer 1990 survey

Jersey's marine aspect demands that rainwater is to some extent marine-influenced and hence Cl-rich. This is evident from Table 14 where Jersey rain is shown to have Cl concentrations between 8.6 and 27.5 mg/l in comparison with coastal California rain and in contrast to rainfall in Chilton, Oxfordshire and continental USA (Table 14). This accounts for some of the Cl present in Jersey groundwater.

Marine aerosols are also likely to have a small effect on groundwater chemistry but the effect is difficult to quantify. Aerosols may be influential in the coastal stretches, particularly in the paths of the prevailing winds (westerly and southwesterly, Section 1.2) but may not extend inland very far. Aerosols are not thought to be major sources of marine-derived Cl in Jersey groundwater however.

Saline intrusion is potentially of much greater importance. In a conventional coastal aquifer which is permeable and low-lying, saline intrusion will be produced by upconing of saline water from the wedge of higher-density marine water beneath fresh groundwater as a result of over-abstraction (Williams, 1990). However, in a hard-rock aquifer where primary porosity is low and groundwater flow is primarily along fissures, a wedge will not be able to develop fully and "saline intrusion" will be represented by irregular, finger-like infiltration along permeable fracture zones. Low-lying coastal parts of Jersey are particularly prone to this type of infiltration.

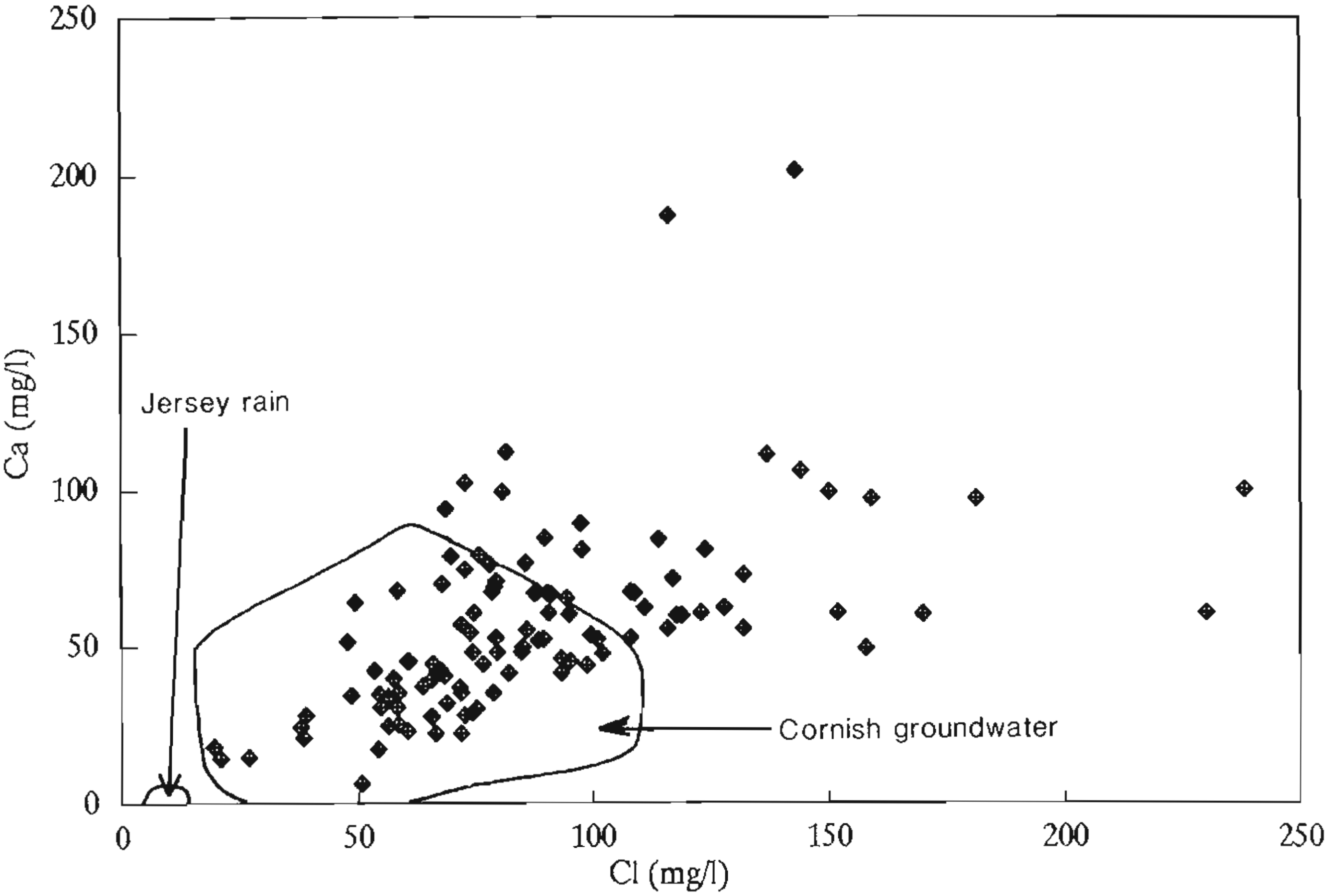
Figures 3.3 and 3.4 show the variations of the major cations Ca, Mg, Na and K with Cl in Jersey groundwater (summer 1990) compared with data for groundwater from a similar lithological terrain (granite and metasediment) in the Carnmenellis area of Cornwall (Smedley et al., 1989). It is clear that Cl concentrations in Jersey groundwater reach much higher values than those from Cornwall and this suggests that mixing with marine water is more important in some of the Jersey samples than in Cornwall. Some coastal parts of Jersey are much lower-lying than is generally the case on the Cornish coast, particularly in the St Clement, Grouville and St Ouen's areas, and this probably accounts for the increased influence of marine water in coastal Jersey.

Figures 3.3 and 3.4 also show the typical chemistry of Jersey rain. Concentrations of Cl and the cations are all either lower than or equal to the most dilute groundwater samples. Increases in elemental concentrations are partly effected by evapotranspiration but this cannot account for the range of concentrations observed in major elements especially since cation/Cl ratios are usually greater in groundwater than in rainfall; a phenomenon which cannot occur by evaporitic concentration. Increases in Cl are most likely related to saline infiltration effects, as is a proportion of the Na and Mg. Other increases in elemental concentrations (of all cations and perhaps a small quantity of Cl) are related to water-rock interaction effects. K concentration is further enhanced by agricultural pollution.

As noted in Section 3.3.1, many of the Jersey groundwaters sampled are relatively acidic, 80% of them being less than pH 7 (summer survey samples). They are typically undersaturated with respect to calcite and gypsum (i.e. these minerals will tend to dissolve to attempt to reach equilibrium) and most are saturated with respect to quartz and chalcedony.

3.6 Water quality maps

In order to investigate the regional variation in Jersey groundwater quality, regional maps of selected chemical parameters have been plotted and are



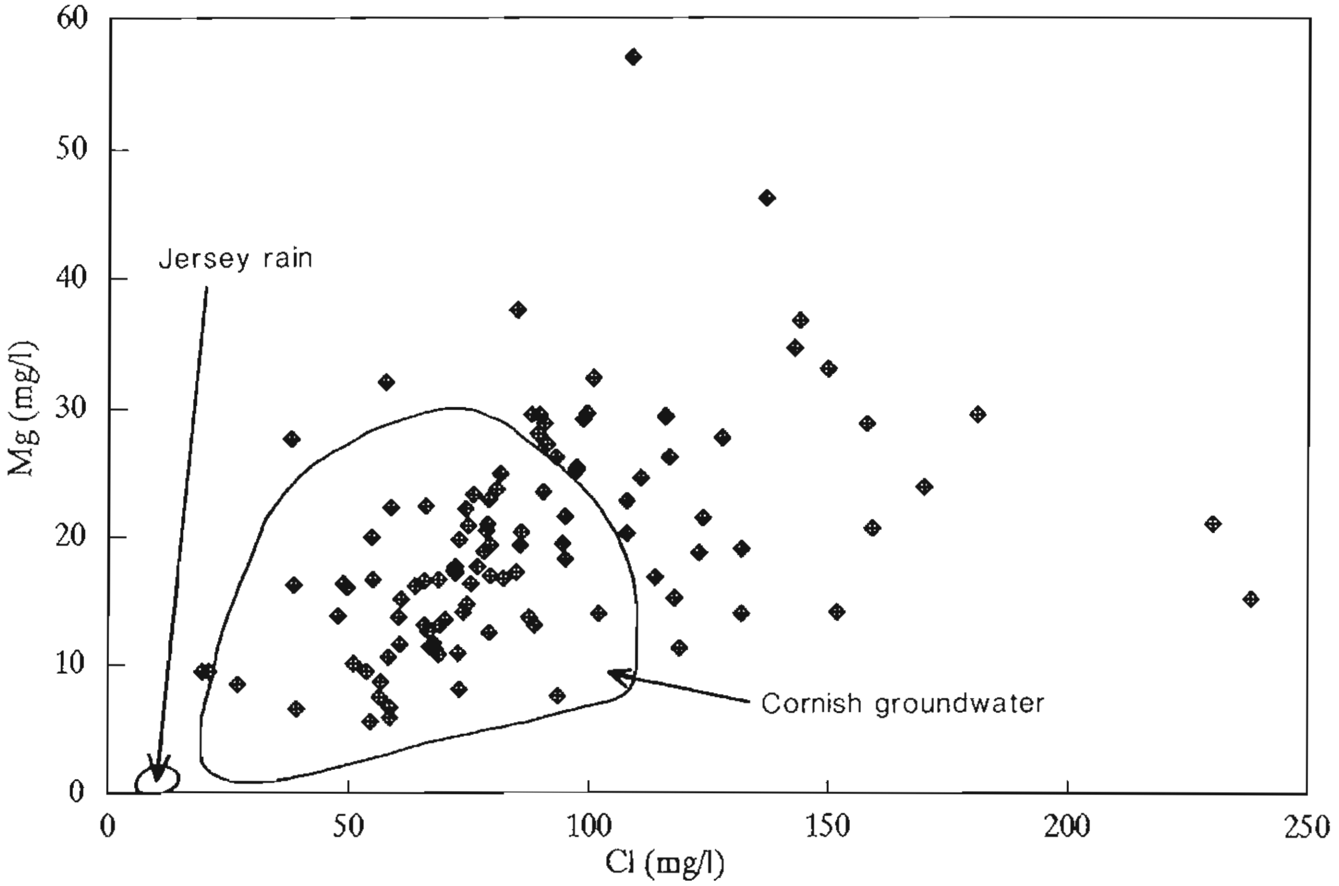
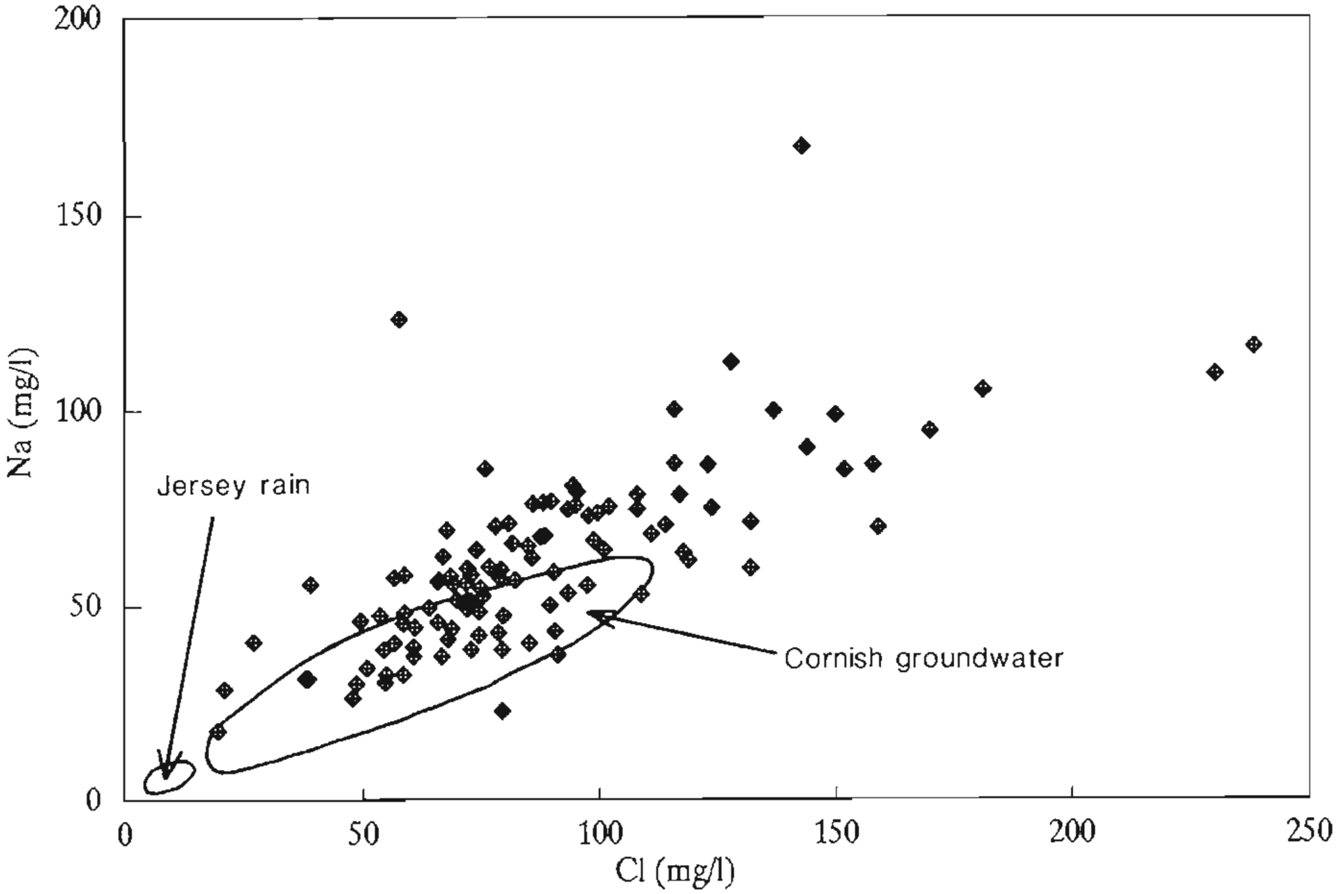


Figure 3.3 Variation of Ca and Mg with Cl in Jersey groundwater from the summer 1990 survey. The typical samples of Jersey 1990 rain are also shown, along with the fields typical of Carnmenellis groundwater, Cornwall 1988 (Smedley et al., 1989)



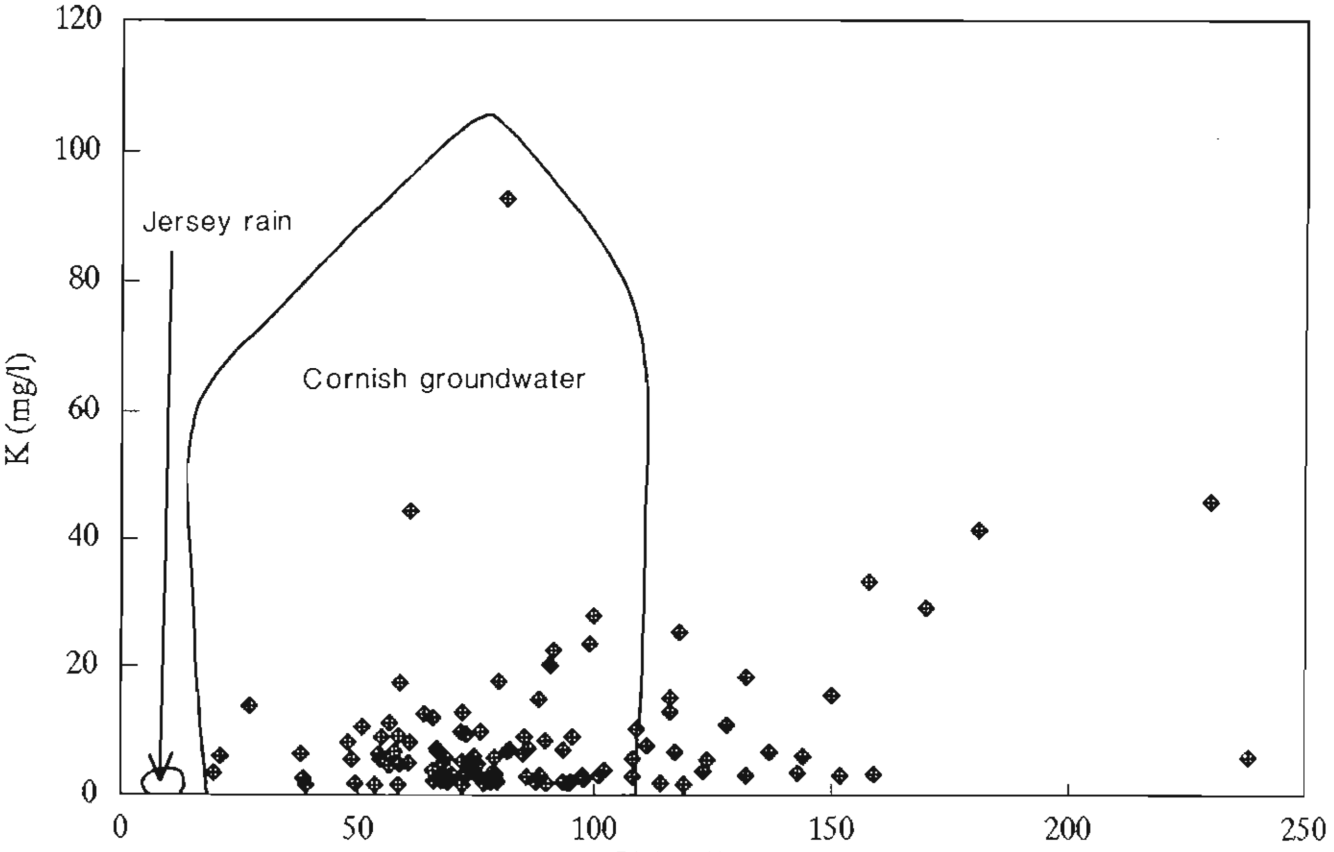


Figure 3.4 Variation of Na and K with Cl in Jersey groundwater from the summer 1990 survey. Typical Jersey 1990 rain is also shown, along with Cornish groundwater for 1988 (Smedley et al., 1989)

Table 14. Compositions of rainwater samples collected at Jersey Airport during 1990 compared to typical compositions from the USA.

Sample	Date sampled	Na	K	Ca	Mg	SO_4	Cl
901108	7.6.90	6.7	1.8	2.2	1.0	19.5	11.1
901109	21.6.90	5.0	1.3	1.1	0.7	9.7	8.6
901352		14.9	0.8	1.26	1.8	7.0	27.5
1		0.56	0.11	0.65	0.14	2.18	0.57
2		9.4	0	0.8	1.2	7.6	17
3		2.64	3.06	1.92	0.75	nr	5.70

nr: not reported

1: Average composition of rain, Aug 1962 to July 1963, North Carolina and Virginia (Gambell and Fisher, 1966).

2: Rain, Menlo Park, California Jan. 1958 (Whitehead and Feth, 1964)

3: Rain, 1975-80 (n = 24), Chilton, Oxfordshire (Edmunds et al., 1987) presented in Figures 3.5 to 3.9. These may be compared with maps of relief, rainfall, lithology, Recent deposits, land use and soils in Figures 1.1 to 1.6.

Groundwater pH values are generally lower in the northern part of Jersey than in the south (Figure 3.5). This variation is apparently related to relief, geology and soils. Since the highest elevations are found to the north, groundwater flow paths will be principally orientated from the north towards the south. Groundwater in the north should be relatively young, recently recharged water and should therefore have had little interaction with mixed lithologies. The geology of northern Jersey is dominated by the North west Granite and by acidic volcanic rocks which have low pH-buffering capacities owing to paucity of clay and carbonate minerals. Soils on the North west Granite are also sandy, largely peaty and usually thinly developed. Soil is absent from some rocky slopes in this area (Figure 1.5). Such soils are generally acidic and pH poorly buffered. Higher pH values in the south are probably derived from water-rock interaction during flow towards the south coast, particularly in the Jersey Shale Formation where a higher proportion of clay minerals and carbonate cement can increase pH values significantly.

SEC (Figure 3.5) is predominantly highest in the southeast (St Clement and the Grouville coastal area) as well as to the north of St Ouen's Bay and at Corbiere in the southwest. The higher values are related to the saline infiltration effects mentioned in Section 3.6. The high SEC value of one sample (Lobster Pot; sample 901136) is undoubtedly related to mixing with saline water since the site is very close to the coast with an elevation of 30 m and a well depth of 145 m. Some drawing-in of marine water at this site is therefore inevitable.

Eh variation (Figure 3.5) indicates that most groundwaters are oxidising with Eh values greater than about 250 mV. The few samples that are fairly reducing are located particularly in the St Saviours area (e.g. Jersey Milk, Highfield Lane) and a few are located on the low-lying south and south-easterly coastal areas (e.g. Randall's Brewery, Parade Park, Royal Jersey Golf Course). The low Eh values derive from groundwaters which have upwelled from deeper sources and which have had longer flow paths and have therefore been subjected to reducing conditions away from the atmosphere.

Dissolved oxygen (DO) concentrations (Figure 3.5) show much apparently random variation but samples from the south have slightly lower concentrations than those in the northern and central parts of the island. The variations are difficult to interpret and are probably the results of mixing of groundwaters with different DO concentrations but some overall agreement with Eh suggests that some waters in the south and south-east are derived from upwelling from deeper, oxygen-poor sources.

The regional variations in Ca, Mg, Na and K are displayed in Figure 3.6. Concentrations of Ca, Mg and Na are largest to the north of St Ouen's Bay, on the coast at Corbiere and in the St Clement-Grouville areas, and as with SEC, indicate the influence of saline intrusion in these low-lying coastal areas. Some higher concentrations of Ca are however apparent further inland in the St Saviour and St Brelade parishes. This is more likely related to water-rock interactions with shale and andesite or rhyolite although a general lack of published chemical analyses of rocks from Jersey makes this hypothesis difficult to quantify. Some slightly higher concentrations of Mg in groundwater from the Jersey Shale Formation may be related to ion exchange reactions involving clay minerals and to dissolution of chlorite.

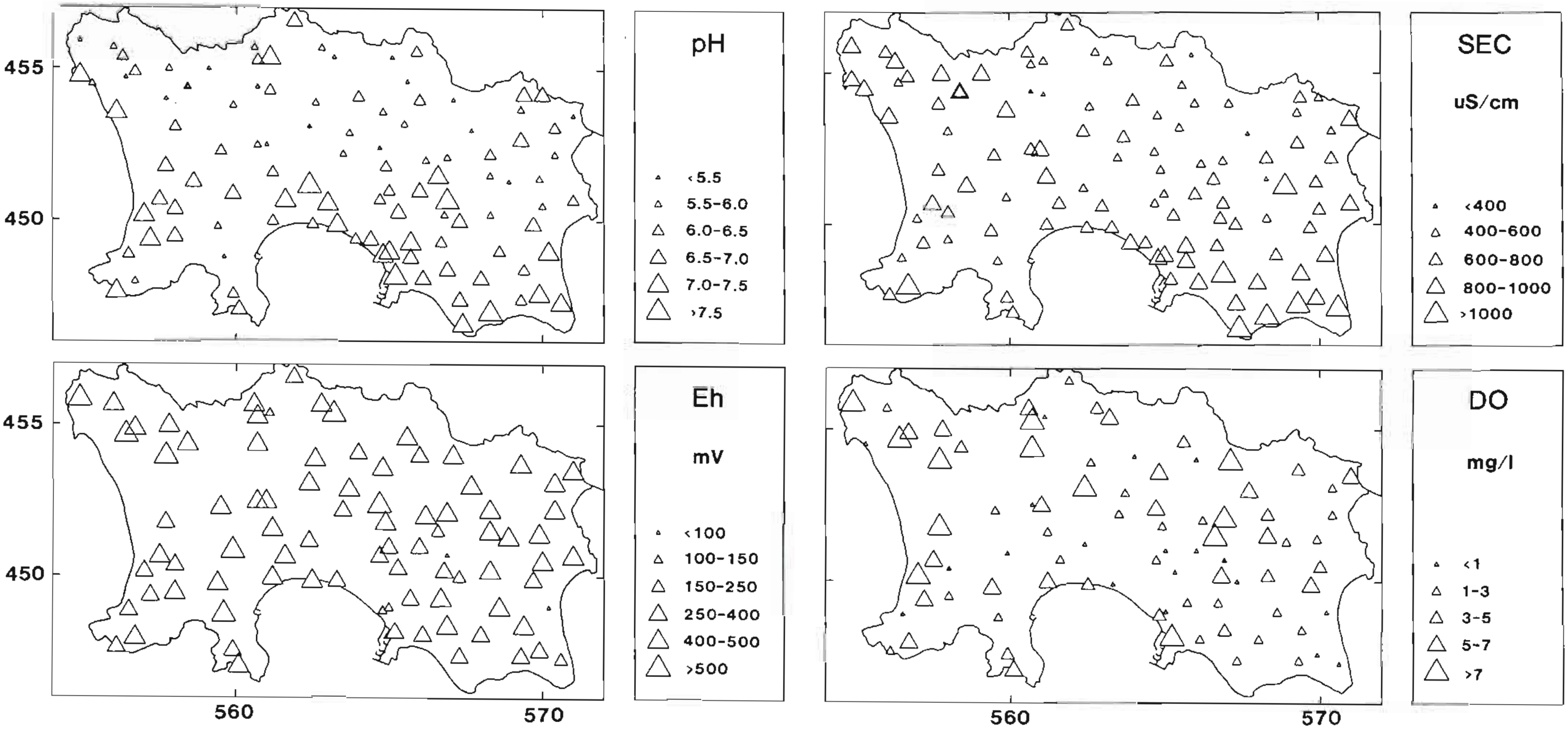


Figure 3.5 Maps of Jersey showing regional variations in pH, SEC, Eh and DO (dissolved oxygen) from the summer 1990 survey

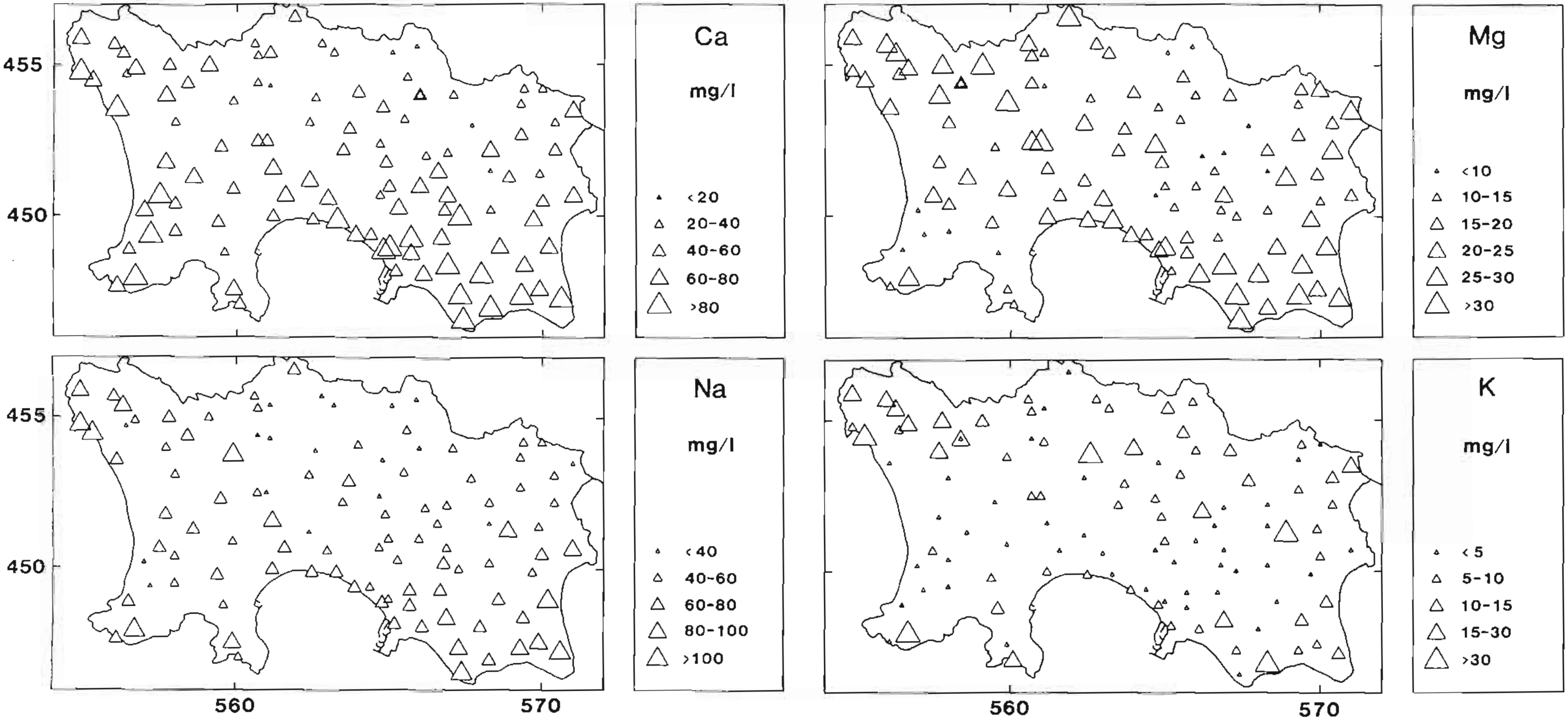


Figure 3.6 Maps of Jersey showing regional variations in Ca, Mg, Na and K (in mg/l) from the summer 1990 survey

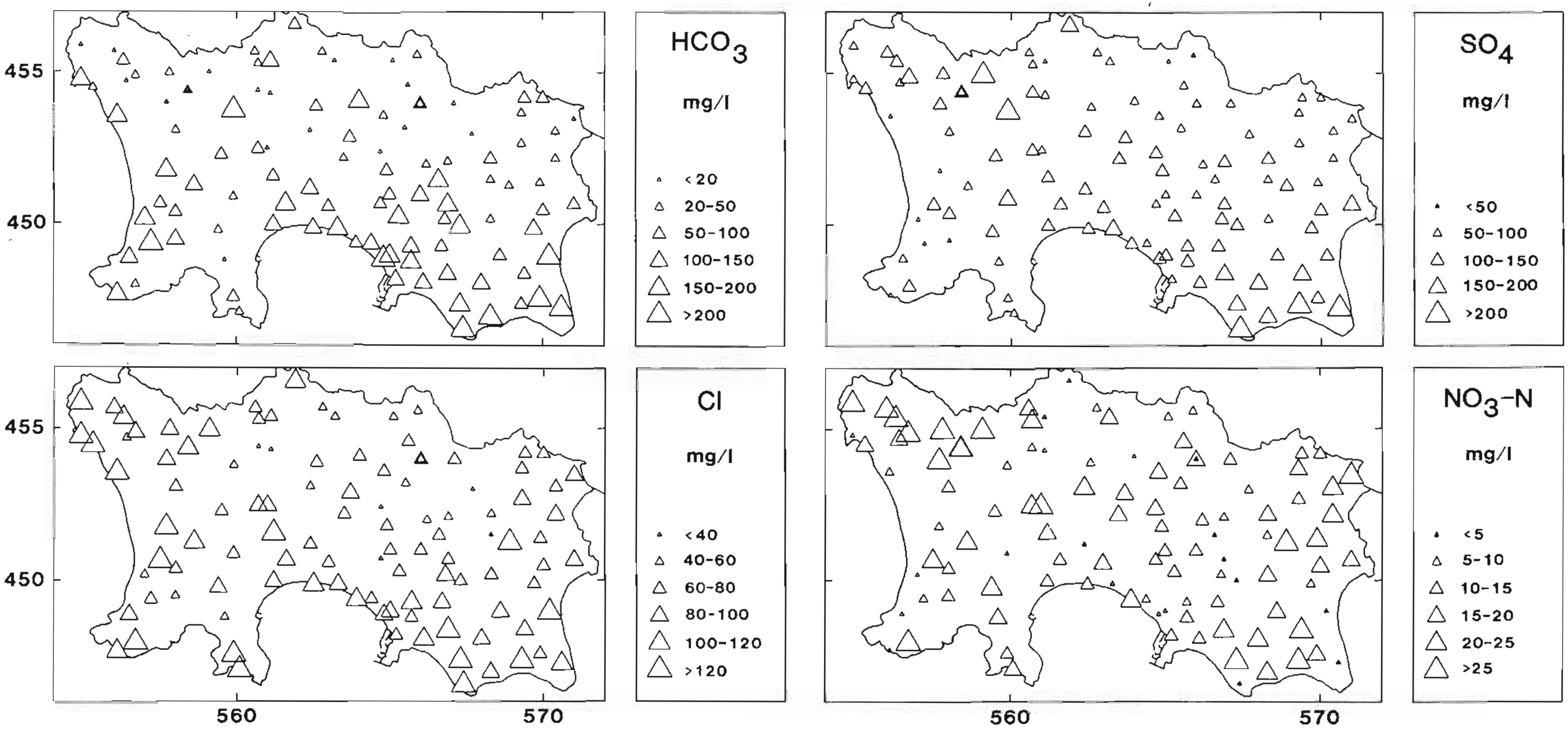


Figure 3.7 Maps of Jersey showing regional variations in HCO_3, SO_4, Cl and NO_3-N (mg/l) from the summer 1990 survey

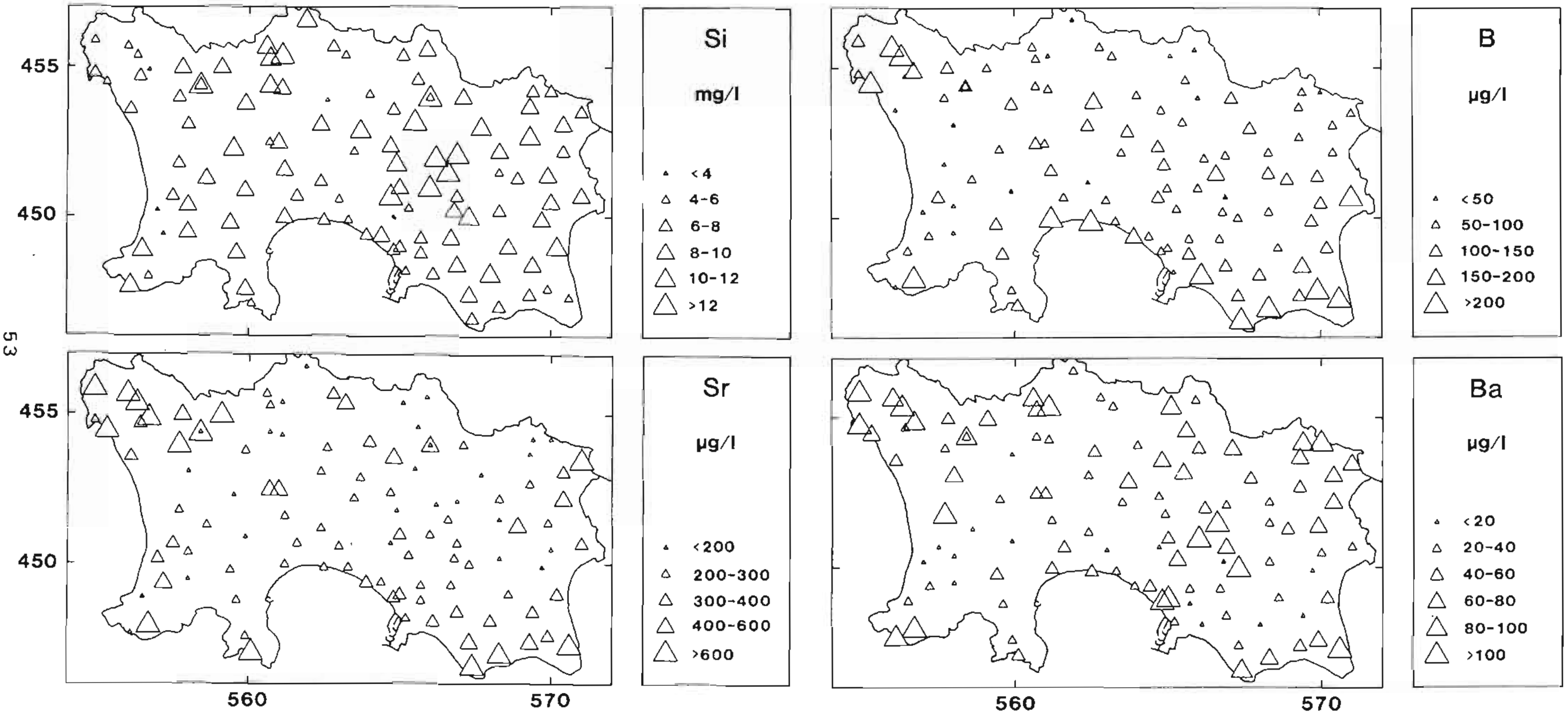


Figure 3.8 Maps of Jersey showing regional variations in Si, B, Sr and Ba from the summer 1990 survey

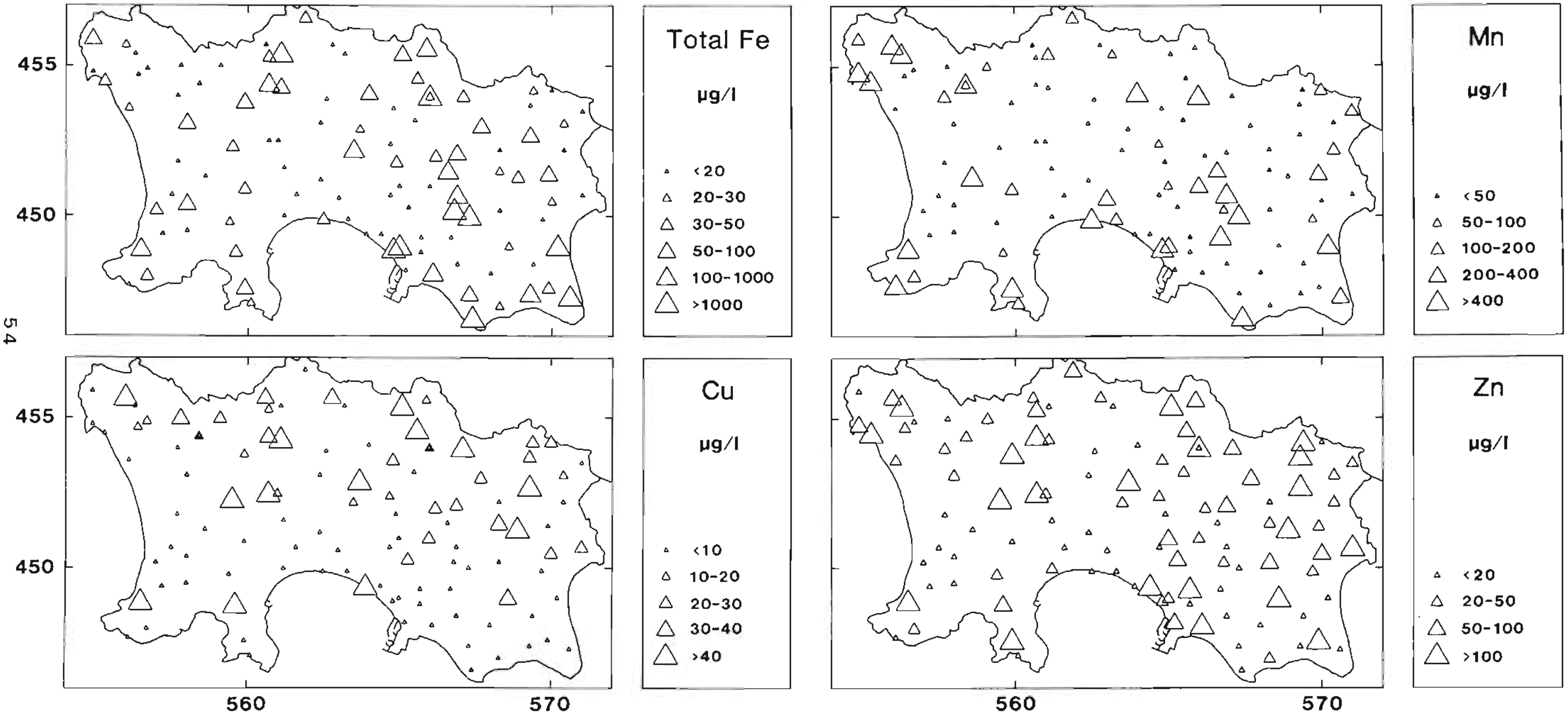


Figure 3.9 Maps of Jersey showing regional variations in Total Fe, Mn, Cu and Zn (μg/l) from the summer 1990 survey

Potassium is consistently higher in groundwater in the north-west of the island (Figure 3.6). This may be derived from the North west Granite (S-type granitic rocks are typically high in K; Cox et al., 1979) but could also be related to agricultural pollution. K is notably lower in the south-central part of the island where ion-exchange reactions in the Jersey Shale Formation and its overlying loam soils render K^+ relatively immobile.

Major anions (Figure 3.7) are dominantly controlled by the same processes which influence the major cations. HCO_3 variation is related to water-rock interaction effects (Section 3.3.9). Concentrations are low in the north and north-western parts of Jersey where groundwaters are likely to be youngest and to have had little aquifer interaction, but are higher in the south where higher concentrations of carbonate are likely to be present. Some high values on the shale correlate with the observation of variable amounts of diagenetic calcite in the interstices (Bishop and Bisson, 1989). A strong correlation between Ca and HCO_3 is apparent.

Chloride and SO_4 variations (Figure 3.7) are apparently dominated by seawater effects, although some Cl may have been desorbed from clay minerals and a minor amount may be pollution-related. Some SO_4 may be derived from oxidation of sulphide minerals in the granite and volcanic rocks.

Nitrate (as N) (Figure 3.7) is derived from both agricultural and domestic pollution sources. Some high concentrations in the north-west correlate well with high K concentrations noted earlier and suggest that the K is in fact pollution-derived and does not originate wholly from granite-water interaction. The regional distribution of high-NO_3 waters is well-illustrated in Figure 3.7. Some low-NO_3 waters in the south and south-east of Jersey correspond to the low-Eh groundwaters referred to earlier. NO_3-N concentration is therefore also redox-controlled and is discussed in more detail in Section 5.2.

Silicon concentrations (Figure 3.8) are apparently highest in the Trinity-St Saviour area and are probably derived by dissolution of silicate minerals in the Jersey Volcanic Group. Over the remainder of the island, Si variations are sporadic.

Boron is highest in the coastal areas with high SEC, Na, Ca, Mg, SO_4 and Cl. It is therefore probably largely marine-derived. B concentration is typically 4.5 mg/l in seawater (Hem, 1985) and saline mixing is therefore likely to noticeably increase B concentrations, especially since none of the Jersey groundwaters (including those suspected of containing a marine component) has B concentrations greater than 0.5 mg/l (Appendix III).

Strontium (Figure 3.8) is high in some samples from coastal areas as a response to seawater effects but concentrations are also high on the North west granite. The same is true of Ba. These locally high concentrations are probably more related to dissolution of feldspars (plagioclase and alkali feldspar respectively) in the granite complex. Ba concentrations are also high in St Saviours area, and may be related to higher concentrations of alkali feldspar in the acid volcanic rocks in this part of Jersey.

Figure 3.9 shows the variation in total Fe and Mn. Variations are not apparently related to lithology. The highest concentrations of both elements are in the coastal sections (in the case of Fe, particularly the south-east coast) and in the St Saviour area, noted previously for having relatively high pH, Ca, HCO_3, Si and Ba and low Eh values and DO concentrations. Both total Fe and Mn are therefore apparently redox-controlled, the solubility of both elements being increased under reducing conditions.

Cu concentrations (Figure 3.9) appear to be slightly higher in the northern part of Jersey than in the south. This is related to the pH since Cu is more soluble in acidic water (Section 3.3.18). The Cu is most likely derived from pipework and plumbing but a minor contribution may be from Cu sulphides in the aquifer.

The variation in Zn concentrations (Figure 3.9) is apparently randomly distributed and may be related to water-rock reactions involving sulphide minerals or may be derived from agricultural or industrial pollution (Section 3.3.18).

Many of the parameters displayed in Figures 3.5 to 3.9 show some systematic regional distributions related to, for example, bedrock lithology and soils or proximity to the coast, and hence can give some broad indication of the water quality to be expected in areas not sampled during the 1990 surveys. However, it must be borne in mind that the sampling density of only 1 per square km would probably give inadequate resolution for accurate predictions to be made on quality of unsampled areas. Extrapolation would be further hampered by the variations in water quality to be expected at different depths (particularly with respect to redox-influenced parameters). This is well illustrated by the two examples of the shallow well (well depth 12 m) and deep borehole (depth 27 m) at the States Farm. The two sources are only a few metres apart, and in the same aquifer but the chemistries are quite different: the borehole-derived groundwater being moderately reducing with an Eh of 274 mV, NO_3-N concentration of 0.18 mg/l and a total Fe concentration of 8.5 mg/l and the well-derived water being oxidising (Eh 353 mV) with an NO_3-N concentration of 19.5 mg/l and total Fe of 0.028 mg/l (Appendices II and III). The analyses also represent groundwater chemical composition over a short time interval. Compositions are likely to vary seasonally by dilution or evaporative concentration.

Figures 3.5 to 3.9 inclusive indicate some minor variations in chemical composition with lithology but the variations are not in many cases distinct. Histograms of pH, HCO_3 and SEC are presented in Figure 3.10 for groundwaters from the major lithological units. Little variation is apparent with lithology in pH except that samples from granite extend down to slightly lower pH values. Some of the higher pH values of sources from granite are also apparently influenced by saline water (which should buffer pH at slightly higher levels). This correlates with a 'tail' of higher HCO_3 and SEC values, also related to saline intrusion effects. The saline mixing effects are more influential in some of the granite-derived waters because those form the low-lying coastal areas of St Clement-Grouville and north of St Ouen's Bay.

Slightly lower SEC values are apparent in shale-derived groundwater but the differences are not great. The general lack of variation in groundwater chemistry with lithology is probably not surprising given that granite and acidic volcanic rocks are chemically similar and that the Rozel Conglomerate Formation represents largely molasse sedimentation which was derived from those igneous complexes - only the Jersey Shale Formation should show some compositional differences with greater abundance of carbonate and clay minerals.

3.7 Stable isotopes

The isotopes of oxygen and hydrogen are dominated by ^{16}O and ^{1}H (99.63% and 99.985% respectively). Small quantities of ^{18}O (0.1995%) and ^{2}H (0.0148%) are however also stable in nature and the ratios of H and O isotopes can vary significantly in the hydrological environment. The lighter isotopes have higher vapour pressures than the heavier masses and hence partition preferentially into the vapour phase. Water vapour should therefore be isotopically lighter with higher proportions of ^{16}O and ^{1}H than the residue left behind. The mass fractionation is highly temperature-dependent.

Stable isotopes of H and O are conventionally quoted relative to a standard seawater composition (Standard Mean Ocean Water, SMOW), the deviation relative to SMOW being quoted as a δ value in per thousand (‰):

$$\delta^{18}\text{O} = \left(\frac{{}^{16}\text{O}/{}^{18}\text{O}_{\text{sample}} - {}^{16}\text{O}/{}^{18}\text{O}_{\text{SMOW}}}{{}^{16}\text{O}/{}^{18}\text{O}_{\text{SMOW}}} \right) 1000$$

and

$$\delta^{2}\text{H} = \left(\frac{{}^{2}\text{H}/{}^{1}\text{H}_{\text{sample}} - {}^{2}\text{H}/{}^{1}\text{H}_{\text{SMOW}}}{{}^{2}\text{H}/{}^{1}\text{H}_{\text{SMOW}}} \right) 1000$$

The δ^{18}O and δ^{2}H values of fresh waters are usually negative values (lighter than seawater) due to the preferential fractionation of the lighter masses into water vapour and the heavier masses into residual seawater. It is well known that water equilibrated in cold conditions (e.g. polar latitudes or glacial palaeoclimates) have lighter δ^{18}O and δ^{2}H compositions (more negative values) than those equilibrated in warmer conditions and Craig (1961) found that meteoric waters in different latitudes obey the general relationship:

$$\delta^{2}\text{H} = 8\delta^{18}\text{O} + 10$$

although the equation describing the correlation between δ^{2}H and δ^{18}O has been found to vary in different parts of the world (e.g. Darling and Bath, 1988).

Stable isotopic results from 14 selected groundwater samples (summer 1990 survey) are presented in Table 15 and compositions are represented graphically along with the Meteoric Water Line of Craig (1961) in Figure 3.10. The compositions are negative as is typical of meteoric water and all fall within a relatively narrow range of δ^{2}H -38 to -31‰ and δ^{18}O of -6.0 to -5.1‰. They also lie close to the World Meteoric Line. Jersey groundwaters are isotopically heavier than samples from the unconfined part of the Chalk aquifer in Berkshire but are comparable with the compositions of shallow Cornish groundwater (Smedley et al., 1989). Some of the Berkshire Chalk samples may have an isotopically lighter palaeowater component which equilibrated in cooler climates but most are believed to be relatively recent groundwaters (Edmunds et al., 1987).

The fact that the Jersey groundwaters are isotopically heavier than Berkshire Chalk groundwaters suggests that either the former contain a larger component of marine-derived water (and hence lie on a mixing line towards the composition of SMOW; Figure 3.11) or they have equilibrated in a warmer contemporary climate, or both. However, none of the samples analysed for δ^{2}H and δ^{18}O are those identified as having a notable saline component (e.g. those from coastal St Clement and Grouville). Likewise, they are isotopically comparable to Cornish groundwaters which are also not believed to contain a significant seawater component (Smedley et al., 1989). It is therefore

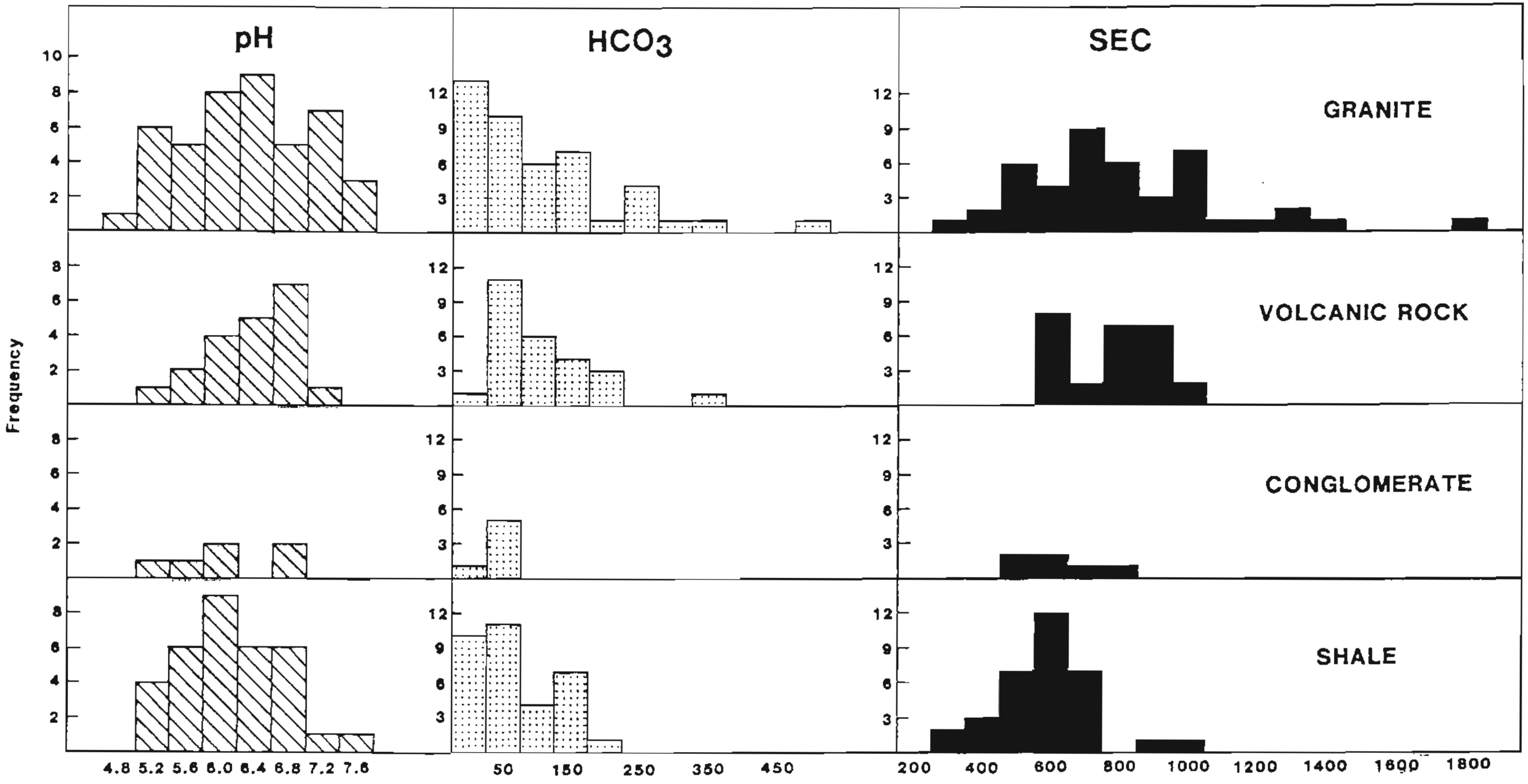


Figure 3.10 Histograms of variation of pH, HCO_3 and SEC in Jersey groundwater samples in the major lithological units from the summer 1990 survey

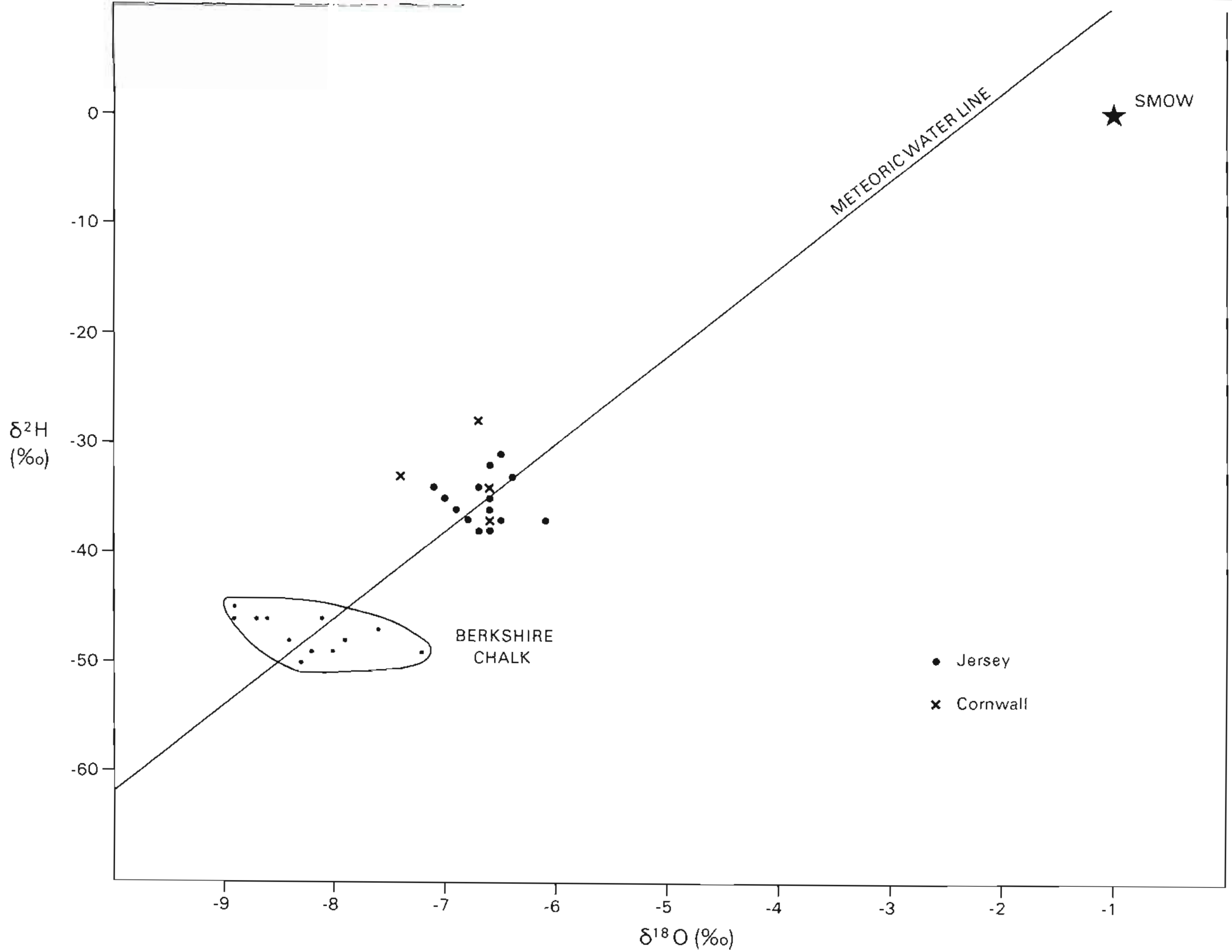


Figure 3.11 Variation of $\delta^{18}O$ with $\delta^{2}H$ (‰ relative to SMOW) for Jersey groundwaters compared with groundwater from the unconfined Chalk aquifer of Berkshire and from shallow Cornish groundwater (Smedley et al., 1989). The Meteoric Water Line is from Craig (1961)

Table 15. Stable isotopic data for selected groundwater samples collected during the Summer Survey 1990. Results are normalised to standard mean ocean water (SMOW) and are given in ‰.

Sample	Locality	$\delta^{18}O$(‰)	$\delta^{2}H$(‰)
901137	La Pointe	-6.0	-35
901143	Va de la Mare Farm	-5.6	-32
901149	Quennnevais Camp Site	-6.1	-34
901152	West View Hotel	-5.5	-31
901164	Harvest Barn	-5.1	-37
901175	Coronation Park	-5.6	-36
901184	Le Couvent	-5.7	-34
901188	Ronez Quarry	-5.7	-38
901194	Summerhill	-5.9	-36
901200	Jersey Milk	-5.8	-37
901214	Tesson Mill	-5.6	-38
901221	Chaise au Diable	-5.6	-35
901223	A E Smith	-5.4	-33
901228	Merton Hotel	-5.5	-37

tentatively suggested that the isotopic compositions of the Jersey groundwater samples reflect relatively young, recently recharged water having equilibrated at contemporary climatic temperatures. Precise estimates of Jersey groundwater age cannot however be made from $\delta^{18}O$ and $\delta^{2}H$ compositions alone: determination of precise ages can only be made using dating techniques such as ^{14}C or tritium (^{3}H).

3.8 Organic compounds

Man-made organic compounds are used in agriculture as herbicides and pesticides, on transport systems as weedkillers, and in industry, for example, as solvents. Industrial solvents do not pose a problem on Jersey, but herbicides and pesticides are widely used and some of these compounds or their breakdown products persist sufficiently to be taken into solution in groundwater.

A comprehensive list of organic compounds commonly in use on Jersey was prepared by the Department of Agriculture and Fisheries. The list includes the active organic compound, trade name, rate of application and time of year at which the application is made. It shows that compounds are most likely to leach down to the water table in the autumn. Some compounds are likely to be adsorbed into the soil matrix but those which may pass through the soil and retain their identity within groundwater include: Bromacil, 2,4-D, Mecoprop, Isoproturon, MCPA, TCA, Metribuzin, Benomyl, Captan, Aldicarb. The weedkillers Atrazine and Simazine may also arrive in groundwater via soakaways or other bypass routes which avoid the soil profile.

As a check on organic pollution of the groundwater, 15 samples were collected and submitted for analysis at the Water Quality Centre, London for BGS. The detection limits for each of seven determinands were set at the EEC mac (in each case 0.010 μg/l). The selected determinands were trichloroacetic acid, MCPA, Mecoprop, Isoproturon, 2,4-D, Simazine and Atrazine.

The sample locations were chosen for the following reasons. Some reducing waters were selected because they may not indicate pollution from agriculture if the nitrate is wholly reduced but may still be polluted by organic compounds. These include samples from Jersey Milk, States Farm borehole and Randall's Brewery. Additional sites were chosen because they had high concentrations of inorganic nutrients, including Grouville Spring, La Chenée, First Tower Laundry, Homefields Farm and Mushroom Farm. A small number of samples were included which were not believed to be at risk of any pollution: Val de la Mare and Chaise au Diable.

In the event only one determinand in each of two samples was above the detection limit. At Grouville Spring the persistent weedkiller Simazine was detected at a concentration of 2.13 μg/l and in the States Farm well, Mecoprop was detected at a concentration of 0.103 μg/l. Simazine is used as a general purpose weedkiller. The reported concentration of Simazine coupled with the high concentrations of inorganic nutrients suggest a highly polluted water derived from a shallow groundwater catchment, and Grouville Spring should not be used for human or animal consumption if these high concentrations persist. Mecoprop is a herbicide used principally on grassland and gardens. Its occurrence in solution in the shallow groundwaters which supply the States Farm Well probably results from the treatment of lawns in the vicinity of the Farm.

The samples show that limited pollution is occurring to some shallow sources, but that deeper sources are as yet free from organic pollution. The small sample size does not permit a definitive conclusion; for the most part, Jersey groundwaters appear free from organic pollution.

4. MICROBIOLOGY

4.1 Sampling and analysis

Samples were taken from the same sources as were sampled for organic analysis excluding Stonewall Farm and Homefields Farm. Samples were collected at the wellhead using standard aseptic techniques and returned to the BGS laboratory at Keyworth within 3 days of collection. The samples were analysed to determine the presence of total heterotrophs, total oligotrophs, fungi (as a check on sampling conditions), denitrifying bacteria, sulphate reducing bacteria and sulphur oxidising bacteria (Gardner and Ince, 1991). The work is qualitative and is designed to determine the range of microbial groups present.

4.2 Potential microbial groups

The pathogens are the best known group of bacteria that may occur in groundwater. These are bacteria which may survive in groundwater but which become pathogenic when they get into the human body. These and other bacteria may be removed from a water supply quite readily by disinfection (e.g. chlorine treatment). Some pathogens may develop best in anaerobic conditions whilst other pathogens require an aerobic environment. Pathogens have not been specifically identified in the current survey as they do not affect any biogeochemical processes within groundwater. However they are included in the general group of 'heterotrophs'.

Oligotrophic bacteria favour low nutrient conditions but are, in general, heterotrophic. Sulphur-reducing bacteria and denitrifying bacteria are of interest because these heterotrophs promote the reduction of sulphur and nitrogen species. They are both anaerobic, but as the water becomes increasingly reducing, the denitrifying bacteria decline in activity and the sulphate reducing bacteria become increasingly active. Indeed some denitrifying bacteria may survive in slightly aerobic conditions.

Some bacteria can use inorganic carbon as their carbon source and these are termed the autotrophs. The sulphur oxidising bacteria are of most interest in this group and they live in aerobic conditions. More information on subsurface microbiology and analytical techniques is given by Ehrlich (1981) and Bitton and Gerba (1984).

4.3 Results and discussion

The analytical results are summarised in Table 16. Both aerobic and anaerobic heterotrophic bacteria were present at all locations except St Helier Nursery and Jersey Milk where neither aerobes nor anaerobes were detected. Oligotrophic bacteria, having a lower nutrient concentration requirement than heterotrophic bacteria, were detected under aerobic conditions at all locations except Val de la Mare and Jersey Milk. Anaerobic oligotrophs were not detected at Chaise au Diable, Randall's Brewery or Grouville Spring. Denitrifying bacteria were detected at all sites except Jersey Milk and Randall's Brewery. Sulphate reducing bacteria were detected at States Farm (borehole), States Farm (well) and Randall's Brewery and an indication of growth was detected at Jersey Milk and Tesson Mill. Sulphur oxidising bacteria were detected at Atlantic Hotel, States Farm (well) and Grouville Spring with an indication of sulphur oxidisers at Chaise au Diable and Randall's Brewery.

Table 16. Summary microbiology results

Sample No.	Locality	Heterotrophs Aerobe (+/-)	Heterotrophs Anaerobe (+/-)	Oligotrophs Aerobe (+/-)	Oligotrophs Anaerobe (+/-)	Denitrifiers (a) An (+/-)	Denitrifiers (b) An (+/-)	SRB's (a) An (+/-)	SRB's (b) An (+/-)	Sulphur oxidisers (pH Drop) (+/-)
901323	Grouville Spring	+/-	+	-	-	+	+	-	-	-
901324	Jersey Milk	+	+	+	+/-	+	+	?	-	+
901326	First Tower Laundry	+	+	+	?	?	+	?	-	-
901327	La Chenee	-	-	+	+	?	+	?	-	-
901328	St Helier Nurseries	+	+	+	+	+	+	?	-	-
901329	States Farm Borehole	+	+	+	+	?	+	+	+	-
901330	States Farm Well	+	+	+	+	+	+	+	+	+
901331	Atlantic Hotel	-	-	-	-	-	-	?	+/-	-
901332	Vale de la Mare	+	+/-	+	+	+	+/-	+/-	+/-	-
901333	Tesson Mill	+	+	+	+	+	+	?	-	-
901334	Chaise au Diable	+	+	+	-	?	+	?	-	+/-
901335	Mushroom Farm	+	+	+	-	?	-	?	+	+/-
901336	Randall's Brewery	+	+	+	?	?	+	?	-	+

An = Anaerobic incubation
(a) = Solid medium
(b) = Liquid medium
\+ = Bacterial or fungal growth observed
\- = No growth observed
+/- = Indication of growth

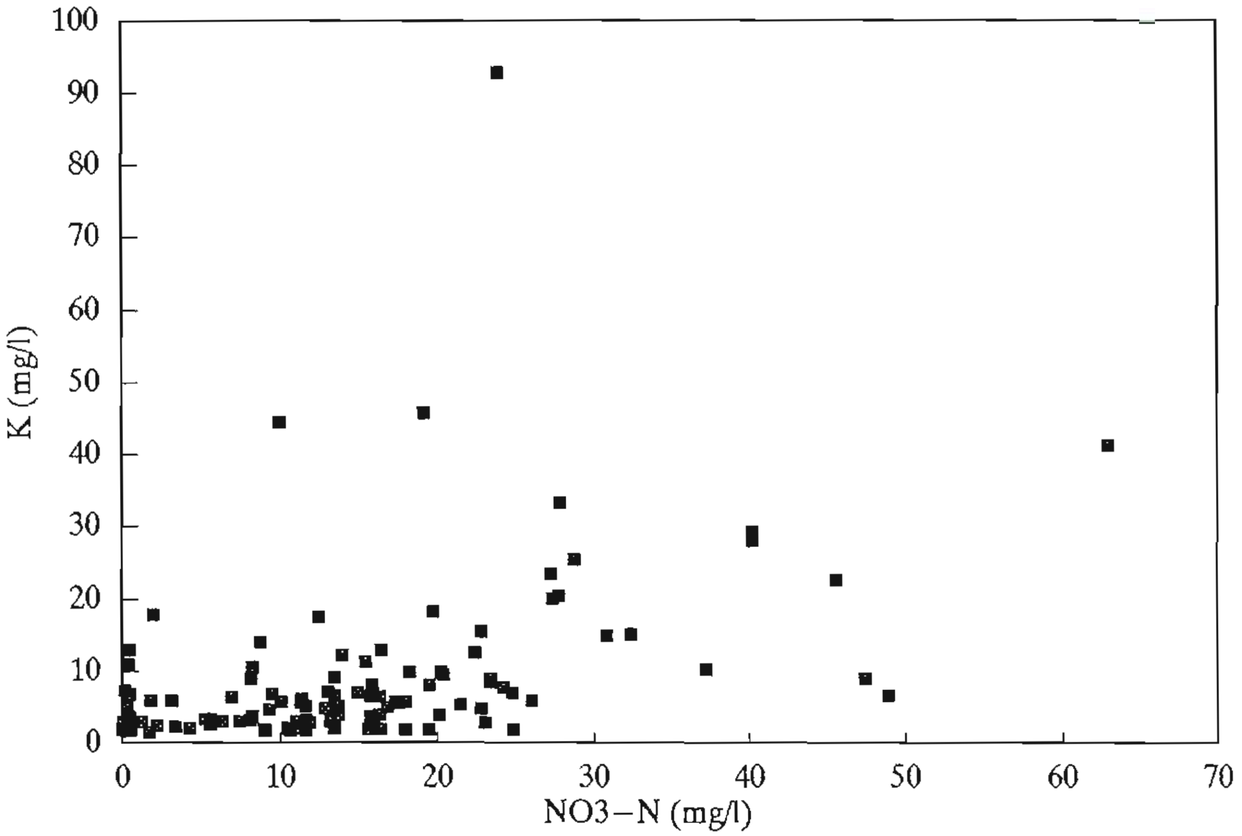
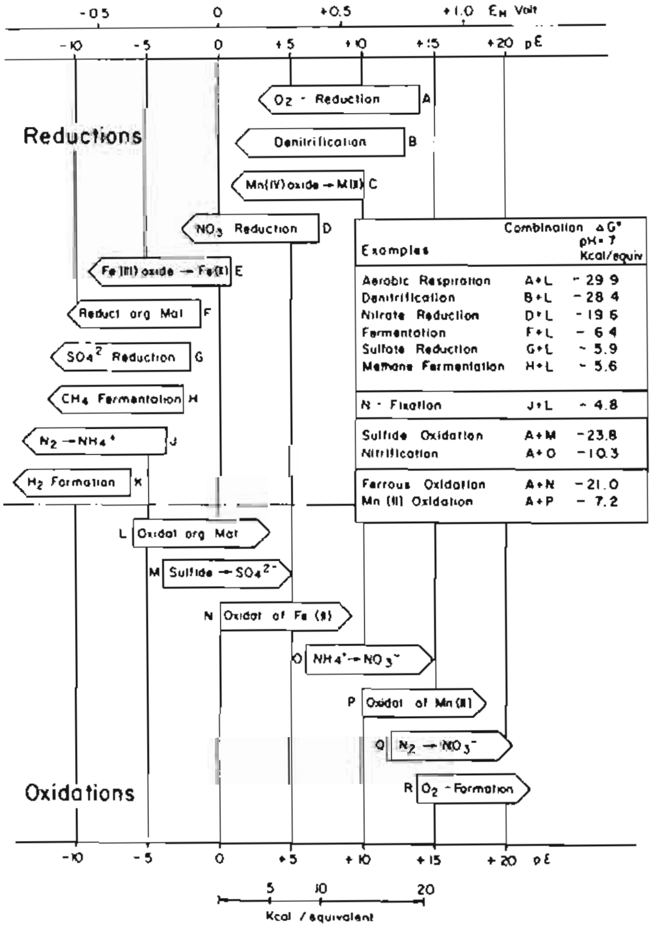


Figure 5.1 Variation of K with NO_3-N in Jersey groundwater samples from the summer 1990 survey



Examples	Combination	$\Delta G°$ pH = 7 Kcal/equiv
Aerobic Respiration	A+L	-29.9
Denitrification	B+L	-28.4
Nitrate Reduction	D+L	-19.6
Fermentation	F+L	-6.4
Sulfate Reduction	G+L	-5.9
Methane Fermentation	H+L	-5.6
N - Fixation	J+L	-4.8
Sulfide Oxidation	A+M	-23.8
Nitrification	A+O	-10.3
Ferrous Oxidation	A+N	-21.0
Mn (II) Oxidation	A+P	-7.2

Figure 5.2 Sequence of redox reactions under different redox potentials (after Stumm and Morgan, 1981)

Jersey groundwater samples discussed in Section 4 showed that populations of both heterotrophic and oligotrophic bacteria are generally present although their presence does not necessarily indicate that they are active and making any notable contribution to redox processes.

The thirteen samples investigated mostly contain denitrifying bacteria although it is notable that two of the samples of most reducing groundwater (Jersey Milk and Randall's Brewery) have either very few or no denitrifiers. This may be because NO_3 is present in concentrations too low for them to survive. Denitrifying bacteria are facultative anaerobes and as such are able to use O_2 as well as NO_3 as the terminal electron acceptor. However, the two reducing samples lacking these bacteria also have very low dissolved oxygen concentrations (<0.1 mg/l). It is therefore suggested that the low NO_3-N concentrations observed in the most reducing groundwaters have not been reduced principally by microbiological means.

Sulphate-reducing bacteria are also largely absent from the few Jersey samples analysed, probably because redox potentials are too high (i.e. groundwater is too oxidising) for optimal growth (Figure 5.2). Both sulphate- and nitrate-reducing bacteria are heterotrophic and hence require a substrate of organic carbon to survive. Although the organic C contents of Jersey groundwaters and host rocks are unknown, they are likely to be low in igneous and metasedimentary lithologies, despite the observation of a few carbon flakes in some horizons of the Jersey Shale Formation (Bishop and Bisson, 1989). It is therefore considered that whilst some redox processes may to an extent be microbiologically-aided in Jersey groundwaters, they are unlikely to be major controlling influences.

Some of the most reducing groundwaters sampled from Jersey are in the Eh range where such processes as oxygen, nitrate, Mn^{4+} and Fe^{3+} reduction are likely to to take place (Figure 5.2). The variation of NO_3-N with Eh in samples from the summer 1990 survey is presented in Figure 5.3. A correlation is clearly apparent, samples with Eh values below about 250 mV having low NO_3-N concentrations. It is tempting to suggest that the correlation is effected by NO_3-N reduction but it is also possible that the low-NO_3 samples were never actually polluted since the reducing waters are probably those which have circulated to greater depths, and may be older waters which have never been subjected to agricultural sources of pollution. This is to some extent supported by the fact that in general, low NO_3-N samples also have low K concentrations (Figure 5.1). The uncertainty cannot be resolved by investigation of pollution by organic compounds since these are low in almost all samples (shallow, oxidising sources as well as reducing sources). It is however believed that the good correlation in Figure 5.3 is more indicative of NO_3 reduction than of other processes, the process being more likely to be chemically- rather than microbiologically-mediated.

The variation of total Fe concentration with Eh is given in Figure 5.4. Fe is given as a log value because of the large range of observed concentrations. There is clearly a negative correlation, with high concentrations being restricted to the most reducing waters. Concentrations range down to detection limits in the more oxidising waters. Fe is therefore clearly redox-controlled in Jersey groundwater.

Figure 5.5 shows the compositions of Jersey samples in a conventional Eh-pH diagram. The location of the $Fe^{2+}/Fe(OH)_3$ boundary is determined by the activity of dissolved Fe in the system, higher activities resulting in an expansion of the Fe^{2+} field at the expense of $Fe(OH)_3$. Jersey groundwaters lie predominantly in the stability field of $Fe(OH)_3$ and any Fe present should

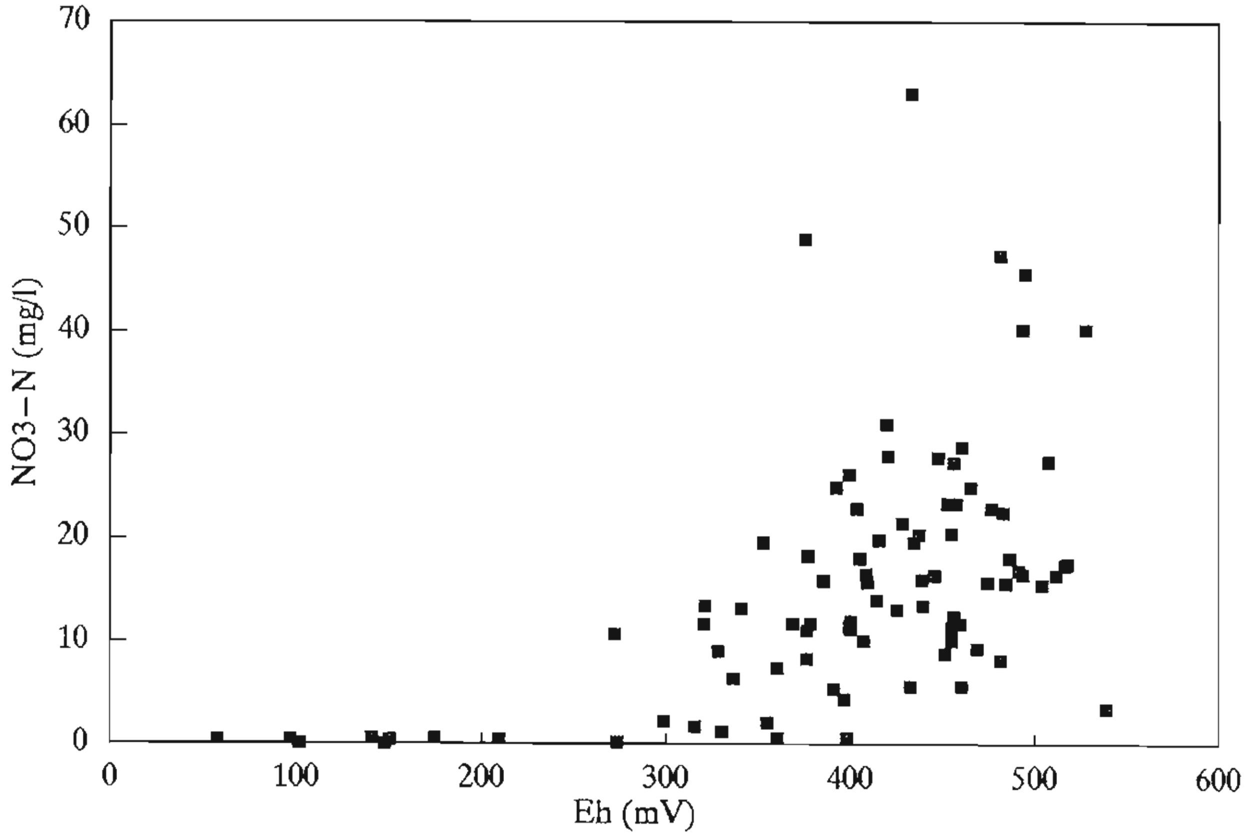


Figure 5.3 Variation of NO_3-N with Eh in Jersey groundwater from the summer 1990 survey

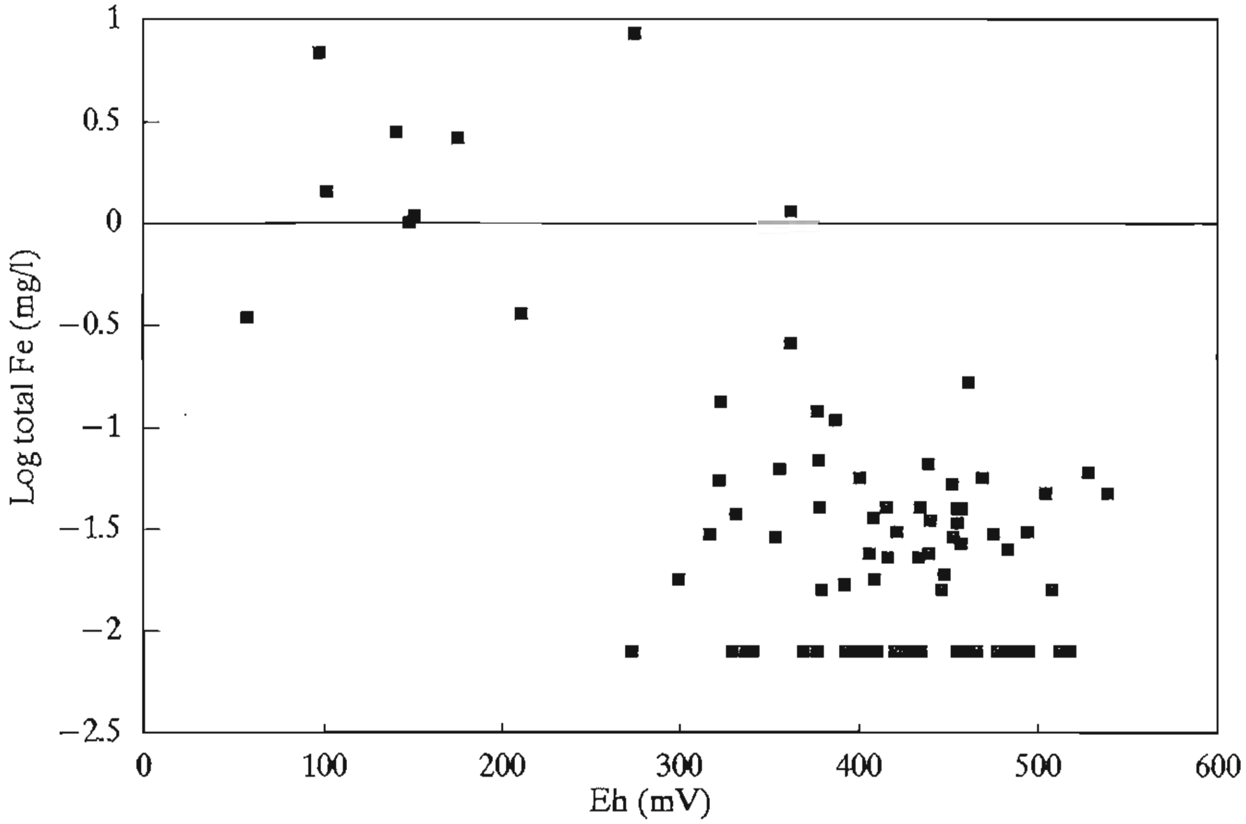


Figure 5.4 Variation of log total Fe with Eh in Jersey groundwater from the summer 1990 survey

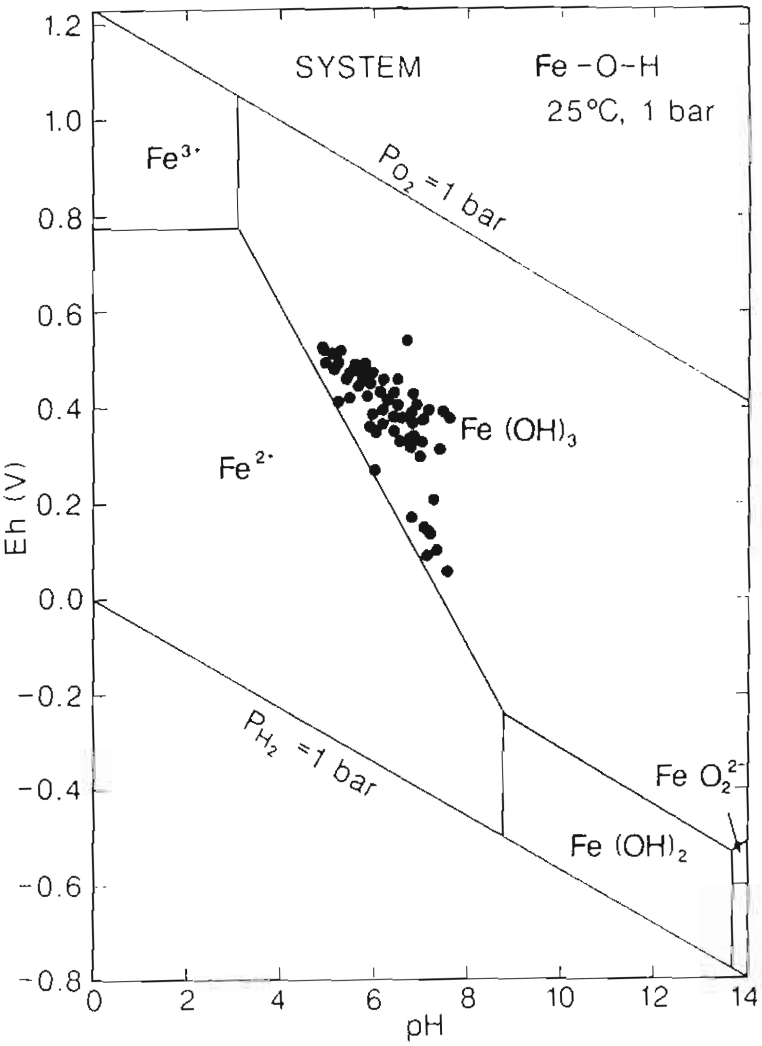


Figure 5.5 Eh-pH diagram for the system Fe-O-H at 25°C and 1 bar pressure. The diagram is constructed with Fe activity of 56 μg/l (after Brookins, 1989)

therefore be precipitated as hydroxide. This explains why Fe concentrations in most samples are relatively low and often below detection limits. The samples lying close to the Fe^{2+} boundary are those with higher dissolved Fe concentrations. In practice, some Fe concentrations in Jersey groundwaters are higher than thermodynamic controls predict, largely because of the presence of colloidal Fe.

The variation of Mn with Eh is shown in Figure 5.6. The correlation is less distinct than with total Fe but in general, oxidising waters have higher concentrations. Mn is therefore also influenced by redox processes.

Figure 5.7 shows the variation of SO_4 with Eh. No correlation is apparent for Jersey groundwater samples. The concentration of SO_4 does not therefore appear to be redox-controlled, probably because environmental conditions are insufficiently reducing for SO_4 reduction to occur. SO_4 concentrations are influenced more by water-rock interactions and saline intrusion.

As suggested earlier, low-Eh groundwaters in Jersey are probably those which have circulated to deeper levels away from supplies of atmospheric oxygen, having had sufficient residence times in the aquifer for reduction reactions to proceed. Despite a few sporadic occurrences of reducing waters in various parts of Jersey, most are apparently concentrated in the low-lying south and south-easterly coastal areas and in the river valley neighbouring St Saviour. Groundwater flow paths on the island are predominantly from north to south in response to relief patterns with discharge being predominantly along the south coast along with some local discharge along river valleys (Figure 6.1). Discharge of groundwater from deeper flow paths is therefore likely to upwell predominantly along these low-lying southerly areas, with some additional upwelling likely in low-lying river valleys. It is suggested that this is the dominant process controlling the distribution of groundwater with low Eh, NO_3 and dissolved oxygen and resultant high Fe and Mn concentrations in Jersey.

5.3 Water-rock interaction

Water-rock interaction processes strongly influence the chemical character of Jersey groundwater. Redox reactions have already been described in some detail and control particularly Fe and Mn, but additional processes such as ion exchange, dissolution and hydrolysis reactions are also important controls.

Following the groundwater-flow model (Figure 6.1), waters in the northern parts of the island are relatively young recharge waters having had little time for water-rock equilibration, with resultant low HCO_3 and poorly-buffered, acidic pH values. Those in the south on the other hand, have generally higher HCO_3 and other ion concentrations as a result of greater degrees of water-rock interaction. Water quality is apparently much more strongly controlled by residence time in the aquifer than by bedrock lithology. In this respect, it is notable that the zone of reducing waters in the St Saviour river valley area, thought to be older, deep-circulation waters, have high pH, Ca, HCO_3, Si and Ba as well as redox-influenced Fe and Mn concentrations. Such elevated concentrations may have been accumulated by water-rock interaction during prolonged residence times in the host rocks.

5.4 Saline intrusion

The impact of saline mixing effects on Jersey groundwater has been discussed in detail in Section 3.5. In general, mixing by intrusion along coastal fractures is highlighted as the most influential process. Whilst this is

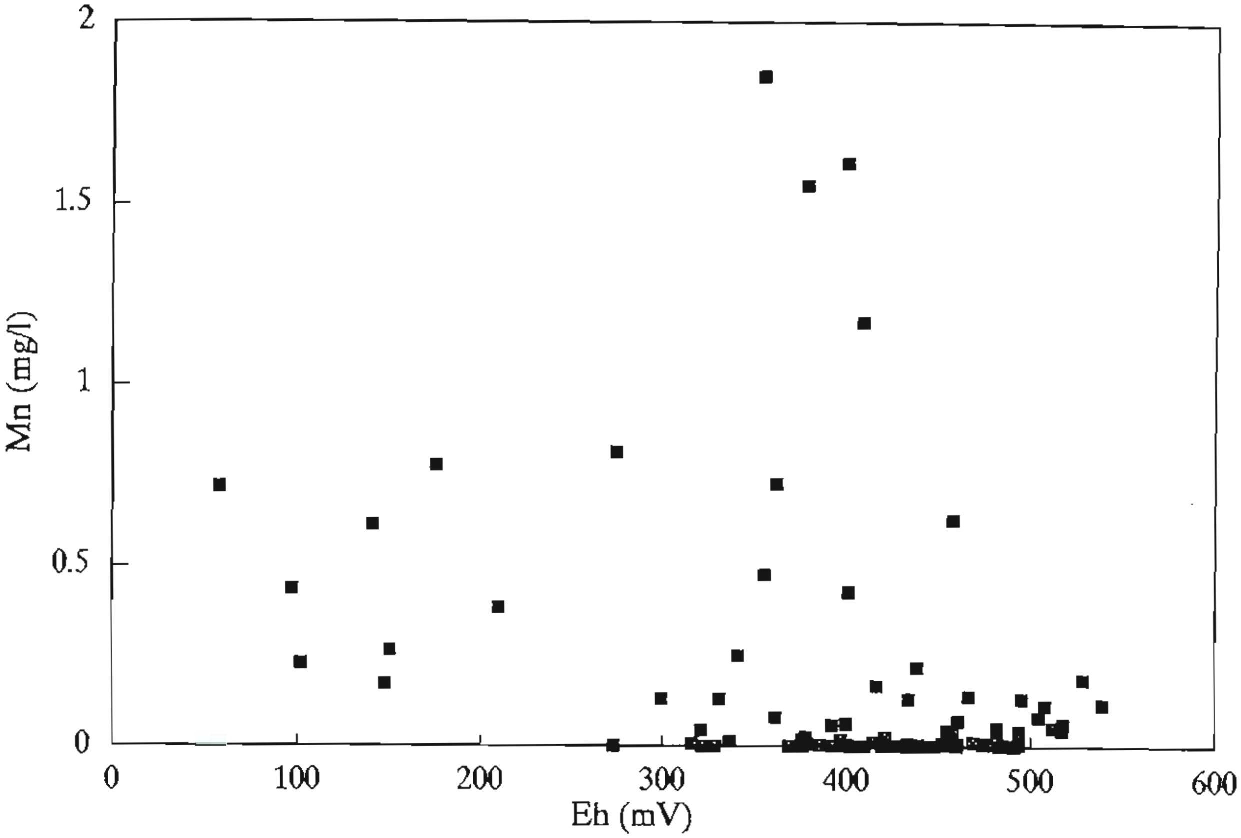


Figure 5.6 Variation of Mn with Eh in Jersey groundwater from the summer 1990 survey

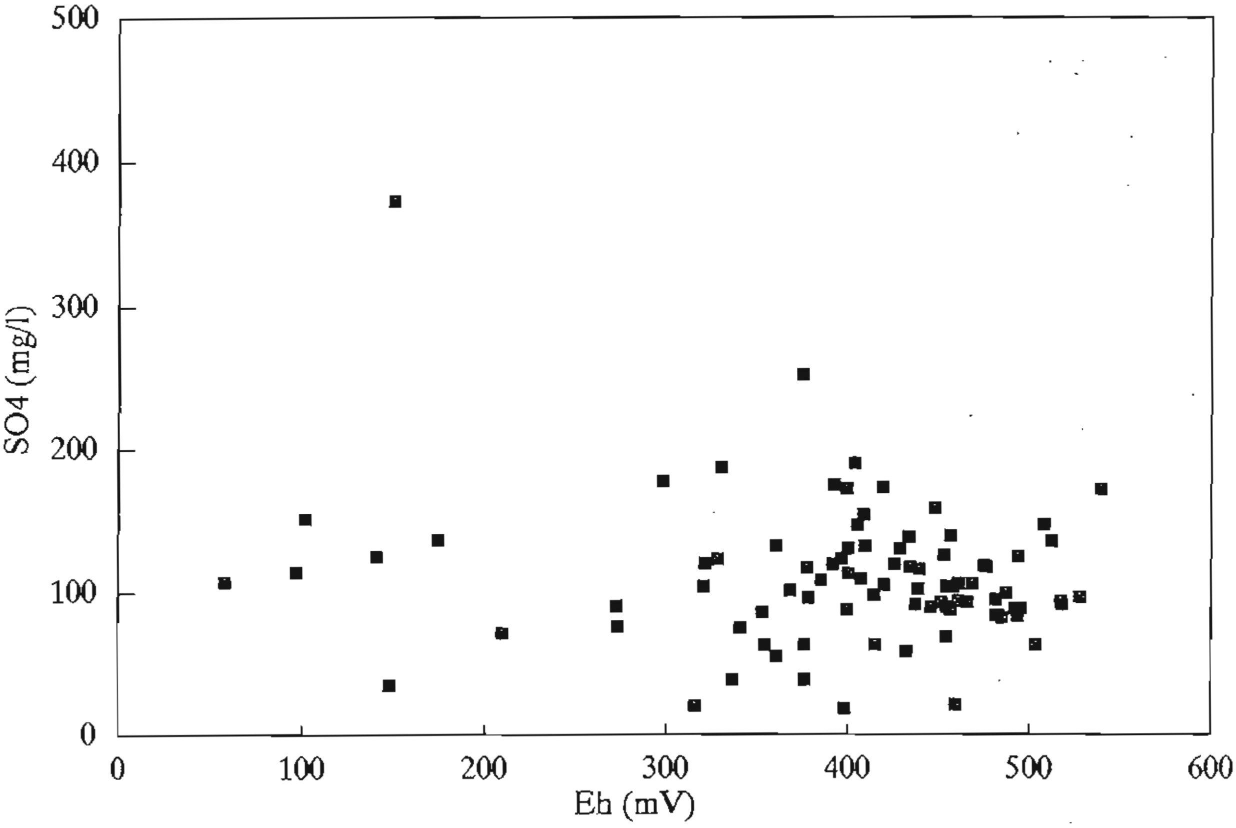


Figure 5.7 Variation of SO_4 with Eh in Jersey groundwater from the summer 1990 survey

apparently important in low-lying coastal areas, particularly in St Clement, Grouville and to the north of St Ouen's Bay, it does not occur at higher elevations and further inland because the hydraulic head of freshwater flowing out towards the sea is too high and the base of the aquifer is in any case above sea level. The seawater component of groundwater in the St Clement area is only small. Representative end member Cl concentration for groundwater is 50 mg/l and for seawater it is 19 000 mg/l. A typical "mixed" groundwater is Sefton Nursery (sample 901238) which has a Cl concentrations of 143 mg/l suggesting that less than 1% of the Cl is seawater derived. However, due to its extreme salinity even these small proportions can give rise to significant water quality problems if groundwater pumping in susceptible areas is continued unchecked.

Groundwater abstraction cannot be further developed in these areas as this would lead to enhanced upconing of saline water and resultant increased salinity problems.

Potential global warming giving a rise in sea level would further exacerbate the saline intrusion effects in the St Clement-Grouville areas and in narrow strips along other parts of the coast (e.g. St Ouen's). A rise in sea level of about 1 m would have no effect however on the quality of most of Jersey's groundwater.

6. OVER EXPLOITATION OR UNDER UTILISATION

6.1 Groundwater flow model

Groundwater flow takes place simply from areas where the water table is elevated to areas where it is not; from beneath higher ground to beneath lower ground. It discharges to surface wherever the water table intersects ground level. It follows that the main recharge areas must be high ground and the main discharge areas low ground. In Jersey there is a dominant north to south flow path with a lesser east-west element centred on individual valleys (Figure 6.1).

In the hard-rock formations found on Jersey, groundwater flow relies on the occurrence of dilated fissures in bedrock. Preferred flow paths will follow major features of disturbed ground. For example, a major series of faults underlies Val de la Mare between the sea and the reservoir (Mourant, personal communication 1990). This may divert water flowing southwards to the west and to St Ouen's Bay.

Most groundwater flow is relatively shallow (borehole evidence suggests between 10 to 40 m below ground level). A small component of flow takes a deeper flow path to upwell as chemically mature water potentially depleted in oxygen. Hydrogeochemistry is therefore a valuable tool with which to delineate areas of recharge, areas of shallow flow and areas where deeper flow paths emerge near surface as deep groundwater discharge.

Figure 3.5 shows that pH and electrical conductivity increase generally from north to south suggesting that groundwaters are younger in the north and older in the south. This is compatible with the basic north-south groundwater flow hypothesis. The same figure shows that oxygen is more abundant in the northern waters than in their older counterparts in the south. The distribution of low Eh values shows specific areas where waters totally depleted in oxygen occur: St Helier, St Saviour and Grouville. These are areas where upwelling of deeper flow path waters may be occurring. It should be stressed that dilution occurs along each flow path as local recharge takes place not only beneath the high ground but wherever the water table is below ground level. Nevertheless, the distribution of Ca, Na, HCO_3 and Cl (Figures 3.6 and 3.7) supports the argument that waters are more mineralised and therefore more mature in the south of the island.

The principle of north to south flow, recharging beneath high ground and discharging to low lying ground is only broken around St Saviour. Here a number of boreholes penetrate volcanic rocks and discharge mineralised, low Eh waters, at higher than normal yields. These are deeper groundwaters which may be rising to the surface here rather than along the south coast of the island because the rock is locally more permeable than elsewhere, providing a line of least resistance to local discharge.

6.2 Resources at risk

The whole bedrock aquifer system is at risk. The available groundwater resources on Jersey are under attack from two separate directions, over-exploitation and pollution.

The theoretical renewable resource amounts to some 5.5×10^6 m^3/a although additional water is available in storage for use between recharge events. The renewable resource is divided between estimated abstraction by pumping of some 3.7×10^6 m^3/a and baseflow (and spring seepage) of 1.8×10^6 m^3/a. It is not

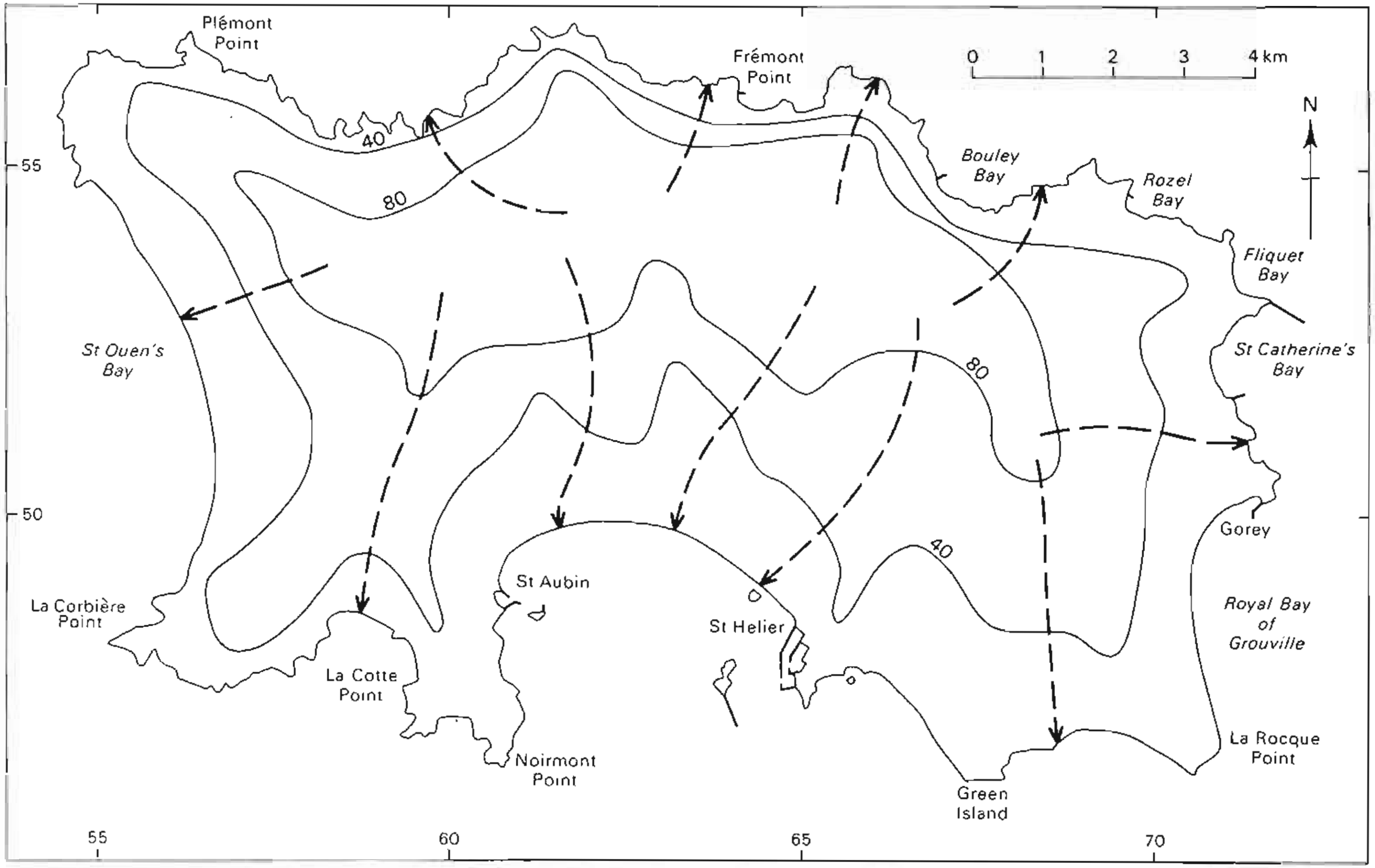


Figure 6.1 Groundwater flow model - piezometric contours (m above Datum) and schematic groundwater flow paths

practical to develop an abstraction system of adequate efficiency to take 70% of the renewable resource without depleting baseflow at least locally if not island-wide. Indeed it is probable that this level of abstraction, if it is correct, is eroding baseflow and mining groundwater from some areas if not from across the whole island.

It is not possible from short-term measurements to quantify erosion of baseflow particularly in an island whose small surface catchments regularly cease to flow. However, there are many reports throughout the summers of 1989 and 1990 of boreholes and wells drying up which were previously thought to be reliable. Many spring flows diminished during these summers and many ceased to flow. Both summers were preceded by dry winters, but available hydrograph data suggest that some recharge did occur in the winters.

Reports of a declining water table are not universal. The worst affected areas are the higher ground of the north where the depth to water table is inevitably greatest and dilation of available fissures is limited by increased overburden (Figure 6.2). Least affected areas are those in lower lying areas where the water table cannot easily decline unless throughflow were to cease altogether. Nevertheless, the evidence suggests that the water table in the north is declining with each succeeding summer and that the resource is not able to replenish itself completely because of general over-exploitation.

Declining water levels may be accompanied by deteriorating water quality. Insufficient historical data are available to substantiate this but it may be that poor water quality at States Farm and St Saviour is exacerbated by local overpumping and upwelling of older mineralised water.

Pollution of groundwater by agricultural nutrients and locally also by sewage from defective soakaways is reflected in the nitrate concentrations of many groundwaters. The juxtaposition of a shallow fissured aquifer and intensive agriculture requires careful management. This has not happened on Jersey and pollution of groundwater is likely to continue until restrictions are placed on land use.

The pollution problem is aggravated by increased use of water throughout the island. Demand has increased not only for irrigation but also for domestic and other purposes. Recycling of water through the groundwater system may help to extend the available resource but it increases the likelihood of carrying surface pollutants in solution back to the water table.

Many reducing waters contain no nitrate. Many of these waters may, however, be polluted as the nitrate has been reduced by bacteria and by chemical reduction. Other nutrients or organic compounds may still be present.

For the most part the effective base of Jersey's shallow aquifers in bedrock is above sea level. Overpumping cannot, therefore, promote widespread invasion of the aquifers by marine water. Evidence of some mixing with seawater (Section 3.5) suggests that parts of St Clement and Grouville and an area north of St Ouen's Bay are already contaminated. Here some sea water is flowing inland through selected fissures down the hydraulic gradient towards centres of pumping (Figure 6.2).

6.3 Under developed resources

There are no areas where the bedrock aquifer is underdeveloped. However, the sand aquifer at St Ouen's Bay can support greater abstraction from new wells around the public supply wellfield at Mont a la Brune (Section 2.4). Computer

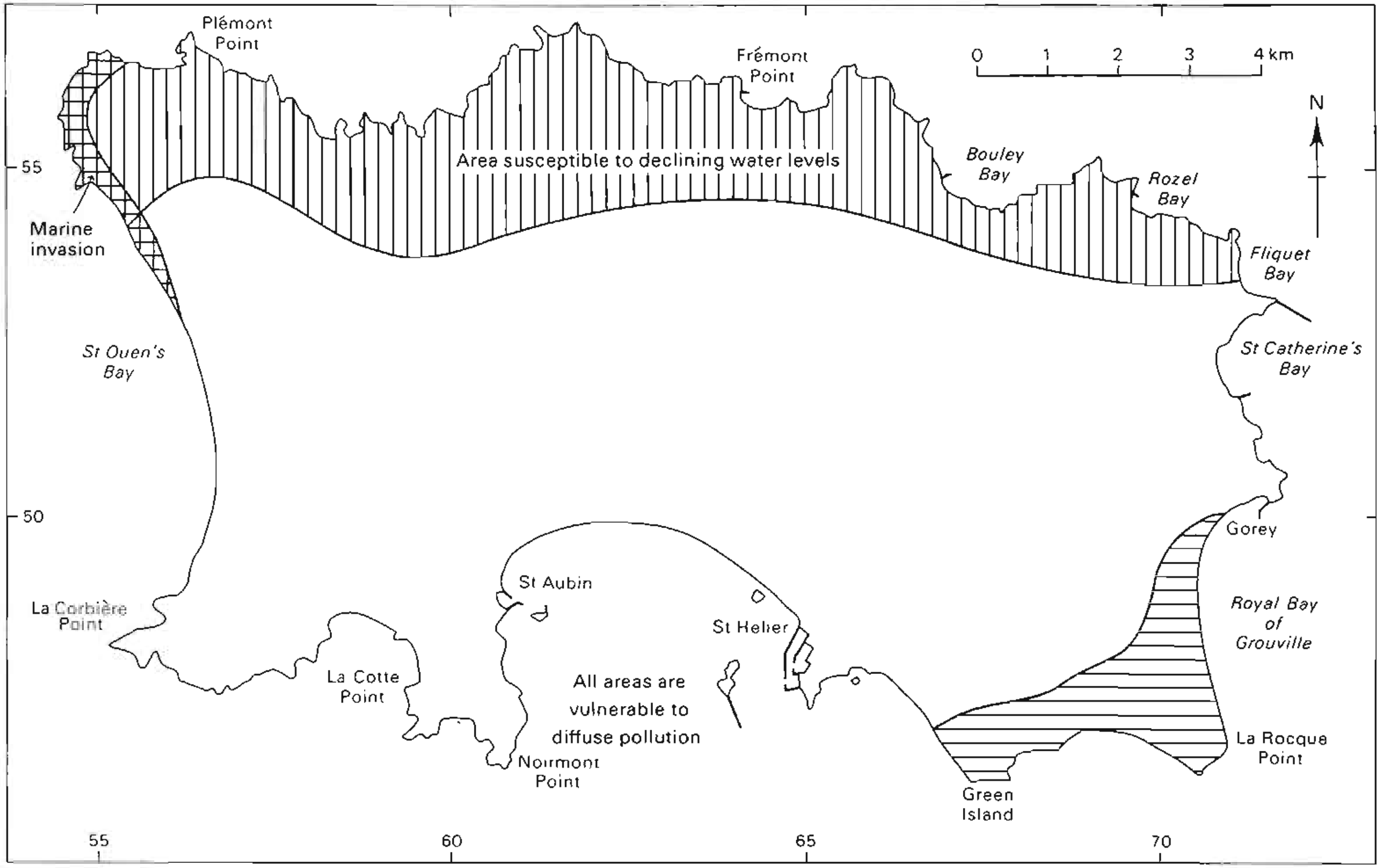


Figure 6.2 Groundwater at risk

modelling has shown that an additional 600 m^3/d can safely be abstracted here. New and proposed golf courses on the sand aquifer will increase the total take but these projects will not interfere with Mont a la Brune. The computer model demonstrates that the saline interface cannot invade the aquifer because the water cannot be abstracted from the shallow boreholes at a sufficiently high rate. The sand aquifer, is therefore, self regulating. Besides, return infiltration from grass irrigation will effectively lessen the total take by the golf courses.

6.4 The future

Except for the sand aquifer at St Ouen's, the groundwater resources of the island are being overpumped and are not wholly replenished in a normal recharge year. All the bedrock groundwater is at risk from diffuse agricultural pollution; there is widespread evidence of elevated nutrient levels. Overpumping may only have started to occur in the last few years perhaps from the mid 1980's onwards. Agricultural pollution has a longer history and even if the use of nitrogen fertiliser was prohibited from now on, the legacy would continue to affect groundwater for many years to come before pollution diminished to an acceptable level.

If the present situation is allowed to continue unchecked, it is likely that groundwater quality will deteriorate and contaminated baseflow may threaten the quality of surface waters. Declining water levels in selected areas would lead to increased problems of derogation between neighbours. Marine intrusion of some areas has already begun and this problem will increase with time so that more brackish conditions will prevail in parts of St Clement and Grouville.

Jersey needs to take stock of the problems identified in this report. In doing so it should recall that this survey is a reconnaissance survey and that estimates of theoretical renewable resource, total groundwater abstraction and baseflow are preliminary figures that will need to be refined as new data become available. It may be that the imbalance between pumping and renewable resource may in reality be less than the estimate; it is easy to increase the estimated total abstraction merely by increasing the number of boreholes believed to be pumping at present.

The main need in the future is for reliable data. Monitoring of pumping volumes and selected groundwater levels should continue and the network may expand to include additional water-level monitoring sites. Water quality monitoring should commence at selected pumping wells to quantify change in quality with time due to marine invasion, declining water levels, and diffuse pollution. Data collection should continue.

A minimum of three years data will enable refinement of many of the conclusions in this study. The need for continued data collection does not, however, dilute the recommendations made in this report, and in the meantime steps can be taken to alleviate the current attack on the groundwater resource. These may include restricting groundwater use and controlling agricultural practice. A blanket restriction on groundwater use is neither practical nor useful. Restrictions by means of licence could, however, be applied to all sources from which more than 3 m^3/d were drawn on average. Using this cut-off the estimated 4,000 domestic sources are excluded but the majority abstraction from the remaining 600/700 boreholes is notified and in places restricted. It may be useful to license all newly drilled boreholes and introduce some form of water law in order to manage the groundwater resources.

REFERENCES

BGS In prep. Hydrogeological Map of Jersey, 1:25,000 scale. (Keyworth: BGS)

Billings, G K and Williams, H H 1967. Distribution of chlorine in terrestrial rocks - a discussion. *Geochemica et Cosmochimica Acta* 31, 2247.

Bishop, A C and Bisson, G 1989. *Classical Areas of British Geology Jersey: description of 1:25 000 Channel Islands Sheet 2* (London: HMSO for BGS).

Bishop, A C and Key, C H 1983. Nature and origin of layering in the diorites of SE Jersey, Channel Islands. *Journal of the Geological Society, London* 140, 921-937.

Bitton, G and Gerba, G P 1984. *Groundwater Pollution Microbiology*. (NY: Wiley).

Bland, A M 1984. Field relationships within the South-west Jersey Granite Complex. *Proceedings of the Usher Society* 6, 54-59.

Calder, I R, Harding, R J and Rosier, P T W 1983. An objective assessment of soil moisture deficit models. *Journal of Hydrology* 60, 329-355.

Casimir, M and Henson, F A 1955. The volcanic and associated rocks of Gifford Bay, Jersey, Channel Islands. *Proceedings of the Geological Association* 60, 30-50.

Champ, D R, Gulens, J and Jackson, R E 1979. Oxidation reduction sequences in groundwater flow systems. *Canadian Journal of Earth Sciences* 16, 12-23.

Cox, K G, Bell, J D and Pankhurst, R J 1979. Petrology of the Igneous Rocks. (London: Unwin).

Craig, H 1961. Isotopic variations in meteoric waters. *Science* 133, 1702-1703.

Darling, W G and Bath, A H 1988. A stable isotope study of recharge processes in the English Chalk. *Journal of Hydrology* 101, 31-46.

Edmunds, W M, Cook, J M, Darling, W G, Kinniburgh, D G, Miles, D L, Bath, A H, Morgan-Jones, M and Andrews, J N 1987. Baseline geochemical conditions in the Chalk aquifer, Berkshire, UK: a basis for groundwater quality management. *Applied Geochemistry* 2, 251-274.

Edmunds, W M and Kinniburgh, D G 1988. Tamar and Torridge groundwater quality and baseflow survey. BGS Report (unpub).

Ehrlich, H L 1981. *Geomicrobiology*. (NY: Marrel Dekker).

Feth, J H 1981. Chloride in natural continental water - a review. *USGS Water Supply Paper* 2176.

Foster, I D L, Ilbery, B W and Hinton, M A 1989. Agriculture and water quality: a preliminary examination of the Jersey nitrate problem. *Applied Geography* 9, 95-113.

Foster, S S D and Crease, R I 1974. Nitrate pollution of Chalk groundwater - a hydrogeological appraisal. *Journal of the Institution of Water Engineers* 28, 178-194.

Gale, I N and Smedley, P L 1989. Iron in groundwater - a survey of the extent and nature of the problem and methods of removal. BGS Technical Report WD/89/29.

Gambell, A W and Fisher, D W 1966. Chemical composition of rainfall, eastern North Carolina and south-eastern Virginia. *USGS Water Supply Paper* 1535-K.

Gardner, S J and Ince, S R 1991. Microbiological analysis of groundwater samples from Jersey. BGS Technical Report WE/91/1.

Helm, D G 1983. The structure and tectonic evolution of the Jersey Shale Formation, St Ouen's Bay, Jersey, Channel Islands. *Proceedings of the Geological Association* 94, 201-216.

Helm, D G 1984. The tectonic evolution of Jersey, Channel Islands. *Proceedings of the Geological Association* 95, 1-15.

Helm, D G and Pickering, K T 1985. The Jersey Shale Formation - a late Precambrian deep-water siliciclastic system, Jersey, Channel Island. *Sedimentary Geology* 43, 43-66.

Hem, J D 1985. Study and interpretation of the chemical characteristics of natural water. *USGS Water Supply Paper* 2254.

Hem, J D and Cropper, W H 1959. Survey of ferous-feric chemical equilibria and redox potentials. *USGS Water Supply Paper* 1459-A.

Hem, J D, Robertson, C E, Lind, C J and Polzer, W L 1973. Chemical interactions of aluminium with aqueous silica at 25°C. *USGS Water Supply Paper* 1827-E.

IGS 1982. Jersey, solid and drift geology map, 1:25,000 scale. (Keyworth: IGS).

James, I F 1989. Water supply management on the island of Jersey. *Proceedings of the Commonwealth Engineers Council Seminar*, Nicosia, October 1989.

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

Kraynov, S R and Solomin, G A 1983. Iron-bearing sub-surface waters and the problems of water supply for household use and drinking. *International Geology Review* 25, 601-608.

Lawrence, A R 1983. The groundwater resources of St Helena. IGS Report WD/OS/83/12.

Lerner, D N, Issar, A S and Simmers, I 1990. *Groundwater Recharge*. International Contributions to Hydrology. Vol. 8. International Association of Hydrogeologists.

Littlejohn, G S, Newman, R L and Kettle, C E 1989. Grouting to control groundwater during basement construction at St Helier. *Ground Engineering* January 1989, 22-30.

McDonald, M G and Harbaugh, A W 1984. A modular finite difference groundwater flow model. USGS National Center, Reston VA.

Meteorological Department 1989. *Jersey Weather 1988.* (St Helier: States of Jersey Harbours and Airport Committee).

Moss, M L and Mellon, M G 1952. Colorimetric determination of iron with 2,2′-bipyridyl and with 2,2′,2″-terpyridyl. *Industry and Engineering Chemistry* (Anal Ed.) 14, 862-865.

Robins, N S 1989. Groundwater resources of Jersey: a review with recommendations for further study. BGS Technical Report WD/89/27.

Robins, N S, Lawrence, A R and Cripps, A C 1990. Problems of ground-water development in small volcanic islands in the Eastern Caribbean. *Proceedings of the International Symposium on Tropical Hydrology and 4th Caribbean Islands Water Resources Congress*, San Juan, Puerto Rico, July 1990.

Smedley, P L, Bromley, A V, Shepherd, T J, Edmunds, W M and Kay, R L F 1989. Fluid circulation in the Carnmenellis Granite: hydrogeological, hydrogeochemical and palaeofluid evidence. In: *Geochemistry of the Rosemanowes Hot Dry Rock Geothermal System Vol. 4.* BGS Research Report SD/89/2.

Stumm, W and Morgan, J J 1981. *Aquatic Chemistry.* (NY: Wiley).

T & C Hawksley 1976. Report on groundwater resources. T & C Hawksley, Aldershot.

Thurrell, R G 1972. The sand resources of St Ouen's Bay Jersey. Report Institute of Geological Sciences (unpub).

Water Resources Association 1972. Derivation of desalination control rules for the Jersey New Waterworks Company Ltd. The Water Resources Association, Medmenham.

Watson Hawksley 1986. St Ouen's Bay aquifer. Preliminary assessment of annual water balance. Watson Hawksley, Aldershot.

Whitehead, H C and Feth, J H 1964. Chemical composition of rain, dry fallout and bulk precipitation in Menlo Park, California, 1957-9. *Journal of Geophysical Research* 69, 3319-3333.

WHO 1972. Guidelines on drinking water quality. (Geneva: WHO)

Williams, A T 1990. St Ouen's Bay: numerical modelling of the groundwater resource of part of the sand aquifer. BGS Technical Report WD/90/40.

APPENDIX I. Physical data for Jersey groundwater samples collected during summer 1990.

Sample	Locality	NGR	Well depth (m)	Water level (m)	Elevation (m)	Discharge (l/s)	Drawdown (m)	Landuse	Lithology
901131	Greystones	557740454080	3.1	1.84	88	1.3		4	GT
901132	Les Mauves	556720454990	12.2		85	0.5		1	GT
901133	Jersey Racecourse	554900455950	128.0		76	1.5		3	GT
901134	A5 St Ouens Bay	557020450230	15.8	7.5	11	4.5	1.65	3	SA
901135	Val de la Mare	557700451840	54.9		40	0.6	45.0	3	SH
901136	Lobster Pot	554920454840	144.8		30	1.0		4	SH
901137	La Pointe	556000455720	21.3		85	0.3		4	GT
901138	Le Bas de l'Etaque	555340454540	57.9	1.70	8	3.0	1.15	4	SH
901139	Atlantic Hotel	556560448940	76.2		58	0.0		3	SAGT
901140	La Moye Golf Course	557200449400	54.9		67	2.5		3	SAGT
901141	Villa Martinique	556160453670	65.8		12	0.0		4	SAGT
901142	Radar Station	556130447700	91.4	16.0	46	1.5	8.40	3	GT
901143	Val de la Mare Farm	557520450790	39.6		25	0.0		4	SASH
901144	Les Quennevais	558050449560	61.0		70	2.0		3	SAGT
901145	St Peters Nurseries	559920450980			82	0.0		1	SH
901146	Geranium Farm	556760448020	2.4	0.5	61	0.4		4	GT
901147	Holiday Village	560180447180	3.0		30	0.0		5	GT
901148	Emahroo	559480449820			73	0.5		3	SH
901149	Quennevais Camp Site	558020450420	76.2		70	2.6		4	SASH
901150	Priory Inn	560660455780			88	0.0		4	GT
901151	Mushroom Farm	561260451630	18.3		49	0.3		3	SH
901152	West View Hotel	560720454400	45.7		100	0.0		4	GT
901153	Besco Laundry	561200450000	4.6		9	0.8		3	SASH
901154	Portelet Hotel	559900447600			30	0.0		3	GT
901155	Les Bourgeons	562400451260	68.6		70	1.0		4	SH
901156	Ville Bagot	557870455060	7.6	3.6	70	0.3	1.0	3	GT
901157	Warwick Farm	564990451860	45.7	9.0	97	0.4		1	VL
901158	St Georges Estate	556360455450			82	0.0		3	GT
901159	Overdale Hospital	564470449450	57.9		64	0.0		2	VL
901160	St Helier Nurseries	564720450710	45.7		76	0.5		4	VL
901161	Stonewall Farm	566070451080	30.5		70	0.0		3	VL

Sample	Locality	NGR	Well depth (m)	Water level (m)	Elevation (m)	Discharge (l/s)	Drawdown (m)	Landuse	Lithology
901162	First Tower Laundry	563900449470	42.7		9	0.0		2	SASH
901163	Glen Hotel	565320450300	5.5	2.44	34	0.0		3	VL
901164	Harvest Barn	565010451010	2.9	1.5	58	0.4	0.1	3	VL
901165	Trinity Manor	565500453280	18.3	6.6	104	0.0		3	VL
901166	First Tower Park	563380449990	61.0		13	1.2		2	SH
901167	Parade Park	564870448980	45.7		9	0.0		2	SASH
901168	Mon Bijou	558080453120	25.0	4.6	88	0.2	0.9	4	SH
901169	Creaux Cottage	558490454410	2.5	1.9	73	0.1	0.1	3	GT
901170	Creaux Cottage	558490454410			73	0.0		3	GT
901171	Greenhills Hotel	560760452540	2.1	1.45	85	0.1	0.08	3	GT
901172	Maison Aleval	561020452540	2.42	1.42	85	0.1	0.13	3	GT
901173	Clifton	563090450640	67.1		36	0.8		1	SH
901174	Bon Air Stables	562650453910		2.68	106	0.1	2.92	3	GT
901175	Coronation Park	562590449990	36.6		9	0.0		3	SASH
901176	Rose Farm Camp Site	559630448830	39.6		58	0.0		3	GT
901177	Greywings	559900453800	30.5	5.2	92	0.0		4	GT
901178	L'Auberge du Nord	562820455790	54.9	4.8	104	0.0		3	GT
901179	Apple Barn	559550452320	31.7	3.7	88	0.0		4	SH
901180	Silver Jubilee Centre	559190455040	79.3	11.8	83	0.1		4	GT
901181	Beechlands	562400453180	6.2	3.1	101	0.1	0.1	3	SH
901182	Casa Mariana	564710452430	46.2	8.9	100	0.2		1	VL
901183	Oakvillas	564820453630	7.1	3.26	113	0.6	0.18	4	VL
901184	Le Couvent	563740452940	23.2	8.0	91	<0.1.		3	SH
901185	Redwood	563210455400	14.1	1.74	109	0.1	0.97	4	GT
901186	Le Rondin Cottage	564060454150	4.2	3.12	109	0.1	0.24	3	VL
901187	Greenfields	561180454360	18.3	4.56	97	0.0		3	GT
901188	Ronez Quarry	561910456640	30.1	10.02	99	0.0		3	GT
901189	Greenfields Tomatoes	556480454700	13.5	5.42	103	0.3	0.11	4	GT
901190	Highfield Hotel	565640454600	29.8	16.26	124	0.5		4	VL
901191	Ferndale	558630451350	21.3	4.80	79	0.5	1.05	4	SH
901192	Highfield Lane	566930450790	29.9		58	0.2		5	VL
901193	4 Victoria Village	566930452170			82	0.5		2	VL
901194	Summerhill	567100454060	24.2	13.64	107	0.5	0.44	3	VL

Sample	Locality	NGR	Well depth (m)	Water level (m)	Elevation (m)	Discharge (l/s)	Drawdown (m)	Landuse	Lithology
901195	States Farm BH	566050454000	27.4		110	2.0		4	VL
901196	States Farm W	566030454080	11.6	6.54	110	0.0		4	VL
901197	La Mare Vineyards	560700455310	8.0	6.25	95	0.1	0.08	4	GT
901198	Aviemore	563570452200	22.5	5.63	79	0.1	1.13	4	SH
901199	Le Petit Clos	567710453090	21.5	6.73	104	0.2	0.97	4	VL
901200	Jersey Milk	567360450010	64.0	18.55	70	3.0		2	VL
901201	Petite Port Cottage	565990455680	42.8	14.6	86	0.1	13.4	3	VL
901202	Gorsefields	565140455400	24.9	5.84	123	0.1	4.16	5	VL
901203	Dr Millar	566220452090	39.8	7.96	92	0.2	0.10	3	VL
901204	Vallee de Rozel	569300453740	37.3	17.79	70	0.3	2.19	3	CG
901205	Bistro Frere	570010454270	109.7	25.30	36	0.5		5	CG
901206	Meadou Springs	568370452280	15.0	5.00	85	2.0	5.32	4	VL
901207	Les Jardins	571070453520	4.9	1.83	21	0.1	0.04	4	CG
901208	2 Clos du Vivier	569360452700	38.1	10.7	76	0.2		2	VL
901209	Manor Farm	570410453120	13.6	10.85	59	0.3	0.15	4	CG
901210	Oakbank	570460452270	45.7	6.13	22	0.1	1.85	4	CG
901211	Hougue Bie Nursery	568370450260	7.6	6.12	85	0.5	0.0	4	VL
901212	Combie Flowers	570060450560			49	0.0		4	VL
901213	La Huitieme	568960451320	18.6	7.29	75	0.2	3.06	4	VL
901214	Tesson Mill	561610450780	55.0	1.0	16	1.0	50.0	4	SH
901215	Poplar Avenue	568380451520	6.1	4.38	84	0.1	0.12	2	VL
901216	La Chenee	569900451480	20.4	2.18	62	0.2	5.52	3	VL
901217	Canning Factory	566880450230	39.9	14.2	76	2.0	7.91	2	VL
901218	Queens Valley	569760449940	61.0	30.0	24	2.0		3	VL
901219	La Chaumire	568600449020	36.0	4.70	49	0.2		4	SH
901220	Les Mourier	561140455400	41.4	0.19	79	0.2	5.21	4	GT
901221	Chaise au Diable	566600451580	54.9		61	3.8	36.6	5	VL
901222	Roseland	566780449380	36.6	12.01	66	2.5	0.54	3	VL
901223	A E Smith	566930448430	61.0		22	2.5		2	GT
901224	Normandie	569980447630		6.30	12	0.1	0.0	1	GT
901225	Samares	567380447480	3.4	1.32	12	0.2	0.0	4	DI
901226	Royal Golf Club	570270449010	18.0	3.28	6	0.5		3	GT
901227	La Ferme	570620447320	9.9	2.83	5	0.1	0.17	4	GT

Sample	Locality	NGR	Well depth (m)	Water level (m)	Elevation (m)	Discharge (1/s)	Drawdown (m)	Landuse	Lithology
901228	Merton Hotel	566100448100	44.2	15.27	37	0.0		2	GT
901229	Randalls Brewery	565000449010	27.4	3.3	9	0.9		2	SASH
901230	Grouville Spring	568040448140	2.6	1.55	33	0.0	0.0	3	GT
901231	Le Coie Hotel	565760449370	20.7		12	0.7		2	SASH
901232	Ann Street Brewery	565750448830	30.5	2.44	9	3.2		2	SASH
901233	Fort Regent Centre	565290448220	92.1	30.0	10	0.3		2	GT
901234	La Motte Garages	568310447060	22.3	3.50	9	0.0		2	DI
901235	Le Puits	569430448400	2.7	2.14	20	0.6	0.0	4	DI
901236	La Mervelle	571070450780	38.1		29	0.0		4	VL
901237	Homefields Farm	569380447420	42.7	15.33	18	1.9		4	GT
901238	Sefton Nursery	567490446600	17.9	4.06	7	0.0		4	DI
901239	Chateau la Chaire	569450454230	57.9		23	0.0		3	CG

Landuse codes: 1: glasshouses
2: urban
3: grassland
4: arable
5: woodland

Lithology codes: CG: conglomerate
DI: diorite
GT: granite
SA: sand
SH: shale
VL: volcanic rocks

APPENDIX II. Major-element data for Jersey groundwater samples from the summer 1990 survey.

Sample	Locality	NGR	SEC	Eh	O_2	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3-N
			uS/cm	mV	mg/l		mg/l							
901131	Greystones	557740454080	710	508	7.7	5.29	43.2	20.0	60.7	28.8	9	147	90.7	27.4
901132	Les Mauves	556720454990	700	448	6.5	6.09	58.2	20.3	67.1	23.4	31	158	90.4	27.8
901133	Jersey racecourse	554900455950	940	528	7.8	4.95	94.6	29.2	60.3	23.8	3	96.1	170	40.2
901134	A5 St Ouens Bay	557020450230	410	316	8.2	7.41	32.0	1.5	67.6	5.8	179	19.8	58.4	1.7
901135	Val de la Mare	557700451840	635	337	7.1	6.77	71.1	2.9	72.9	19.0	190	38.3	132	6.4
901136	Lobster Pot	554920454840	990			7.15	116	5.8	100	15.2	178	57.4	238	1.8
901137	La Pointe	556000455720	800	457	3.0	5.52	66.2	23.4	43.7	29.1	15	139	98.9	27.3
901138	Le Bas de L'Etaque	555340454540	960		0.7	5.79	109	45.6	60.5	21.0	25	116	230	19.2
901139	Atlantic Hotel	556560448940	585	361	0.5	6.22	74.2	1.9	41.4	7.5	128	54.5	93.4	0.6
901140	La Moye Golf Course	557200449400	660	377	5.4	7.13	38.4	3.6	102	8.0	229	38.5	72.9	8.3
901141	Villa Martinique	556160453670	820			7.40	69.7	3.2	97.0	20.6	200	49.5	159	8.1
901142	Radar Station	556130447700	650	399	1.5	7.09	61.2	1.6	60.0	11.2	173	18.4	119	<1.0
901143	Val de la Mare Farm	557520450790	885	429	6.8	6.86	74.6	5.3	80.6	21.4	78	130	124	21.5
901144	Les Quennevais	558050449560	425	460	2.8	6.51	47.1	1.6	42.1	9.4	129	20.7	53.6	11.7
901145	St Peters Nurseries	559920450980	590	539	0.7	6.72	56.4	2.2	44.4	22.3	49	171	66.0	3.4
901146	Geranium Farm	556760448020	1300	434	5.2	5.75	105	41.1	97.3	29.5	23	138	181	63.0
901147	Holiday Village	560180447180	735	416	5.2	6.61	59.2	18.2	55.5	14.0	32	62.5	132	19.8
901148	Emarhooh	559480449820	780	453	7.0	5.86	78.6	8.9	45.1	18.2	27	125	95.2	23.4
901149	Quennevais Camp Ste	558020450420	620	321	0.1	6.79	59.7	1.8	44.4	17.6	65	103	76.7	11.7
901150	Priory Inn	560660455780	625	487	5.1	5.70	56.8	5.7	34.9	20.9	21	99.2	78.9	18.0
901151	Mushroom Farm	561260451630	825	410	2.9	6.18	85.7	3.6	60.6	18.7	57	131	123	15.8
901152	West View Hotel	560720454400	400	461	7.6	5.43	31.1	2.5	21.0	16.2	12	105	38.6	5.6
901153	Besco Laundry	561200450000	750	426	5.1	6.30	75.7	7.1	55.1	20.3	105	119	86.0	13.1
901154	Portelet Hotel	559900447600	730	377	4.5	6.46	84.5	2.9	60.6	14.1	88	63.1	152	11.1
901155	Les Bourgeons	562400451260	560	397	0.9	7.52	38.6	2.1	70.6	19.3	101	122	79.5	4.3
901156	Ville Bagot	557870455060	920	494	6.0	5.82	73.2	28.0	53.7	29.6	33	124	99.6	40.2
901157	Warwick Farm	564990451860	570	455	2.8	6.21	57.1	5.7	40.4	16.6	69	103	68.6	11.3
901158	St Georges Estate	556360455450	860			6.20	86.2	15.1	55.7	29.4	57	126	116	32.4
901159	Overdale Hospital	564470449450	610			6.80	59.3	1.6	57.0	17.1	140	86.6	72.2	9.1

Sample	Locality	NGR	SEC uS/cm	Eh mV	O_2 mg/l	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3-N
							mg/l							
901160	St Helier Nurseries	564720450710	405	273	1.5	6.04	55.1	1.6	27.8	6.5	83	89.6	39.2	10.7
901161	Stonewall Farm	566070451080	660	341	0.3	6.61	50.9	2.9	74.6	10.8	133	74.1	72.8	13.2
901162	First Tower Laundry	563900449470	850			6.35	67.9	7.6	62.3	24.5	61	125	111	24.2
901163	Glen Hotel	565320450300	690	369	0.9	6.84	51.1	3.1	78.7	13.5	161	101	70.0	11.7
901164	Harvest Barn	565010451010	600	400	<0.1	6.10	48.1	6.0	48.2	14.7	73	87.5	74.6	11.4
901165	Trinity Manor	565500453280	480			5.65	45.2	9.1	30.4	10.5	18	78.0	58.3	13.5
901166	First Tower Park	563380449990	770	299	<0.1	7.02	72.8	2.4	80.9	25.3	152	177	97.6	2.2
901167	Parade Park	564870448980	870	141	3.4	7.19	65.6	6.7	112	24.8	346	124	81.7	<1.0
901168	Mon Bijou	558080453120	555			6.29	52.2	4.8	30.1	16.3	41	72.5	75.4	12.9
901169	Creaux Cottage	558490454410	820	461	3.6	5.42	63.4	25.3	59.7	15.2	14	93.3	118	28.8
901170	Creaux Cottage	558490454410	715			5.87	75.1	3.8	47.7	14.0	26	106	102	20.2
901171	Greenhills Hotel	560760452540	740	458	0.2	5.82	49.9	8.4	52.1	27.9	54	103	89.5	23.4
901172	Maison Aleval	561020452540	810	482	6.1	5.17	40.0	8.9	49.9	37.5	12	83.4	85.2	47.4
901173	Clifton	563090450640	760			7.11	59.1	3.1	69.0	22.8	90	145	79.2	16.0
901174	Bon Air Stables	562650453910	520	455	1.6	5.80	39.3	44.3	22.8	11.5	69	67.7	60.6	10.0
901175	Coronation Park	562590449990	695	408	4.2	6.39	74.5	5.6	52.6	22.7	116	109	108	10.1
901176	Rose Farm Camp Site	559630448830	450	504	1.9	5.13	40.1	11.3	24.8	8.6	8	62.3	56.5	15.5
901177	Greywings	559900453800	990			6.00	123	6.7	39.7	32.0	230	204	57.7	9.5
901178	L'Auberge du Nord	562820455790	475	482	3.7	5.86	32.2	9.0	30.4	16.6	36	94.6	55.0	8.2
901179	Apple Barn	559550452320	625	440	2.2	6.08	69.0	2.1	42.2	11.6	52	115	67.7	13.5
901180	Silver Jubilee Ctre	559190455040	1000			5.38	52.4	10.2	66.9	57.0	10	214	109	37.2
901181	Beechlands	562400453180	620	477	7.3	5.3	47.8	4.8	34.9	22.2	9	117	58.7	22.8
901182	Casa Mariana	564710452430	510	512	6.5	5.26	31.0	6.3	24.3	27.5	7	135	37.9	16.4
901183	Oakvillas	564820453630	540	492	5.4	5.91	36.9	5.0	45.0	13.7	29	88.1	60.5	16.9
901184	Le Couvent	563740452940	695	475	1.5	5.74	65.0	6.3	47.9	17.2	52	118	84.9	15.8
901185	Redwood	563210455400	490	518	6.2	5.17	29.9	5.5	34.4	16.3	8	90.4	48.7	17.5
901186	Le Rondin Cottage	564060454150	625	355	0.8	6.43	47.3	17.7	47.9	16.9	160	63.1	79.6	2.0
901187	Greenfields	561180454360	320			6.04	28.4	5.9	14.0	9.4	17	85.5	21.0	3.1
901188	Ronez Quarry	561910456640	765	331	1.1	6.90	64.0	3.0	52.2	32.3	83	187	101	1.2
901189	Greenfields Toms.	556480454700	510	517	8.6	5.23	30.1	5.6	34.8	19.9	6	93.3	54.7	17.4
901190	Highfield Hotel	565640454600	570	494	4.0	5.28	51.2	12.9	22.3	17.6	14	82.9	72.2	16.5

Sample	Locality	NGR	SEC uS/cm	Eh mV	O_2 mg/l	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3-N
							mg/l							
901191	Ferndale	558630451350	870			6.52	78.0	2.8	67.3	20.2	103	98.2	108	23.1
901192	Highfield Lane	566930450790	620	58	<0.1	7.55	42.9	3.6	67.2	20.4	158	107	78.7	0.4
901193	4 Victoria Vill.	566930452170	465	469	9.7	5.86	57.0	4.6	33.8	7.4	39	105	56.4	9.3
901194	Summerhill	567100454060	540	415	7.03	5.3	45.4	12.1	27.6	16.5	11	97.1	65.8	14.0
901195	States Farm BH	566050454000	450	274	0.22	6.03	36.8	7.2	21.9	12.5	52	75.2	66.6	0.2
901196	States Farm Well	566030454080	538	353	0.57	6.07	26.0	8.1	51.6	13.8	36	85.5	47.7	19.5
901197	La Mare Vineyards	560700455310	600	455	10.0	6.25	57.7	9.4	28.0	19.7	33	88.8	72.9	20.4
901198	Aviemore	563570452200	585	386	2.8	6.0	44.1	8.1	45.2	15.1	41	108	60.9	15.9
901199	Le Petit Clos	567710453090	392	452	6.4	5.49	40.6	13.9	14.4	8.4	18	92.2	27.0	8.8
901200	Jersey Milk	567360450010	687	175	<0.1	6.84	43.8	2.6	94.0	10.7	163	136	68.7	<1.0
901201	Petite Port Cott.	565990455680	342			6.32	38.4	6.3	17.0	5.5	21	33.1	54.4	6.9
901202	Gorsefields	565140455400	708			5.11	33.7	10.6	6.1	10.0	4	40.7	50.9	8.3
901203	Dr Millar	566220452090	410	457	1.5	5.74	57.5	17.5	25.1	6.6	25	86.9	58.6	12.5
901204	Vallee de Rozel	569300453740	50	446	4.7	5.93	55.8	3.8	39.4	13.1	43	88.8	65.7	16.4
901205	Bistro Frere	570010454270	490			6.91	42.1	3.8	28.8	22.1	61	52.8	74.4	13.7
901206	Meadou Springs	568370452280	650	435	3.2	6.47	45.9	1.8	63.9	16.0	87	117	49.5	19.5
901207	Les Jardins	571070453520	838	495	5.6	5.02	37.2	22.4	66.6	27.1	5	87.6	91.2	45.6
901208	2 Clos du Vivier	569360452700	620			6.60	56.3	6.9	41.3	16.7	46	95.3	82.1	15.0
901209	Manor Farm	570410453120	488	483	2.6	6.07	49.3	12.6	37.2	16.1	31	83.3	63.9	22.4
901210	Oakbank	570460452270	673	466	2.4	5.78	53.0	6.9	46.0	26.1	26	92.9	93.2	24.8
901211	Hougue Bie Nursery	568370450260	555	485	4.0	5.58	55.2	1.9	31.9	13.1	23	81.6	69.0	15.6
901212	Combie Flowers	570060450560	615	439	3.2	5.83	62.2	6.7	42.0	11.3	56	102	66.8	16.0
901213	La Huitieme	568960451320	1010	421	2.3	5.50	85.7	33.2	49.2	28.8	30	104	158	27.9
901214	Tesson Mill	561610450780	778	401	2.2	7.22	61.8	2.7	76.4	19.3	159	112	85.6	11.9
901215	Poplar Avenue	568380451520	282	433	6.7	5.92	17.7	3.3	17.8	9.4	24	58.0	19.6	5.6
901216	La Chenee	569900451480	632	438	2.1	5.79	55.5	9.9	36.6	17.3	34	90.9	71.9	20.3
901217	Canning Factory	566880450230	674	361	6.3	5.93	67.8	2.9	51.9	13.1	63	131	88.5	7.4
901218	Queens Valley	569760449940	638	392	6.8	6.79	54.3	3.3	60.8	20.8	135	119	74.8	5.3
901219	La Chaumiere	568600449020	800	406	2.3	6.30	75.5	1.9	60.4	21.5	64	146	95.1	18.0
901220	Les Mourier	561140455400	488	148	<0.1	7.19	22.7	1.9	52.5	12.4	106	34.8	79.3	<0.04
901221	Chaise au Diable	566600451580	608	210	7.9	7.30	41.3	4.9	69.9	11.2	178	70.9	68.0	0.36

Sample	Locality	NGR	SEC	Eh	O_2	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3-N
			uS/cm	mV	mg/l					mg/l				
901222	Roseland	566780449380	735	401	1.5	6.45	67.4	2.0	67.0	13.7	88	130	87.6	11.2
901223	A E Smith	566930448430	1110	404	4.4	6.70	98.4	15.4	99.2	33.0	146	189	150	22.8
901224	Normandie	569980447630	845	378	0.2	7.08	84.9	9.9	79.2	23.2	225	116	75.9	18.3
901225	Samares	567380447480	978	400	2.4	6.52	90.1	5.9	106	36.7	171	171	144	26.1
901226	Royal Golf Club	570270449010	965	97	0.3	7.16	112	10.9	62.4	27.6	288	113	128	0.44
901227	La Ferme	570620447320	1300	151	<0.1	7.09	100	12.9	187	29.3	329	372	116	0.46
901228	Merton Hotel	566100448100	980	322	3.0	6.65	78.2	6.6	71.7	26.1	150	120	117	13.5
901229	Randalls Brewery	565000449010	895	102	<0.1	7.33	54.8	2.9	89.0	25.1	184	150	97.5	0.07
901230	Grouville Spring	568040448140	1000	393	2.4	6.53	76.4	1.8	84.4	29.5	112	174	89.7	24.9
901231	Le Coie Hotel	565760449370	915	329	1.7	7.04	70.3	1.8	84.1	16.8	135	122	114	9.0
901232	Ann Street Brewery	565750448830	860			6.90	70.1	2.0	76.1	18.8	157	135	78.0	10.5
901233	Fort Regent Centre	565290448220	715	379	9.7	7.62	64.1	5.1	54.2	14.1	113	94.9	73.9	11.7
901234	La Motte Garages	568310447060	1200			7.51	70.6	92.6	99.3	23.6	241	197	80.7	24.0
901235	Le Puits	569430448400	1000	420	3.0	6.42	76.2	14.8	67.5	29.5	77	172	88.2	30.9
901236	La Mervelle	571070450780	900	408		6.27	80.5	1.8	65.4	19.4	85	153	94.5	16.5
901237	Homefields Farm	569380447420	1400	376	2.8	6.24	99.6	6.6	111	46.2	67	252	137	48.9
901238	Sefton Nursery	567490446600	1800			7.14	167	3.4	201	34.6	494	401	143	<1.0
901239	Chateau la Chaire	569450454230	605			6.64	48.8	5.2	35.1	17.3	55	77.2	72.1	13.7

Additional NH_4-N data:
901192: 0.06 mg/l; 901200: 0.03 mg/l; 901220: 0.03 mg/l; 901222: <0.01 mg/l; 901229: <0.01 mg/l; 901238: 0.93 mg/l.

APPENDIX III. Trace-element data for Jersey groundwater samples collected during summer 1990.

Sample	Locality	Si	Al	P	Li	Sr	Ba	Total Fe	Fe^{2+}	Mn	Cu	Zn
							mg/l					
901131	Greystones	6.2	<.10	0.5	<.007	1.18	0.034	0.016	<0.04	0.114	<.01	0.021
901132	Les Mauves	3.1	<.10	0.5	<.007	1.46	0.088	0.019	<0.04	<.003	0.01	<.020
901133	Jersey Racecourse	5.6	0.71	0.5	<.007	1.28	0.176	0.060		0.186	<.01	<.020
901134	A5 St Ouens Bay	3.5	<.10	<.3	<.007	0.321	0.014	0.030	<0.04	0.009	<.01	<.020
901135	Val de la Mare	7.9	<.10	<.3	<.007	0.280	0.102	<.015	<0.04	0.014	<.01	<.020
901136	Lobster Pot	7.9	<.10	1.3	0.009	0.247	0.165	<.015		0.790	<.01	0.070
901137	La Pointe	6.0	<.10	1.0	<.007	0.908	0.092	0.027		0.627	0.05	0.089
901138	Le Bas de l'Etaque	4.1	<.10	1.6	<.007	0.820	0.065	0.032		0.462	<.01	0.105
901139	Atlantic Hotel	11.8	<.10	<.3	<.007	0.156	0.029	0.261	0.28	0.725	0.08	0.104
901140	La Moye Golf Course	3.1	<.10	<.3	<.007	0.467	0.038	<.015	<0.04	<.003	<.01	<.020
901141	Villa Martinique	6.0	<.10	<.3	<.007	0.360	0.050	0.022	<0.04	0.020	<.01	0.022
901142	Radar Station	10.0	<.10	<.3	0.012	0.162	0.228	<.015	<0.04	1.61	<.01	<.020
901143	Val de la Mare Farm	7.2	<.10	<.3	<.007	0.355	0.014	<.015	<0.04	<.003	<.01	<.020
901144	Les Quennevais	9.6	<.10	<.3	<.007	0.181	<0.004	<.015	<0.04	<.003	<.01	<.020
901145	St Peters Nurseries	8.5	<.10	<.3	0.008	0.190	<0.004	0.048		0.116	<.01	<.020
901146	Geranium Farm	5.8	0.13	0.5	<.007	2.00	0.162	0.041		0.133	<.01	0.027
901147	Holiday Village	5.6	<.10	0.3	<.007	0.684	0.056	0.023		0.166	<.01	<.020
901148	Emahroo		9.0	<.10	<.3	<.007	0.257	0.045	0.029	0.004	<.01	0.026
901149	Quennevais Camp Site	8.5	<.10	<.3	0.015	0.235	0.011	0.055		0.046	<.01	<.020
901150	Priory Inn	10.6	<.10	<.3	0.007	0.236	0.084	<.015		<.003	0.04	0.042
901151	Mushroom Farm	9.8	<.10	<.3	<.007	0.255	0.033	<.015		<.003	<.01	<.020
901152	West View Hotel	10.6	<.10	<.3	<.007	0.159	0.029	0.168		0.007	0.03	0.160
901153	Besco Laundry	8.0	<.10	<.3	<.007	0.228	0.043	<.015		<.003	<.01	0.023
901154	Portelet Hotel	8.1	<.10	<.3	<.007	0.210	0.026	0.070		1.55	<.01	2.85
901155	Les Bourgeons	6.2	<.10	<.3	<.007	0.243	0.022	<.015		0.018	<.01	<.020
901156	Ville Bagot	8.3	<.10	0.6	<.007	0.525	0.053	<.015	<0.04	0.005	0.04	<.020
901157	Warwick Farm	10.8	<.10	<.3	0.007	0.152	0.027	0.034	<0.04	0.004	<.01	<.020
901158	St Georges Estate	5.6	<.10	0.9	0.008	0.923	0.101	<.015		1.33	<.01	0.578
901159	Overdale Hospital	9.3	<.10	<.3	<.007	0.243	0.046	<.015		<.003	<.01	0.279

Sample	Locality	Si	Al	P	Li	Sr	Ba	Total Fe	Fe^{2+}	Mn	Cu	Zn
		mg/l										
901160	St Helier Nurseries	12.6	<.10	<.3	<.007	0.131	0.005	<.015	<0.04	<.003	<.01	<.020
901161	Stonewall Farm	12.2	<.10	<.3	<.007	0.206	0.168	<.015	<0.04	0.249	0.02	0.028
901162	First Tower Laundry	6.8	<.10	<.3	<.007	0.302	0.040	<.015	<0.04	0.003	0.04	<.020
901163	Glen Hotel	5.9	<.10	<.3	<.007	0.268	0.075	<.015	<0.04	<.003	0.02	0.053
901164	Harvest Barn	9.9	<.10	<.3	<.007	0.375	0.058	<.015	<0.04	0.064	<.01	0.060
901165	Trinity Manor	13.5	<.10	<.3	<.007	0.173	0.065	<.015	<0.04	0.011	<.01	0.040
901166	First Tower Park	4.3	<.10	<.3	<.007	0.228	0.038	0.018	<0.04	0.132	<.01	<.020
901167	Parade Park	7.6	<.10	0.3	<.007	0.363	0.176	2.81	2.68	0.611	<.01	0.046
901168	Mon Bijou	7.1	<.10	<.3	<.007	0.199	0.072	0.058		0.007	<.01	0.044
901169	Creaux Cottage	7.0	0.17	<.3	<.007	0.779	0.082	<.015	<0.04	0.068	<.01	0.024
901170	Creaux Cottage	12.4	<.10	<.3	0.014	0.200	0.025	0.016		1.23	0.01	0.033
901171	Greenhills Hotel	5.7	<.10	<.3	<.007	0.473	0.059	<.015	<0.04	0.044	0.14	0.184
901172	Maison Aleval	8.9	<.10	<.3	<.007	0.517	0.043	<.015		0.041	0.01	0.029
901173	Clifton		5.9	<.10	<.3	<.007	0.231	<0.004	<.015	0.303	<.01	<.020
901174	Bon Air Stables	3.3	<.10	<.3	<.007	0.293	0.045	<.015	<0.04	0.044	<.01	<.020
901175	Coronation Park	6.4	<.10	<.3	<.007	0.259	0.045	0.036	<0.04	1.17	<.01	<.020
901176	Rose Farm Camp Site	9.3	0.10	<.3	<.007	0.231	0.036	0.048	0.06	0.082	0.08	0.090
901177	Greywings	9.3	<.10	<.3	0.010	0.274	0.006	0.096	0.11	0.023	0.01	0.103
901178	L'Auberge du Nord	7.0	<.10	<.3	<.007	0.343	0.026	<.015		0.050	0.04	0.037
901179	Apple Barn	10.7	<.10	<.3	<.007	0.143	0.024	0.035	<0.04	<.003	0.06	0.164
901180	Silver Jubilee Centre	9.2	<.10	<.3	<.007	0.755	0.063	<.015	<0.04	0.069	0.03	0.042
901181	Beechlands	8.1	<.10	<.3	<.007	0.260	0.039	<.015	<0.04	0.010	<.01	<.020
901182	Casa Mariana	8.6	<.10	<.3	<.007	0.259	0.024	<.015	<0.04	0.051	0.01	0.021
901183	Oakvillas	6.3	<.10	<.3	<.007	0.494	0.072	<.015		<.003	0.02	0.036
901184	Le Couvent	11.7	<.10	<.3	<.007	0.238	0.072	0.030		0.006	0.06	0.228
901185	Redwood		5.9	0.10	<.3	<.007	0.438	0.030	<.015	0.063	<.01	<.020
901186	Le Rondin Cottage	4.9	<.10	<.3	<.007	0.363	0.028	0.063		0.476	<.01	<.020
901187	Greenfields	9.2	<.10	<.3	<.007	0.150	0.023	0.093		0.028	0.04	0.048
901188	Ronez Quarry	11.0	<.10	<.3	0.017	0.187	0.038	0.038		0.133	<.01	0.064
901189	Greenfields Tomatoes	8.0	<.10	<.3	<.007	0.390	0.032	<.015		0.045	0.02	0.041
901190	Highfield Hotel	6.4	<.10	<.3	<.007	0.185	0.069	0.031		0.042	0.16	0.059

Sample	Locality	Si	Al	P	Li	Sr	Ba	Total Fe	Fe_{2+}	Mn	Cu	Zn
		mg/l										
901191	Ferndale		9.3	<.10	0.5	<.007	0.299	0.010	<.015	0.699	<.01	<.020
901192	Highfield Lane	7.3	<.10	<.3	<.007	0.202	0.078	0.345	0.38	0.717	<.01	<.020
901193	4 Victoria Village J63	14.9	<.10	<.3	<.007	0.111	0.026	0.057		0.011	0.02	0.052
901194	Summerhill	8.9	<.10	<.3	<.007	0.249	0.073	0.041		0.011	0.19	0.099
901195	States Farm BH	19.3	<.10	<.3	<.007	0.150	0.052	8.49	6.60	0.810	<.01	<.020
901196	States Farm W	4.7	<.10	1.2	<.007	0.496	0.042	0.029		1.85	0.01	0.142
901197	La Mare Vineyards	10.4	<.10	<.3	<.007	0.231	0.074	0.040		0.008	0.01	0.074
901198	Aviemore		5.5	<.10	<.3	<.007	0.241	0.032	0.109	0.005	0.02	0.037
901199	Le Petit Clos	10.1	<.10	<.3	<.007	0.090	0.051	0.053		0.009	0.03	0.064
901200	Jersey Milk	11.7	<.10	<.3	0.007	0.260	0.105	2.59	2.72	0.776	<.01	<.020
901201	Petite Port Cottage	9.4	<.10	<.3	<.007	0.100	0.037	0.148	0.16	0.045	0.01	0.061
901202	Gorsefields	6.6	0.13	<.3	<.007	0.093	0.098	0.094		0.030	0.10	0.250
901203	Dr Millar	12.3	<.10	<.3	<.007	0.101	0.041	0.040	<0.04	0.012	0.03	0.039
901204	Vallee de Rozel	9.8	<.10	<.3	<.007	0.148	0.070	0.016		<.003	0.02	0.131
901205	Bistro Frere	7.3	<.10	<.3	0.008	0.180	0.143	<.015		0.132	0.02	<.020
901206	Meadou Springs	8.4	<.10	<.3	<.007	0.201	0.035	<.015		<.003	<.01	<.020
901207	Les Jardins	6.8	0.29	0.3	<.007	0.984	0.069	<.015	<0.04	0.131	<.01	0.025
901208	2 Clos du Vivier	10.6	<.10	<.3	<.007	0.213	0.042	0.076		0.029	0.05	0.347
901209	Manor Farm	8.6	<.10	<.3	<.007	0.332	0.067	0.025		<.003	0.02	0.037
901210	Oakbank		7.7	<.10	<.3	<.007	0.406	0.073	<.015	0.137	<.01	0.021
901211	Hougue Bie Nursery	6.1	<.10	<.3	<.007	0.154	0.026	<.015		0.003	<.01	0.058
901212	Combie Flowers	9.0	<.10	<.3	<.007	0.169	0.040	0.024		0.005	0.02	0.073
901213	La Huitieme	7.2	<.10	<.3	<.007	0.564	0.057	0.031		0.027	0.07	0.102
901214	Tesson Mill	6.3	<.10	<.3	<.007	0.260	0.042	<.015		<.003	<.01	<.020
901215	Poplar Avenue	4.7	<.10	<.3	<.007	0.188	0.030	0.023		0.010	0.04	0.044
901216	La Chenee	8.2	<.10	<.3	<.007	0.209	0.064	0.067		0.217	<.01	0.046
901217	Canning Factory	9.7	<.10	<.3	<.007	0.212	0.005	1.15	1.12	0.079	<.01	0.026
901218	Queens Valley	8.7	<.10	<.3	0.008	0.181	0.010	0.017		0.059	<.01	0.045
901219	La Chaumire	9.3	<.10	<.3	<.007	0.263	0.021	0.024	<0.04	<.003	0.03	0.109
901220	Les Mourier	18.8	<.10	<.3	0.012	0.149	0.113	1.01	0.98	0.172	<.01	<.020
901221	Chaise au Diable	12.2	<.10	<.3	0.007	0.257	0.120	0.364	0.31	0.385	<.01	<.020

Sample	Locality	Si	Al	P	Li	Sr	Ba	Total Fe	Fe^{2+}	Mn	Cu	Zn
							mg/l					
901222	Roseland	9.4	<.10	<.3	<.007	0.256	0.040	<.015	<0.03	0.429	<.01	<.020
901223	A E Smith	8.2	<.10	<.3	<.007	0.367	0.021	<.015	<0.03	<.003	<.01	<.020
901224	Normandie	5.8	<.10	0.3	<.007	0.397	0.061	0.041		0.028	<.01	0.358
901225	Samares		8.3	<.10	<.3	<.007	0.434	0.022	0.057	0.004	<.01	<.020
901226	Royal Golf Club	10.0	<.10	<.3	<.007	0.385	0.057	6.76	5.78	0.437	<.01	<.020
901227	La Ferme	4.5	<.10	1.6	<.007	1.25	0.149	1.09	1.11	0.266	<.01	<.020
901228	Merton Hotel	6.6	<.10	<.3	<.007	0.311	0.020	0.135		<.003	<.01	0.243
901229	Randalls Brewery	7.2	<.10	<.3	<.007	0.313	0.166	1.42	1.54	0.230	<.01	0.028
901230	Grouville Spring	10.4	<.10	<.3	<.007	0.370	0.009	<.015	<0.03	<.003	<.01	<.020
901231	Le Coie Hotel	7.8	<.10	<.3	<.007	0.294	0.024	<.015		<.003	<.01	0.124
901232	Ann Street Brewery	6.8	<.10	<.3	<.007	0.257	0.007	<.015		<.003	<.01	<.020
901233	Fort Regent Centre	5.4	<.10	<.3	<.007	0.211	0.023	0.016		0.008	<.01	0.068
901234	La Motte Garages	6.2	<.10	0.5	<.007	0.654	0.072	0.025	<0.03	0.022	<.01	0.047
901235	Le Puits	8.4	<.10	<.3	<.007	0.365	0.020	<.015		<.003	<.01	<.020
901236	La Mervelle	8.4	<.10	<.3	<.007	0.304	0.022	0.018	<0.03	<.003	0.03	0.116
901237	Homefields Farm	7.7	<.10	<.3	<.007	0.472	0.046	0.121	0.09	0.018	<.01	<.020
901238	Sefton Nursery	7.0	<.10	3.4	<.007	0.608	0.087	5.09	3.60	0.706	<.01	<.020
901239	Chateau la Chaire	6.5	<.10	<.3	<.007	0.200	0.100	0.029	0.03	0.007	0.02	0.124

APPENDIX IV. Data for Jersey groundwater samples collected in autumn 1990.

Sample	Locality	NGR	SEC	pH	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3-N	NO_2-N	NH_4-N
			uS/cm						mg/l					
901323	Grouville Spring	568040448140	945.	6.15	76.1	1.9	83.0	28.6	112.	171.	53.0	26.6	<0.005	0.01
901324	Jersey Milk	567360450010	785.	6.40	42.9	2.7	99.9	11.4	169.	134.	81.0	<0.2	<0.005	0.05
901325	Stonewall Farm	566070451080	730.	5.95	50.7	2.9	71.4	10.4	131.	75.1	74.5	13.7	0.009	0.01
901326	First Tower Laundry	563900449470	910.	6.00	67.8	7.6	62.6	24.4	62.	128.	107.	22.8	<0.005	<0.01
901327	La Chenee	569900451480	670.	5.80	56.1	9.5	35.8	16.1	34.6	97.5	69.0	19.2	<0.005	<0.01
901328	St Helier Nurseries	564720450710	535.		55.7	1.6	30.4	7.2	45.5	95.0	42.5	10.2	<0.005	0.01
901329	States Farm BH	566050454000	420.		40.4	9.2	17.8	8.6	19.5	90.5	49.5	1.0	0.012	0.05
901330	States Farm Well	566030454080	550.		24.3	8.0	46.8	15.1	28.8	83.7	46.5	18.6	<0.005	0.02
901331	Atlantic Hotel	556560448940	695.		77.6	2.1	47.9	8.8	122.	75.8	99.0	1.1	<0.005	0.03
901332	Val de la Mare	557700451840	865.		64.5	3.2	86.5	18.6	266.	39.5	103.	3.6	<0.005	<0.01
901333	Tesson Mill	561610450780	825.		60.6	2.6	73.4	18.3	155.	112.	62.5	10.6	<0.005	0.02
901334	Chaise au Diable	566600451580	650.		43.0	4.9	70.9	11.4	181.	70.3	68.0	<0.2	<0.005	0.04
901335	Mushroom Farm	561260451630	945.	6.15	86.6	3.6	63.9	19.8	56.	142.	114.	15.0	0.036	0.02
901336	Randalls Brewery	565000449010	890.	6.65	54.5	2.9	89.6	24.7	184.	153.	96.0	<0.2	<0.005	0.11
901337	Homefields Farm	569380447420	1450.	6.25	99.3	6.3	113.	45.9	71.	257.	143.	44.8	<0.005	<0.01

Sample	Locality	Si	Al	P	Li	Sr	Ba	Total Fe	Fe^{2+}	Mn	Cu	Zn
							mg/l					
901323	Grouville Spring	10.7	<0.1	<0.3	<0.007	0.360	0.008	<0.015		<0.003	<0.01	<0.02
901324	Jersey Milk	11.9	<0.1	<0.3	0.007	0.277	0.109	2.47	2.54	0.781	<0.01	0.02
901325	Stonewall Farm	12.2	<0.1	<0.3	<0.007	0.201	0.159	<0.015		0.214	0.01	<0.02
901326	First Tower Laundry	7.0	<0.1	<0.3	<0.007	0.301	0.04	<0.015	0.088	<0.003	<0.01	<0.02
901327	La Chenee	9.0	<0.1	<0.3	<0.007	0.172	0.063	<0.015	0.063	0.176	<0.01	0.05
901328	St Helier Nurseries	12.6	<0.1	<0.3	<0.007	0.139	<0.004	<0.015	<0.06	<0.003	0.03	0.06
901329	States Farm BH	12.1	<0.1	<0.3	<0.007	0.107	0.057	1.46	1.43	0.305	<0.01	0.06
901330	States Farm Well	6.2	<0.1	2.0	<0.007	0.421	0.045	0.016	0.076	0.404	0.04	0.26
901331	Atlantic Hotel	11.4	<0.1	<0.3	<0.007	0.177	0.034	0.059	0.095	0.463	0.11	0.16
901332	Val de la Mare	7.3	<0.1	<0.3	<0.007	0.296	0.197	<0.015	<0.06	0.156	<0.01	<0.02
901333	Tesson Mill	6.6	<0.1	<0.3	<0.007	0.255	0.038	<0.015	<0.06	<0.003	<0.01	<0.02
901334	Chaise au Diable	12.6	<0.1	<0.3	0.008	0.264	0.125	<0.015	0.43	0.379	<0.01	<0.02
901335	Mushroom Farm	9.9	<0.1	<0.3	0.008	0.270	0.037	<0.015	0.076	0.008	0.02	0.07
901336	Randalls Brewery	7.4	<0.1	<0.3	<0.007	0.313	0.169	1.62	1.64	0.234	<0.01	0.07
901337	Homefields Farm	8.3	<0.1	<0.3	<0.007	0.465	0.046	0.031	0.11	0.012	<0.01	<0.02