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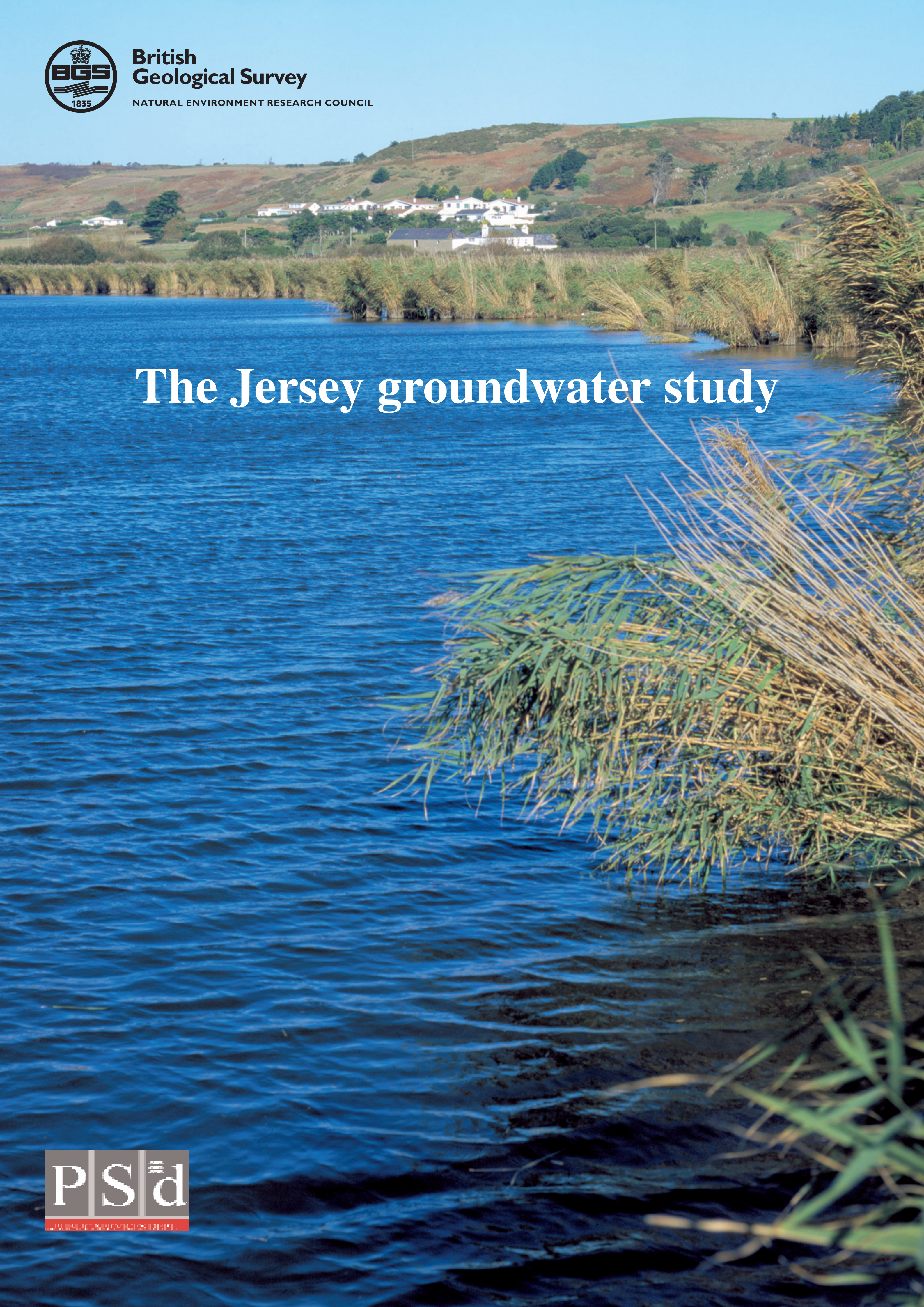

The Jersey groundwater study

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N S Robins and P L Smedley

This report was prepared for the States of Jersey Public Services Department

BRITISH GEOLOGICAL SURVEY

RESEARCH REPORT RR/98/5

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Cover photograph

The National Trust for Jersey

Bibliographical reference

Robins, N S, and Smedley, P L. 1998. The Jersey groundwater study. *British Geological Survey Research Report* RR/98/5. 48pp.

Keyworth, Nottingham British Geological Survey 1998

Acknowledgements

The Jersey groundwater study encompasses the combined efforts of people from a number of different organisations and disciplines. Contributors include field workers, analysts, modellers, agronomists, environmentalists, sociologists, economists, engineers and lawyers, as well as hydrologists, hydrogeologists and hydrogeochemists. The authors of this report are grateful to all of them, not least for the unstinting interest and encouragement provided by staff at all levels within the Public Services Department, and to colleagues within BGS and IH for direct contributions to the study as well as for discussion and periodic scientific review. In addition, the significant role of the Groundwater Review Group in guiding the study towards a sensible conclusion has been extremely valuable. But above all, the authors thank the people of Jersey for providing access to wells, boreholes and springs, for their hospitality and good-humoured tolerance of our enquiries.

Preface

The work described in this report represents a seven year programme of investigation led by the British Geological Survey on behalf of the Jersey Public Services Department. The programme was instigated after a succession of relatively dry winters in the late 1980s and the realisation that many boreholes on the island at that time were failing. At the same time it was also realised that much of the groundwater, including baseflow to surface waters, was polluted.

Although much of the work has been carried out by the BGS Hydrogeology Group, major contributions have also been made by others, most notably the staff of the Public Services Department, the Institute of Hydrology and the School of Environmental Sciences at the University of East Anglia. The work has been influenced and steered throughout by the Groundwater Review Group under Dr John Sharp, and has always enjoyed the encouragement and enthusiasm of Roger Culverwell at the Public Services Department.

This report highlights the principal issues relating to groundwater in Jersey. It is not intended as a stand alone report, and reference should also be made to earlier project reports and publications for supporting detail. The recommendations are, however, very striking: the groundwater resources are not managed and there is an urgent need to implement the proposed Water Pollution Law, and then to consider the drafting of groundwater resource regulations.

It is intended that a definitive description of the hydrogeology of Jersey will be produced in due course. This will await sufficient time series data to support trend analysis, the release of data from the St Helier storm drain investigation, and the completion of a number of other areas of hydrogeological enquiry which are ongoing.

April 1998

Executive summary

Between 1988 and 1992 rainfall was below average in Jersey and water resources were stressed. BGS was commissioned to review the groundwater resources of the island in 1990; it was apparent that groundwater is a finite resource under considerable demand, and that much of the water is polluted to some degree. The main island aquifer is a shallow zone of weathering, generally only 25 m in thickness below the water table, which occurs within ancient igneous and sedimentary rocks. There are thin coastal sand aquifers along the west and parts of the east coasts of the island. Average annual rainfall is 877 mm and annual potential transpiration ranges from 648 to 754 mm. The island has an area of 117 km^2 and a resident population of 84 000; it supports intensive agriculture over 55% of the land area. Demand for groundwater abstracted from boreholes and wells is about 3.6 Mm^3 a^{-1}.

The typical sustainable borehole yield is about 0.5 l s^{-1}; the highest known yield is 4 l s^{-1}, but this is exceptional. The groundwater is unconfined although it may occur under a confining head within fractures. Groundwater flow is principally from north to south with the main discharge area along St Aubin's Bay. Analysis of borehole hydrographs suggests that annual recharge rates lie between 30 and 300 mm a^{-1}, but a variety of techniques enable refinement of this estimate. A catchment and modelling study produced, in conjunction with historical data, an island-wide recharge estimate of 132 mm over a 28-year period (1968 to 1995). During the dry periods of 1975/76 and 1989/91 there was no recharge and baseflow to surface waters was greatly diminished. Other techniques support these results.

About half the long-term available recharge, or renewable resource, is currently used either as groundwater abstraction or as baseflow in surface water. In dry years, water levels fall, baseflow declines and many boreholes go dry, particularly on higher ground. The overall water balance is little affected by irrigation returns and interception of rainwater by hardstanding, and these in any case tend to counteract each other.

Groundwater quality is characterised by oxidising waters of Na-Ca-HCO$_3$ or Na-Ca-Cl type, although some samples have a high SO$_4$ concentration. The overall inorganic composition of the groundwater has changed little over the seven-year period of monitoring. Around 80% of the groundwaters sampled are acidic (pH <7), and most are undersaturated with respect to calcite. Most groundwaters are oxidising, but reducing waters occur in the south and south-east of the island and in parts of St Saviour. These reflect upwelling of deeper and longer groundwater flowpaths from the north of the island.

All the groundwater is susceptible to surface pollutants because the aquifer is shallow and generally unconfined. Nearly 70% of the groundwater samples collected over the seven-year investigation had nitrate concentrations in excess of the European Community maximum admissible concentration for drinking water of 11.3 mg N l^{-1}. Many sources also periodically exceed the limit for K and NH$_4$. Investigation of nitrate profiles in the unsaturated zone suggests downward percolation of polluted water at a rate of 1 m in 2 to 3 years and leaching losses from agricultural land of between 23 and 52 kg N ha^{-1} a^{-1}. These losses are of a similar order to those found under heavily cropped land in the UK. Nitrogen isotope analysis enabled the component of N derived from fertiliser and sewage/animals to be investigated. This showed that the majority of the nitrate derives from soil organic nitrogen and ultimately from fertiliser. Some natural denitrification occurs in the reducing waters in the south of the island. Organic pollutants, notably pesticides, are increasingly being detected in groundwater.

As yet there is no Jersey law in place which enables the effective management of the groundwater resource. The physical and chemical evidence collected during this survey indicate that management is necessary in order to safeguard the resource for future generations.

Contents

LIST OF PHOTOGRAPHS

‘Tis in my opinion, the greatest wonder of this Island that whereas ‘tis but, as it seems, a great rock standing in the midst of the salt sea, it abounds, beyond what is seen in any country under Heaven, with both fresh excellent springs, which gush out of the hard rock and bubble everywhere . . .

from Philip Falle’s *Description of Jersey*, 1694

. . .the nitrate level in the Island`s drinking water will continue to remain outside the EU maximum admissible concentration of 11.3 mg N l^{-1} *(sic). Many private water supplies already well exceed the EU recommendation . . . damaging to the perception of Jersey as an environmentally clean island. If the level continued to rise, it could eventually become a health hazard.*

The *Nitrate and Pesticide Joint Working Party Report*, 1996

St Ouen’s Pond.

1 Introduction

1.1 BACKGROUND

The year 1988 was the first of four consecutive years of below average rainfall in Jersey. At that time, the additional surface water storage facility provided by the Queen's Valley Reservoir was not available, and the States of Jersey was moved to invoke Emergency Powers during the summer of 1989 in an attempt to conserve the remaining water resources. This realisation of possible resource inadequacy at times of drought was coupled with an increasing awareness both of deteriorating surface and groundwater quality, and a lack of data with which to assess the situation. An invitation was made to the BGS Hydrogeology Group by the then Public Buildings and Works Department[1] and the Jersey New Waterworks Company to review the groundwater resource potential, and to recommend a course of action which would allow the proper evaluation of the resource and most appropriate way to manage it.

This initial review led to BGS being commissioned in 1990 by the Public Services Department (PSD) to undertake a thorough investigation of the groundwater resources of the island. The study has continued over the subsequent seven years under the auspices of the PSD and of the Groundwater Review Group, the latter the project steering group consisting of local geological experts. The project incorporates a number of specialist inputs, notably an instrumented catchment study carried out by the Institute of Hydrology, a nitrate provenance investigation by the School of Environmental Sciences at the University of East Anglia, and pollution studies by the WRc. This report aims to bring all these diverse inputs together, along with other existing sources of information, to provide a comprehensive and up-to-date statement on the hydrogeology and hydrogeochemistry of Jersey groundwater. It is proposed that this report will be developed further into a definitive standalone statement on the hydrogeology of Jersey once sufficient time series data are available to underscore the project findings.

1.1.1 The issues

Jersey experiences immense problems over the effective protection, capture and exploitation of its surface and groundwater resources. The fresh water resources of Jersey fall as precipitation on the island; a component of the rainfall is returned to the atmosphere as evaporation, another component flows overland or through the soil zone to surface streams or other surface waters, and a third component infiltrates the soil zone and passes down through the substrate to the water table to become groundwater. Much of this groundwater ultimately discharges as baseflow to streams and to surface water reservoirs, or directly to the sea along the coast.

The first issue is that the resource is limited Although the water resources are renewable, in any given year the extent of renewal depends on the quantity and distribution of the rainfall. Demand on the available water resources has increased with population growth, increased standard of living, and increased needs of industry, particularly agriculture and the leisure amenities.

The second issue is the poor quality of some of the groundwater Poor water quality develops as a result of natural processes controlled by redox conditions, sea water intrusion in coastal areas and prolonged residence times in an aquifer, or by pollution from agricultural, industrial or domestic sources.

There are a number of related peripheral issues. These include acceptable standards for water quality in public supply, acceptable land use practice, and inadequate regulation and management pertaining to groundwater as a resource. However, these are, for the most part, internal political issues which are not the subject of this report. Needless to say, visitors will judge the island according to the drinking water standards they are used to at home; not all of the standards enjoyed in the UK are currently in place in Jersey.

1.1.2 Previous work

Despite the large dependence of the Jersey community for its water supply on groundwater or the discharge of groundwater as baseflow to surface waters, little attempt had been made, prior to the BGS studies, to investigate the potential of the resource.

Interest was first shown in wells and springs by islander Mr J Green whose records allow some small historical insight into groundwater use. There was also the work of Dr Klupfel, during the German Occupation of the island in World War II, who spent much of his time working on a well inventory. This early work was later expanded by off-island consultancy projects, notably that carried out by T & C Hawksley (1976) and Watson Hawksley (1986). Additional data were collected by the drillers working on the island, although these records are of limited technical value. Data are also available from borehole journals, deposited in the UK National Geosciences Database by off-island drillers who worked in Jersey from time to time.

Collectively, these early data suggest that there has been a significant increase in the number of groundwater abstraction sources developed since the 1940s. Available evidence suggests that the water table has remained broadly at the same depth below the ground surface for many parts of the island, but does not account for the situation during intervening periods of water scarcity (see section 2.1.3). The data make little consideration of groundwater quality, although a record of chemical analyses for the public supply boreholes at Mont à la Brune suggests little long term change in major ion concentrations, including nitrate since 1974. Nevertheless, a serious nitrate pollution problem was developing throughout the 1980s, if not before, which was first reported by Foster et al. (1989). The severity of the pollution found in this early study led to it being used as a

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[1] The Public Buildings and Works Department was amalgamated with the Resources Recovery Board in 1990 to form the Public Services Department.

case study — alongside Chernobyl and acid rain — in a school text book on pollution (Foster, 1991).

1.1.3 Work programme

Given the apparently worsening groundwater situation of the late 1980s, the following work programme was devised for the present study. This was initially envisaged as a one-year study which would attempt to:

- establish a hydrogeological database, which would include a well and borehole inventory, groundwater level and groundwater abstraction data, and groundwater chemistry;
- quantify the relationship between groundwater and surface water;
- evaluate the groundwater resource potential of the St Ouen's sand aquifer.

This first year of study was able to provide a land mark report on the understanding of the groundwater resources of Jersey. However, it also raised a significant number of questions which needed answers before any rational management of the aquifer could be addressed. The study was, therefore, widened in scope with two principal aims:

- to quantify the resource potential in terms of volume;
- to quantify the degree of pollution in the Jersey bedrock aquifer and to identify the sources of the pollutants.

These aims could only be resolved by monitoring groundwater levels and quality over a number of years and it is only now sensible to report on this work. The overall work programme comprised the following highlights:

1990	measurement and sampling from a core sample set of 109 groundwater sources; establishment of a monitoring network of water level and groundwater chemistry at six-monthly intervals, and of abstraction annually; microbial study; numerical groundwater modelling of St Ouen's sand aquifer; reporting[2];
1991	island-wide groundwater flow model; monitoring;
1992	investigation of point and diffuse source pollution; monitoring; publication of the Hydrogeological Map of Jersey;
1993	estimates of evapotranspiration; instrumentation of the Trinity catchment; monitoring;
1994	nitrogen profile study; monitoring; consolidation of results in the technical literature[3];
1995	nitrogen provenance study using nitrogen stable isotopes; groundwater degradation study; monitoring;
1996	landfill investigation, infiltration calculation; analysis and reporting[4] of the Trinity Catchment Study; monitoring.
1997	cavern-drip water chemistry investigation; monitoring; reporting.

In addition, a number of parallel studies have provided hydrogeological data. These include the Beauport and Crabbé landfill investigations, and data from the development of the storm drainage cavern at St Helier.

Collectively, these studies have involved three research institutes, two universities, and a variety of consultant engineers. The data now obtained allow reliable estimates to be made of the renewable groundwater resource, and of the sources and amounts of pollution.

1.2 JERSEY — THE ISLAND

1.2.1 Physiography and climate

Jersey, the largest island in the Channel Island group, is 16 km east to west and between 6 and 10 km north to south with a total area of 117 km^2. It comprises a plateau with an elevation of between 60 and 120 m above datum. The plateau is divided by a series of north to south incised valleys draining the higher ground of the northern part of the island to discharge along the south coast (Figure 1). From west to east the principal valleys are: St Peter, St Lawrence or Waterworks Valley, Les Grands Vaux and Queen's.

The northern coast is cliff-bound with small sandy coves. The west coast includes the wide sands of St Ouen's Bay, and the east coast includes the low lying Royal Bay of Grouville south of Gorey and the cliff lined St Catherine's Bay to the north. St Aubin's Bay dominates the south coast, with cliff lined bays to the west and a broad low lying rocky foreshore to the east. Elevations rise steeply away from the coast except behind St Ouen's Bay, the Royal Bay of Grouville and parts of St Aubin's Bay. The highest ground is situated adjacent to the north coast; between St John and Trinity elevation exceeds 130 m above datum. Spring tides may attain a range up to 12 m.

Prevailing winds are westerly and south-westerly and occasionally north-easterly. The climate is dominantly temperate maritime. Average annual rainfall is 877 mm (1951 to 1980) but areal distribution varies; there is significantly less rainfall in the west and south-west of the island than in the east. Mean annual temperature is 11.5°C, average sea temperature is 12.3°C, and relative humidity varies from 75% in early summer to 85% in the winter months. Mean annual potential transpiration lies in the range 648 to 754 mm.

1.2.2 Geology and soils

The oldest rocks of Jersey are the Jersey Shale Formation which are part of the Brioverian Supergroup (Figure 2). The shale is overlain by Brioverian volcanic rocks which progressed from andesitic to rhyolitic composition as volcanism proceeded. The rocks were then folded and metamorphosed during the Cadomian Orogeny and intruded by acid and basic igneous rocks including granite, granophyre, diorite and gabbro. Subsequent uplift and erosion led to the deposition of the Cambro-Ordovician Rozel Conglomerate Formation (Bishop and Bisson, 1989).

The dominant structural trend in Jersey is east-north-east to west-south-west. This is manifested in a series of deep-seated lines of structural weakness, one of which underlies the Val de la Mare valley and the St Ouen's sand deposits. A lesser trend from north-north-west to south-south-east is also apparent.

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[2] Hydrogeological and hydrogeochemical survey of Jersey, BGS Technical Report WD/91/15.

[3] Robins and Smedley (1994): Hydrogeology and hydrogeochemistry of a small hard-rock island — the heavily stressed aquifer of Jersey.

[4] The Trinity Catchment Study final report, 1996, IH Technical Report.

Photograph 1 Jersey from the air [Tourism Department].

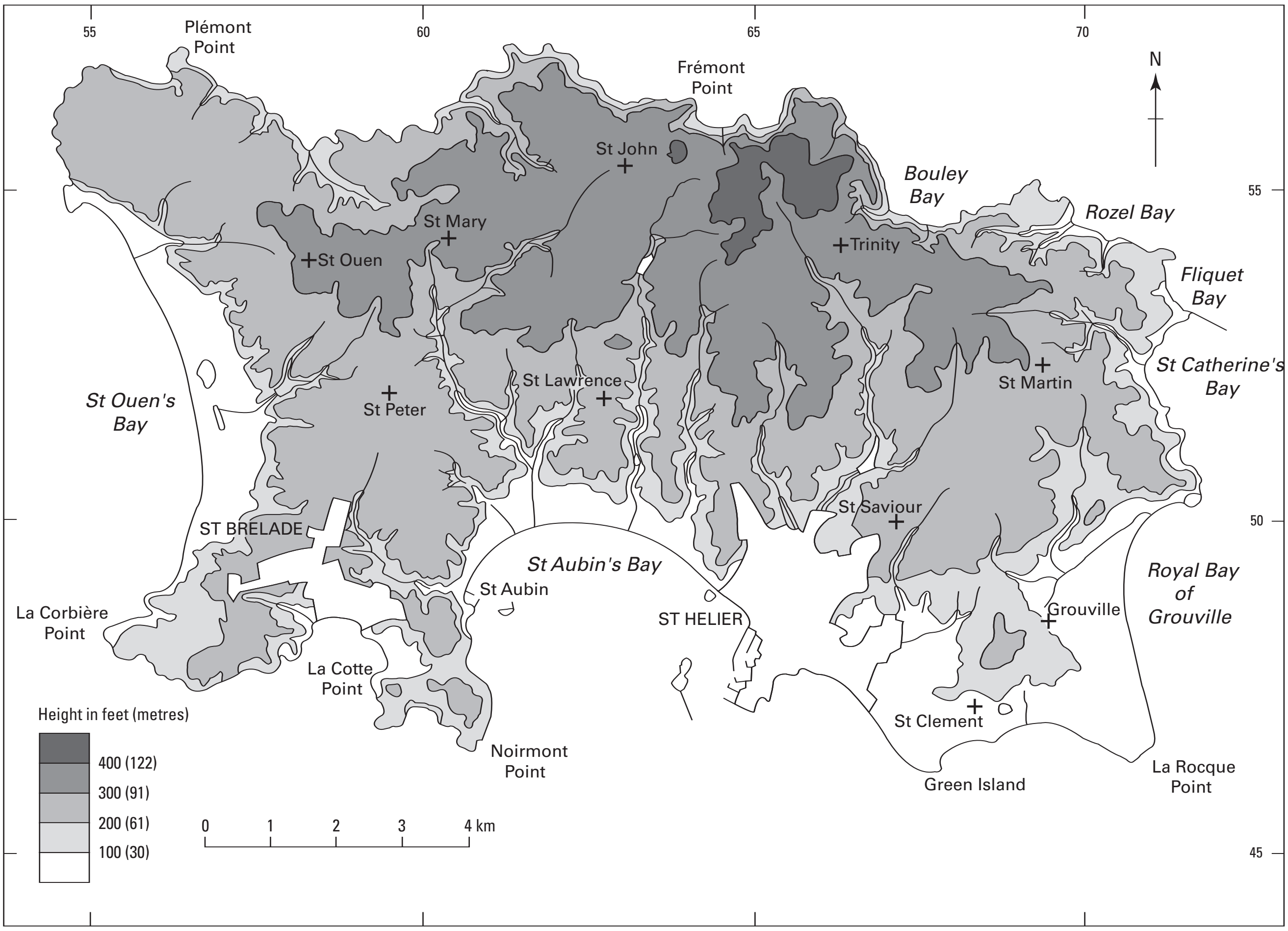
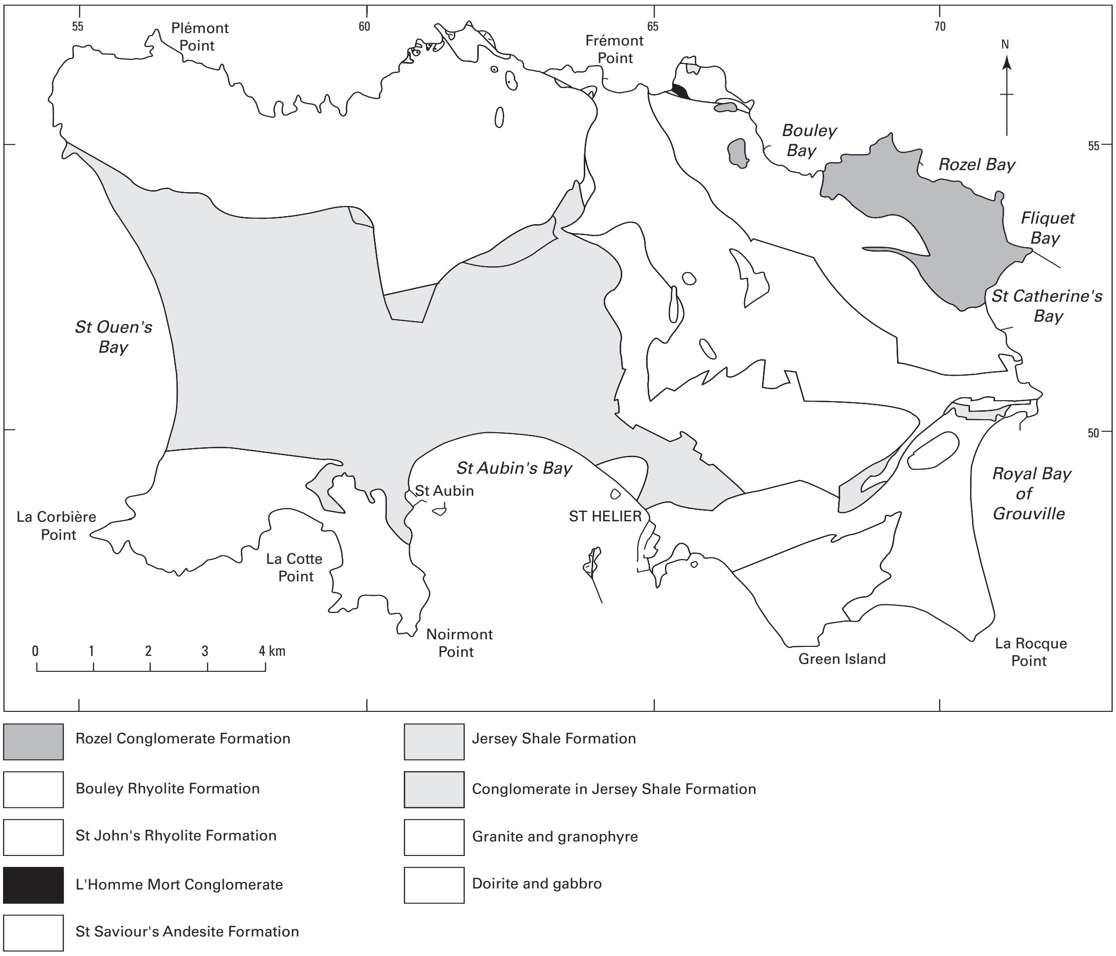


Figure 1 Topography and place names.

Figure 2 Solid geology.



Photograph 2 The St Ouen's sand aquifer and St Ouen's Pond [The National Trust for Jersey].

No further deposition took place over Jersey until the Quaternary (Figure 3). 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. These deposits influence soil type such that loess deposits coincide with loamy brickearth and sandy or peaty soils develop wherever the loess is absent.

1.2.3 Land use

Some 55% of the land area of the island is under cultivation, and in 1993 5% of the total land area (651 ha) was under some form of irrigation (Agricultural & Fisheries Committee, 1994). The principal crops that same year occupied the following land areas:

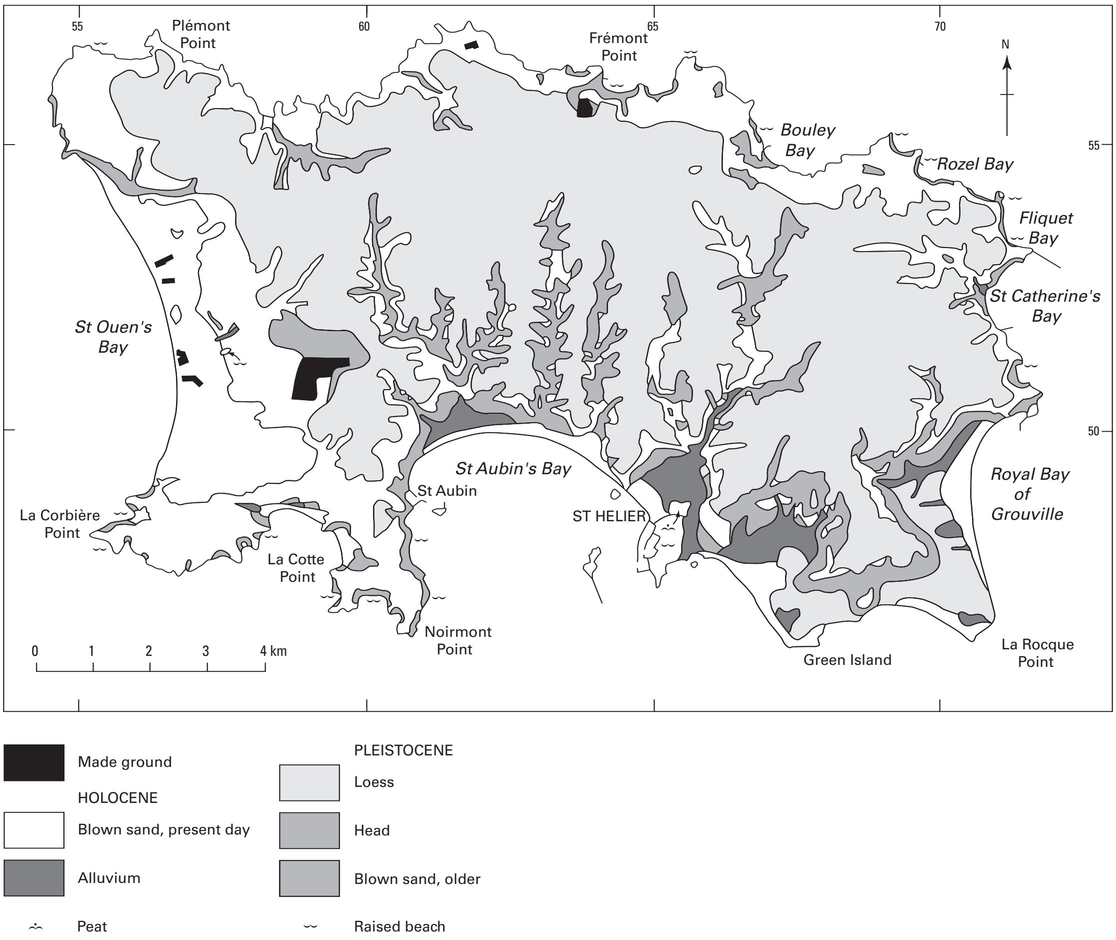


Figure 3
Quaternary geology.

Photograph 3
Les Mourier Valley
in granite [Tourism Department].

	ha		ha
early potatoes	3144	maincrop potatoes	214
cauliflowers	604	tomatoes	35
courgettes	240	calabrese	266
outdoor flowers	310	grassland	2307

Two crops per year can be obtained on some land and in addition, glasshouse production is also significant. The grassland supports over 4000 milkers out of a total dairy herd of nearly 7000.

The remainder of the island is divided between urban use, recreational (e.g. parks and golf courses), and small areas of rocky slopes and scrubland along some valleys and sea cliffs. The main urban area is centred on the town of St Helier which overlooks St Aubin's Bay and which was partly developed over reclaimed marsh land in the early Nineteenth Century. Rooftop and highway drainage in the urban areas tend to inhibit the potential for rainwater infiltration to the water table. The parks and golf courses are intensely cultivated with particular attention given over to nutrient and herbicide application and summer irrigation.

1.3 DEMAND FOR WATER

1.3.1 Demography

The resident population of Jersey was reported at 85 150 in the 1996 Census. During the first half of the Twentieth Century the population remained constant at about 50 000. In post-war years it has steadily risen, reaching 59 000 by 1961, 69 000 by 1971, 76 000 by 1981 and 84 000 by 1991. There are also currently some 20 000 tourist beds available in the island. Although the population is centred on the urban areas of the southern part of the island, there is a widespread and intensive distribution of rural dwellings across the whole of the land area.

Approximately 85% of people receive mains reticulated water supply and 82% have mains sewerage. The remainder have private water supplies, principally from groundwater, although there is some rooftop rainwater collection; these users discharge foul water to soakaways and septic tanks, although some also use private treatment or tight tanks. There are believed to be approximately 5200 private domestic premises dependent on groundwater sources.

1.3.2 Industry, agriculture, finance and leisure

Jersey supports light and service industries such as food processing, brewing, soft drinks, laundry and dry cleaning, photographic, as well as sand extraction and quarrying. All of these activities offer some degree of pollution risk to groundwater, but in all cases the risk can be minimised through *a duty of care* on the part of the operator. However, in perspective, the Jersey economy is based around the financial and tourist industries, with significant assistance from investment holdings; light industry and agriculture together only contribute about 6% of the Gross National Product.

Although no longer a significant influence on the Gross National Product, agricultural activity is very intense. The agricultural community, along with other landowners, more or less enjoys free riparian access to surface water and unregulated use of available groundwater; it is enthusiastic in the use of fertilizer to maintain the fertility of sandy soils which are naturally low in organic matter, and in the application of pesticides. These activities are not conducive to the optimum management of the water resources of the island.

1.3.3 Demand and recent trends

Water meters were placed on a number of boreholes under the Emergency Powers granted during the drought in 1989. The metered sources remaining have been used to provide a coarse idea of groundwater use and total groundwater demand by dividing the sample of 76 metered sources into categories of like uses (Table 1). For example, there were 24 boreholes with meters which were used for agricultural purposes (including irrigation) and the mean rate of abstraction from these over the sample period was 7.7 $m^3 d^{-1}$. Assuming that the density of agricultural boreholes and wells was 4 per km^2 and that there were 500 in all, this gives a total consumption or total demand of 3850 $m^3 d^{-1}$ (as it is seasonal it is more correctly reported as 1.4 $Mm^3 a^{-1}$). The same estimate can be made for other categories such as hotels and hospitals, industry and leisure. In the case of groundwater consumption for private domestic use, the 1991 Census reported 5400 households were dependent on wells and boreholes for supply, with a slight decline reported in the 1996 Census with 5196 households. Some of these, perhaps a quarter of them, may be shared sources, in which case the total number of private domestic wells and boreholes could be about 4000.

Though these estimates are approximate, they are the best available, because once the Emergency Powers were rescinded, the number of metered sources inevitably declined. The data suggest that the overall consumption of groundwater at that time was about 3.6 $Mm^3 a^{-1}$. Any improvement on these consumption estimates can only now be made with legislative support to increase the sample coverage.

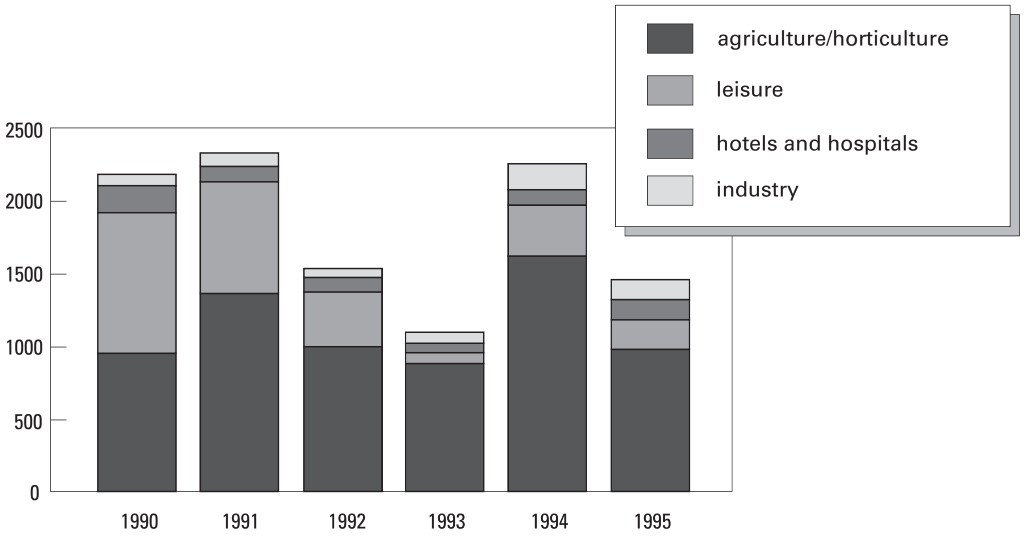
Given the assumptions and bearing in mind that the metered sample set has inevitably reduced in size with time, being modified by causes such as loss of access and pump abandonment during the monitoring programme, there are no real discernable trends during the 1990s (Figure 4).

Table 1 Estimated groundwater use 1989 to 1991.

Water use	Sample population	Mean consumption ($m^3 d^{-1}$)	Estimated number of sources	Annual abstraction (Mm^3)
agriculture	24	7.71	500	1.4
domestic	6	0.6	4000	0.9
leisure	9	42.4	50	0.8
public supply*				
hotels and hospitals	20	4.5	60	0.1
industry	10	10.9	20	0.1
total (including uncategorised)	76		4490	3.6

* Jersey New Waterworks Company figures.

Figure 4 Groundwater consumption ($Mm^3\ a^{-3}$) for selected categories of use.



Demand is variable from year to year with the dry warmer summers of 1991, 1992 and 1994 being greatest. It is likely that overall demand has been steady during the sample period.

However, a slight increase in groundwater use could be expected because approximately 70 new boreholes are drilled and commissioned each year, although about half of these are reported to be replacements for defective or dry boreholes (Baudains et al., 1993). It is possible that this slight increase in borehole numbers may be countered by a reduction in the use of domestic boreholes and wells through the expansion of mains water reticulation coverage.

2 Hydrogeology

2.1 PHYSICAL

2.1.1 The aquifers

A shallow, fractured bedrock aquifer underlies most of the island. Sustainable well and borehole yields are, for the most part less than 0.5 l s^{-1}, many less than 0.1 l s^{-1}. The highest sustainable yield known on the island is just less than 4 l s^{-1} from a borehole in the Volcanic Group (collectively the Bouley Rhyolite Formation, the St John's Rhyolite Formation and the St Saviour's Andesite Formation; Figure 2). The performance of boreholes varies geographically but lithological controls in the basement rocks are not a significant control (lithological control over groundwater chemistry is also small — see section 3.1.1.). Short-duration pumping tests tend to reflect local storage rather than the bulk parameters of the aquifer (Table 2), and the mean transmissivity value for the bedrock aquifer is 30 m^2 d^{-1}. This is a high value considering the nature of the aquifer and the performance of boreholes that draw on it. As there are many dry and low yielding boreholes unsuitable for testing, this figure approximates the best conditions available within the aquifer.

Site engineering investigations beneath St Helier and in the Queen's Valley indicate that the hydraulic conductivity of granite, migmatite and of the Jersey Shale Formation lies in the range 10^{-3} to 1 m d^{-1} (data supplied by PSD). A MODFLOW finite difference groundwater flow model developed by BGS in 1992 suggested that the range in hydraulic conductivity was 10^{-1} to 10 m d^{-1}, with the highest values occurring inland of St Aubin's Bay. However, the higher values probably reflect a pessimistic estimate of recharge, and an overall value for the main shallow bedrock aquifer is more likely to lie in the range 10^{-3} to 1 m d^{-1}.

Depth to the water table is generally only a few metres increasing to 10 to 30 m beneath higher ground. The piezometric surface follows a subdued version of the surface topography. For the most part, groundwater storage and transport is shallow and within the top 25 m of the saturated rock (i.e. from the water table to 25 m below it). This is borne out by the mean depth of penetration of boreholes on Jersey; it reflects reduced dilation of available cracks and fractures with increasing depth and pressure of overburden to the degree that the fractures can no longer conduct water. However, a few boreholes have encountered useable quantities of groundwater at depths up to 84 m below ground surface, and these may penetrate the deeper lines of structural weakness that trend east-north-east to west-south-west across the island. These features encourage deeper flow of groundwater than is normal elsewhere on the island, but the flow is of relatively limited volume with regard to the overall transport of groundwater beneath the island from recharge area to point of discharge[1].

It is not uncommon to intersect water under a confining head within a fissure during drilling. This happens when a fracture is penetrated which is interconnected to a higher elevation and which is also saturated, so that the water rises under the pressure difference to the water level of the higher elevation fissure. The classic example of this is the well at Fort Regent. This well was excavated using explosive charges, and was reportedly dry to a depth of 72 m. One final blast at that depth caused water to enter the well and rise up to a static level some 21 m below ground level, a level which reflects the water table beneath that part of Fort Regent. Needless to say, with a column of water some 30 m deep in the well, pumping has to be of short duration as it is almost entirely from storage within the well, with overnight recovery before more water can be withdrawn. A contemporary writer (Jones, 1840) describes the well as follows:

> After sinking through 235 feet of compact rock, and upon firing a blast the spring was laid open . . . when water poured in like a torrent, to the great astonishment of the miners, who were still suspended in the bucket, waiting the effects of the explosion . . . Twenty four men working for two hours can with ease pump into the [surface] cysterns 800 gallons of water.

This rate of abstraction is equivalent to a short term yield of 0.5 l s^{-1}.

In addition to the bedrock aquifer there are relatively thin Holocene sands which form shallow superficial aquifers behind St Ouen's Bay and the southern part of the Royal Bay of Grouville. The St Ouen's Bay sands are thickest in the southern part of the bay and become interbedded with peat horizons to the north. The sand aquifer is thin and protected from the sea by a rock lip so that a normal saline wedge is unable to develop and saline intrusion is not a cause for concern. The low-lying sand aquifer behind the southern half of the Royal Bay of Grouville is also interbedded with peat, is shallow, but is susceptible to saline intrusion during periods of intense pumping from boreholes in the coastal area.

2.1.2 Flow-paths

The level of the main water table (there are some local perched water tables particularly at times of prolonged and intensive rain) is shown on the Hydrogeological Map of Jersey (BGS, 1992). The configuration of the piezometric level readily allows flowpaths to be constructed. These indicate a regional or island-wide pattern of groundwater flow which discharges to the sea (Figure 5), and a local or catchment-wide flow pattern which discharges water as baseflow to surface water-courses.

Much of the island-wide flow concentrates on St Aubin's Bay as an outlet; this discharge can be seen on the foreshore across much of the bay at low tide, when a fresh to brackish seepage is maintained from the lower foreshore until it is again submerged by the rising tide. Very little groundwater flows to sea across the north coast where the

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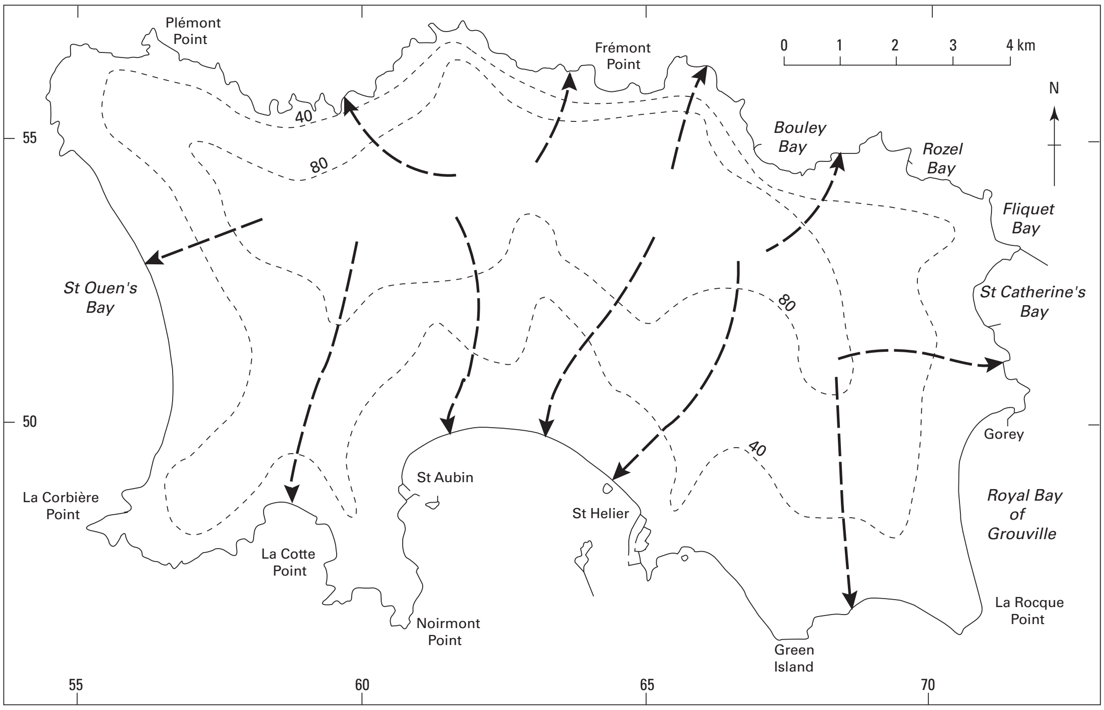
[1] This deeper fracture bound groundwater should not be confused with the mystical underground rivers that water diviners portray flowing from east to west bringing water from the Pyrenees to succour Jersey (and Essex in south-east England) under the driving force of the moon (Langlois, 1992; Baudains, 1992). No evidence to substantiate this vision has ever been presented by the diviners.

Table 2 Mean aquifer properties.

Formation	Specific capacity ($l\ s^{-1}\ m^{-1}$)	Population	Transmissivity ($m^2\ d^{-1}$)	Population
granite/diorite	0.8	11	35	6
Volcanic Group	1.2	15	25	4
Jersey Shale Formation	0.6	7	40	2
Rozel Conglomerate Formation	1.2	4	—	0
St Ouen's Sand Aquifer*	0.4	4	40	5

* Saturated aquifer thickness is only about 8 m, i.e. specific capacity is limited by the base of the aquifer, with a hydraulic conductivity of about 5 m d^{-1} (Watson Hawksley, 1982).

Figure 5 Island-wide groundwater levels and flow-paths.



aquifer appears to thin; the working face of Ronez Quarry, for example, is virtually dry, but there are a few modest seepages which are highlighted by iron-staining on the rock face. Discharge to the west and east coasts is controlled by topography and by the shallow sand aquifers that are present along parts of these coasts.

Groundwater flow is mostly shallow and the age of the groundwater is generally only a few tens of years (see section 3.1.2). The greater volume of flow takes place in the upper 25 m of saturated bedrock, preferring shorter, catchment-scale flow-paths. A small component of flow may take deeper pathways through selected and preferred deeper fissure systems, which mainly represent the longer island-wide flowpaths (see section 2.1.1). Such deeper systems have been located up to a depth of nearly 80 m below the water table at one site in Les Grands Vaux, although the sustainable yield of the boreholes is modest and their water quality distinctive (see section 3.1). Baudains et al. (1993) assert that there are many such sources, although they provide no supporting evidence.

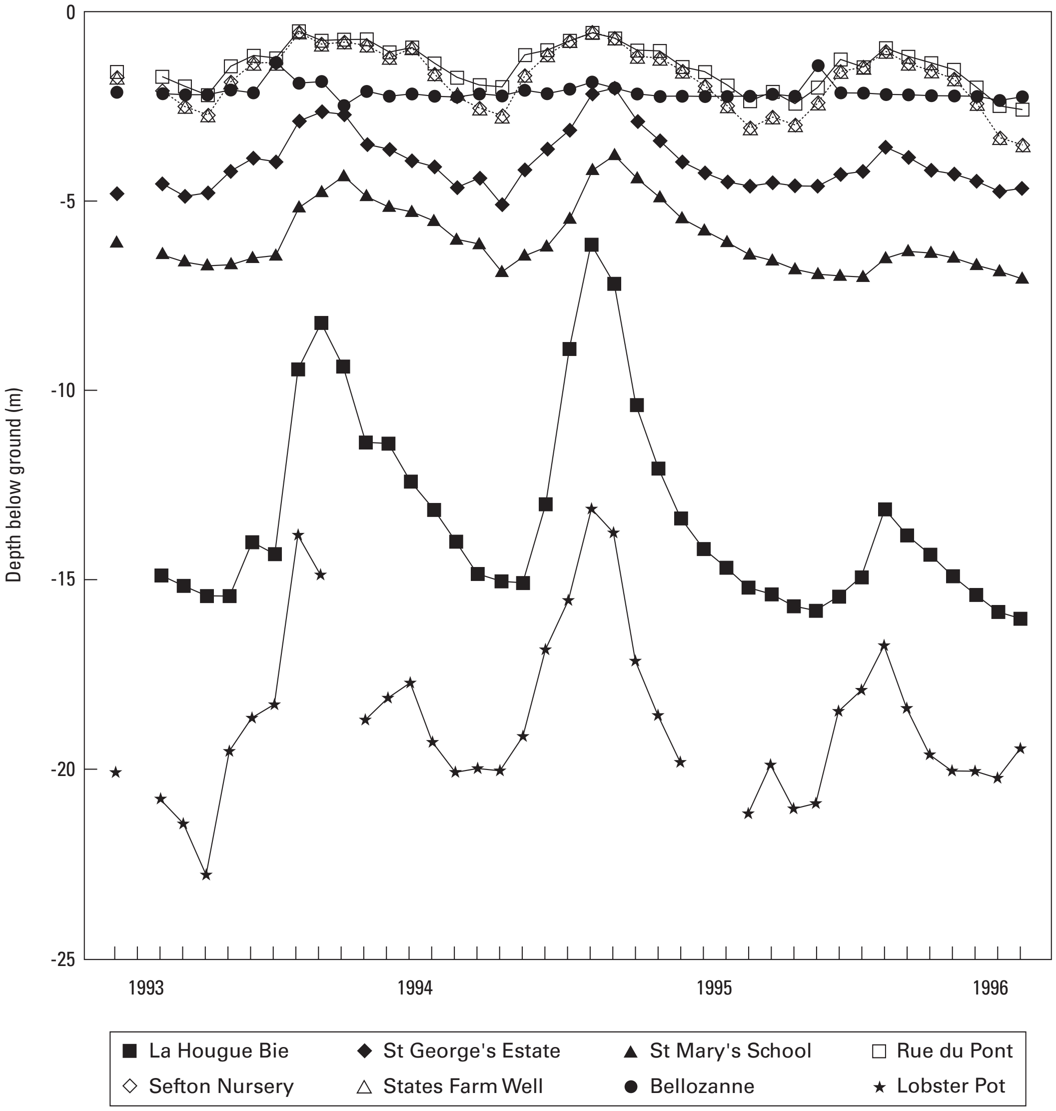
2.1.3 Storage

Hydrographs of borehole water levels are a means of determining the volume of recoverable groundwater in an aquifer. However, there are a number of difficulties in the analysis of Jersey hydrographs. One is that the density of abstraction boreholes is such that no observation point can be free from the influence of pumping, another that streams and reservoirs provide constant head boundaries which influence many sites, and a third that water level change in a fractured aquifer rarely has a linear relationship with storage.

Many Jersey borehole hydrographs fall to the same individual recession base-level beyond which little natural drainage appears to occur. This is the case for example at La Hougue Bie, St George's Estate and St Mary's School (Figure 6). It may be that the reduction in saturated thickness and, therefore, also of transmissibility, inhibits flow and further drainage, or it may be that the hydraulic conductivity is declining with depth and the aquifer becomes effectively impermeable below a certain level (i.e. the aquifer has been dewatered). Although many of the boreholes in which the water level has declined to this common level are still able to yield groundwater, albeit in reduced quantities, some go dry, only returning to production after a substantial recharge event. A combination of both dewatering and reduction in hydraulic conductivity with depth is, therefore, likely.

Not all boreholes recede to a common level (Figure 6). One group of hydrographs has exhibited a small but steady decline each year throughout the monitoring period (Rue du Pont, Sefton Nursery, States Farm Well) whereas another exhibits a steady trace (Bellozanne) or an irregular hydrograph (e.g. Lobster Pot). The first group indicates a steadily declining water table and a diminishing resource; the second indicates a water table that is influenced by a local constant head boundary; and the third a coastal borehole situated in an area of discharge where there is a steep and variable

Figure 6 Borehole hydrographs.



hydraulic gradient to the coast. The first group which shows a steady decline in water level are, however, the majority.

Groundwater storage can be estimated by multiplying the range in saturated thickness (above the level of natural drainage) by effective porosity. The hydrographs provide information on typical ranges: from only 0.2 m a^{-1} at St John, 5 m a^{-1} at Jubilee Youth Centre to a maximum observed range of 10 m a^{-1} at La Hougue Bie. A typical range is from 3 to 6 m a^{-1}. These variations reflect changes in effective porosity from one location to another as well as the hydraulic influences described above. That being so, an effective porosity of between 1 and 5% suggests a range in storage of between 30 to 300 mm a^{-1} equivalent depth of recharge.

2.1.4 Baseflow

Groundwater baseflow to surface waters can be calculated by conventional baseflow separation techniques. The baseflow data so derived allow a correlation with recharge as the one must sustain the other. However, there is a second component of baseflow which is less easy to derive, which is direct discharge into the sea. This occurs from two mechanisms: the first is from shallow coastal flowpaths which derive from recharge into a coastal catchment which discharges directly to the sea, and the second is from deeper and longer flowpaths which derive from inland catchments and flow ultimately to the coast, for example along St Aubin's Bay. The latter are relatively small in volume for the reasons given above, but are extremely difficult to quantify. Local flow path volumes can be determined on a catchment basis (see section 2.2).

2.1.5 Water balance

The water balance for the island is given by:

$$P = AE + Q \pm \Delta S \pm \Delta G$$

where P is precipitation, AE is actual evapotranspiration, Q is streamflow and direct runoff to sea, ΔS is the net change in soil moisture storage, and ΔG is the net change in groundwater storage. The capture and storage of surface water and its distribution and removal by way of mains reticulation and sewerage does not affect the balance, but loss of water from distribution pipes and sewers, however, provides a net gain. Groundwater abstraction discharged to soakaways and irrigation provides a net loss which is given by the volume abstracted less the volume returned; the volume returned may be as high as 60% of the volume abstracted.

Calculation of change in groundwater storage can be carried out by determining the other variables in the balance over a defined period of time (see section 2.2). During a period of recharge such as a normal winter, a net gain would be expected, whereas a net loss could be anticipated during the summer months. Indeed this is indicated by the borehole hydrographs (Figure 6), although recharge during the 1995/96 winter was of very limited extent. For the most part, recharge starts in November or December, and continues until February or March.

2.2 RECHARGE

Groundwater recharge is governed by:

- volume, timing and intensity of rain events;
- meteorological variables such as humidity, radiation, temperature and windspeed which control evaporation and transpiration rates;
- physical characteristics of the soil which determine soil moisture storage capacity and infiltration and percolation rates;
- vegetation types which determine water use and transpiration;
- topography, which together with rainfall intensity, soil characteristics and vegetation cover, determines the magnitude of rapid response runoff;
- aquifer characteristics which determine the relationship between groundwater and baseflow.

These factors can be investigated by detailed observation of weather, and ground survey of soil, soil moisture and vegetation. There are many techniques to estimate recharge, however, all are subject to uncertainties and errors (Lerner et al., 1990). The pragmatic approach is to compare estimates from a number of methods.

2.2.1 Instrumented catchment

An instrumented catchment was established in 1993 above the Grands Vaux Reservoir and centred on Trinity[2] with the aim of estimating recharge from the catchment water balance. The catchment area is 6.34 km^2, representing just over 5% of the area of the island. It is orientated north-south and rises from a permanent gauging weir at an elevation of 46 m above datum to Les Platons at an elevation of 13 m above datum. It is largely rural with intensively cropped arable land as well as grassland, but it also includes the villages of Trinity and Victoria Village. The expansion of mains water and sewerage is beginning to lessen the use of private supplies and soakaways in the area. Surface impoundment, rooftop runoff and groundwater are also used for irrigation, vegetable processing and dairy farming, light industry and by Jersey Zoo.

The catchment instrumentation comprised: six rainguage sites, four soil moisture sites monitored with a down-tube capacitance probe, an automatic weather station which was installed at Howard Davis Farm, and continuous streamflow measurement at the permanent weir. In addition, selective monitoring of groundwater abstraction and borehole water levels was carried out. Monitoring commenced in April 1993 and continued until March 1996.

Photograph 4 Typical borehole set-up for agriculatural purposes during a specific capacity test [Public Services Department].

2.2.2 Measurements from the catchment study

Over the first two years of the study the annual rainfall for the catchment was respectively 1205 mm and 1361 mm, and in the third and final year it was 776 mm (the long-term average for Howard Davis farm is 849 mm).

Baseflow separation, based on a standard statistical algorithm (Gustard et al., 1992), showed that on average 67% of the total streamflow derived from groundwater (i.e. the Base Flow Index was 0.67), whilst 33% had reached the stream by more rapid surface or near surface routes. Soil moisture was in deficit throughout the late spring, summer and early autumn in 1993, but the heavier rainfall of 1994 resulted in the longest period of groundwater recharge with the soil moisture in deficit for only a short period (Figure 7). In 1995, prevailing dry weather produced the longest period of deficit observed.

The data from the weather station enabled estimates of the catchment mean daily potential evapotranspiration (Et) to be made using the Penman (1948) method. For much of the first two years, rates were below the long-term average, but exceeded it for a large part of the third year.

2.2.3 Catchment modelling

The purpose of the modelling was to build upon the monitoring programme in order to predict daily values of actual evapotranspiration, soil moisture, groundwater recharge

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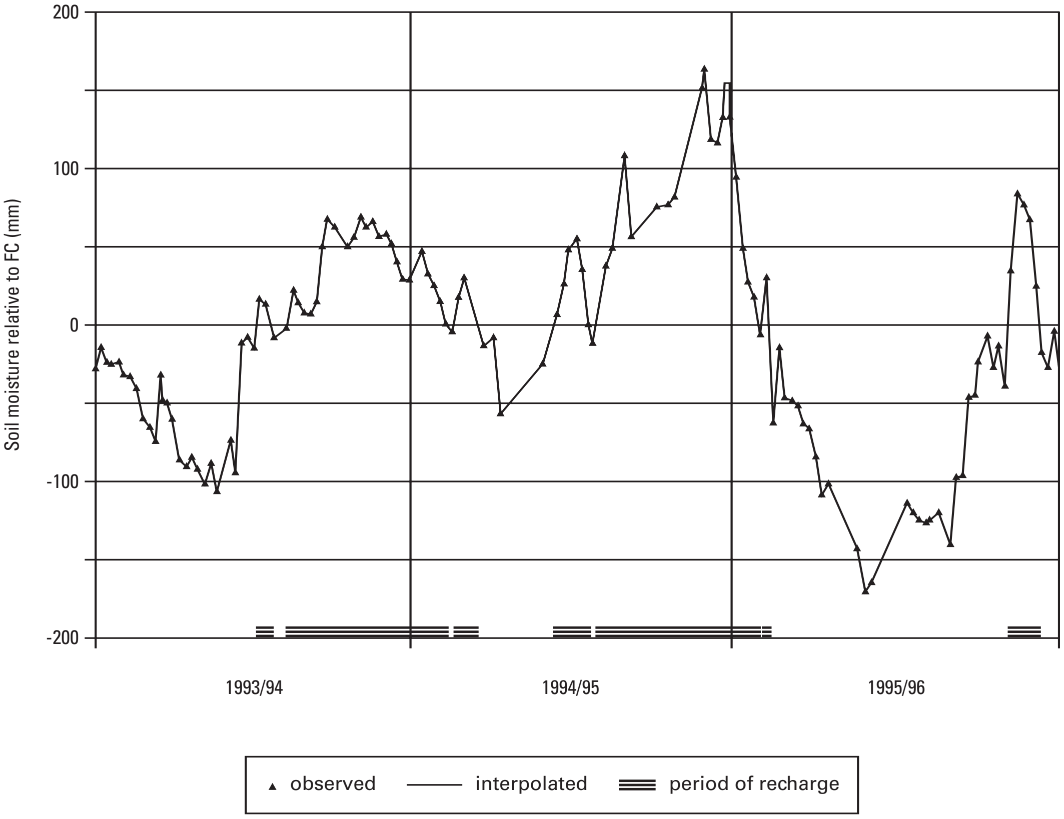
[2] For details, reference should be made to Blackie et al. (1996).

Figure 7 Soil mositure (as an equivalent depth greater or less than field capacity) relative to field capacity at Trinity Manor (after Blackie et al., 1996).



and streamflow from inputs of daily rainfall and potential evapotranspiration. It was assumed that the aquifer underlying the catchment was a discrete unit with no cross-flow to adjacent aquifers and no island-wide flowpath out of the catchment area (the actual volume of such a flowpath would in reality be relatively small).

The model was designed around a number of interconnected stores. Rainfall enters a surface store from which water may be lost to evaporation. Once rainfall exceeds the capacity of this store the excess is transferred to a quickflow store, representing direct runoff, and a soil moisture store. When the soil moisture store is at or exceeds the field capacity, soil moisture drains to the groundwater store as recharge. The process is controlled by a set of variables including the runoff coefficient, crop factor, root constant, permanent wilting point and the soil draining rate. The model operates on a daily time-step.

Calibration of the model was achieved by comparing model output for streamflow and soil moisture with observed field data. Incorporation of historical meteorological data then enabled the model to be run over the 28-year period from 1968 to 1996. Land use surveys indicated that the catchment was representative of land use throughout Jersey, and after application to the catchment the model was rerun for the whole island using island-average rainfall as input.

The model indicated that for the catchment, average annual recharge was 234 mm, and the corresponding value for the whole island was 132 mm. The difference is largely attributable to rainfall. During the 28 year simulation period the average rainfall for the island was 844 mm while the catchment average was 991 mm. However, the results each year were highly variable (Table 3, Figure 8), and during the periods 1975/1976 and 1981 to 1991 recharge was negligible and baseflow greatly diminished.

2.2.4 Other recharge estimates

In addition to the hydrological model, several other methods for estimating groundwater recharge have been attempted (Table 4). An initial estimate of 48 mm a^{-1} was made using simple soil moisture deficit calculations from available monthly data. It was recognised from the outset that this figure could be in error although it did provide a working value for recharge during the early stages of the survey.

Investigation of the profile of nitrate concentrations (section 3.2.2) in the soil water of the unsaturated zone at selected horizons (Chilton and Bird, 1994) indicated that water was moving downwards at a rate of 1 m in two to three years. Given a porosity of 35% this suggests an average annual recharge rate of between 67 and 100 mm.

The chloride mass balance technique indicates a similar range in values of annual recharge. However, this technique assumes 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 rainwater, groundwater and surface water hinder the sensible application of this technique.

More sophisticated methods have indicated that island-wide recharge is greater than 100 mm a^{-1}. For the most part, providing that the conceptualisation is correct, a model should provide a better indication of recharge in any given year than estimates derived by other methods, and the best available estimate is consequently that of 132 mm a^{-1}.

2.2.5 Induced recharge and runoff

About 1 400 ha of the early potato crop are covered in perforated polythene between February and April each year. This may promote additional runoff although there is usually little sign of erosion channels or other evidence of induced runoff at the bottom end of covered fields. Steep

Table 3 Estimated island water balance (mm) 1968 to 1996.

Year	Rainfall	Actual Et	Runoff	BFI	Recharge
1968/69	818	644	154	0.45	89
1969/70	874	662	200	0.51	104
1970/71	748	633	143	0.50	60
1971/72	708	595	122	0.38	33
1972/73	723	602	150	0.48	50
1973/74	763	626	103	0.28	60
1974/75	995	664	272	0.62	184
1975/76	617	624	105	0.46	0
1976/77	827	459	270	0.61	235
1977/78	1026	669	315	0.63	197
1978/79	838	605	258	0.60	157
1979/80	1007	670	307	0.63	191
1980/81	929	641	305	0.64	196
1981/82	996	586	447	0.73	328
1982/83	1034	668	369	0.67	246
1983/84	886	640	237	0.59	136
1984/85	833	595	225	0.56	127
1985/86	783	653	147	0.47	69
1986/87	877	621	275	0.64	179
1987/88	964	658	259	0.59	149
1988/89	704	628	143	0.46	54
1989/90	641	553	117	0.39	18
1990/91	645	569	79	0.19	11
1991/92	607	587	60	0.08	0
1992/93	944	639	233	0.55	181
1993/94	1015	596	385	0.67	300
1994/95	1166	615	539	0.72	389
1995/96	668	597	133	0.44	25
Mean	884	618	227	0.58	130

slopes, particularly in the coastal areas of the north and east coast may also enhance local runoff. More particularly, the influence of storm drains in the urban areas, the airport and elsewhere, roof catchments and rainfall directly to open water further restrict the potential for infiltration, but few of these are readily quantifiable.

On the plus side it is likely that about 20% of irrigation water will return to groundwater (a value of 30% is normally adopted for spray irrigation, but much of the irrigation in Jersey is root fed). This may amount to about 0.3 Mm^3 a^{-1} from both agriculture and leisure uses together. In addition, the 1996 Census reports some 4687 households connected to septic tanks and soakaways. Given average usage of 0.6 m^3 d^{-1}, this amounts to an addition return of 0.003 Mm^3 a^{-1}. Leakage from mains water pipes is believed to be very small and gains from streams and reservoirs are, in any case, mostly negative.

If the area given over to effective storm drainage and to open water amounts to only 2.3 km^2, then the loss to infiltration at a rate of 132 mm a^{-1} balances the 0.303 Mm^3 a^{-1} gain from irrigation and soakaways. It is likely, therefore, that these inducements will effect a small overall net loss rather than a gain, although it is not possible to quantify them further, and their effect on the overall water balance is likely to be small.

2.2.6 Resource potential

The catchment modelling indicates that the likely island-wide long-term average recharge or depth of infiltration is 132 mm. This has to sustain groundwater baseflow to streams, discharge to the sea and direct abstraction to boreholes. In addition, there is a contribution from return water from soakaways and septic tanks and from irrigation activities.

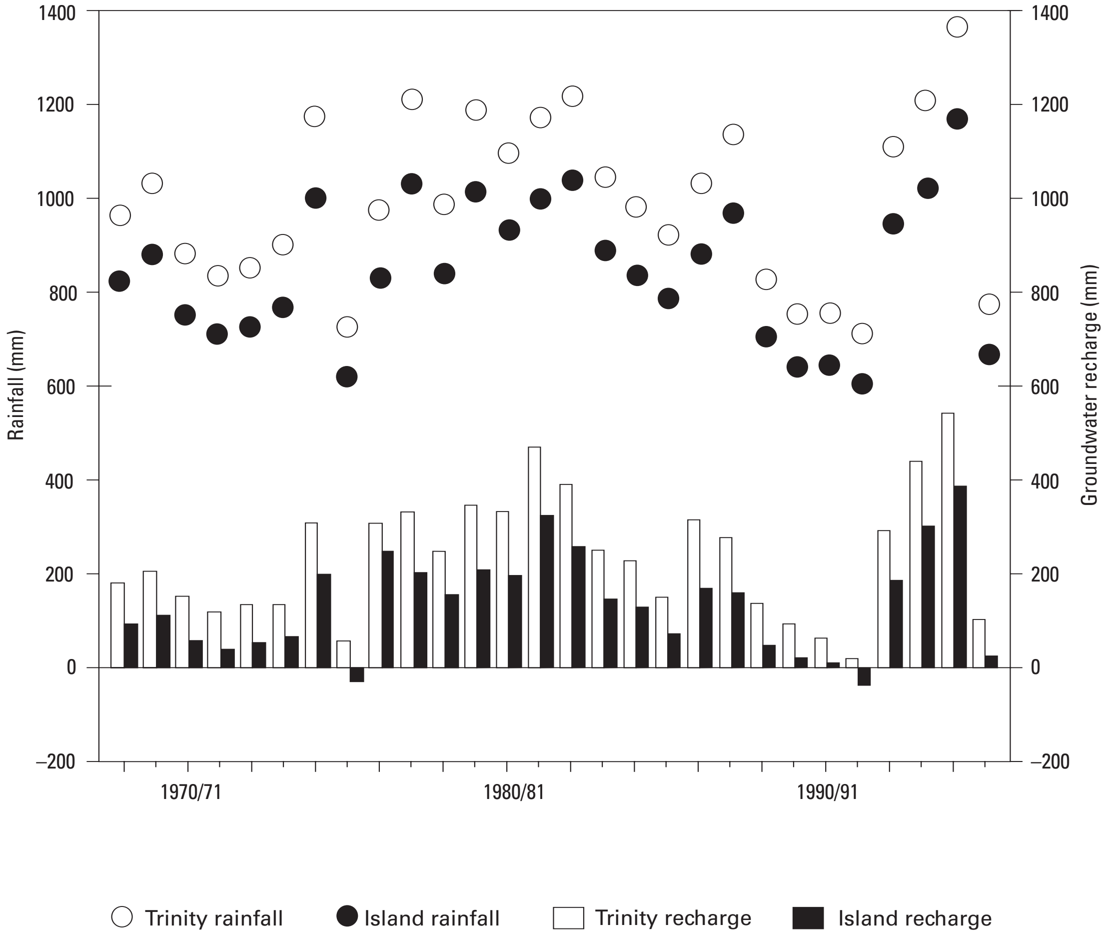
Comparison of the 28-year mean island-wide gross recharge of 132 mm with the known demands on groundwater and on baseflow indicates that just over half the available resource is used by man. Groundwater consumption amounts to about 3.6 Mm^3 a^{-1} (section 1.3.3) which is equivalent to a depth of water of 30 mm distributed over the whole of the island. Demand on baseflow from surface reservoirs and mains water supply is around 6 Mm^3 a^{-1}, equivalent to 55 mm a^{-1}. Only 58% (BFI 0.58) of this derives from groundwater baseflow (Table 3) and this represents 32 mm equivalent depth of gross recharge. The total demand on gross recharge is therefore 62 mm, i.e. just over half the long-term mean of 132 mm.

Thus, in average and wetter than average years, the demand is met, but in drier than average years there is a net loss to the groundwater store and problems may be encountered in satisfying demand. Any surplus is discharged to sea at the coast, any short term deficit is reflected in drying up of boreholes and springs particularly along the north coast and away from the natural areas of discharge along, for example, St Aubin's Bay. These sources quickly recover at the onset of the next significant recharge event. More significantly any shortfall in recharge will immediately have an adverse effect on baseflow given the current rate of groundwater abstraction. However, the resource is stressed in low rainfall years. These are becoming more common with climate change — there have been four years of less than 30 mm rainfall between 1988 and 1996.

Table 4 Estimates of groundwater recharge.

Source	Method	Recharge (mm a^{-1})	Comments
Watson-Hawksley (1986)	island-wide water balance	30	
Robins and Smedley (1994)	soil moisture modelling and baseflow analysis	48	based on monthly rainfall data
Chilton and Bird (1994)	nitrate profiles	67–100	
Blackie et al. (1996)	rainfall-runoff-recharge simulation	132	model calibration and validation based on Trinity catchment study
section 2.1.3	borehole hydrographs	30–300	

Figure 8 Modelled gross recharge over the 28 year period 1968 to 1996 (after Blackie et al., 1996).



3 Groundwater quality

3.1 HYDROGEOCHEMISTRY

3.1.1 Regional chemical trends

Hydrogeochemical investigations over the last seven years have established the main chemical characteristics of the groundwaters of Jersey. Most exploited sources abstract from shallow parts of the aquifers where flow is enhanced by fracturing. Groundwaters are largely of Na-Ca-HCO_3 or Na-Ca-Cl type with a few having relatively high SO_4 concentrations. The high Na and Cl (and SO_4) components reflect in particular the influence of maritime rainfall on local recharge, although salinity is further enhanced by localised saline intrusion in low-lying coastal areas and inputs from agricultural and domestic sources add a further contribution of Cl in particular. The local baseline Cl concentration is around 40 mg l^{-1}.

The concentrations of total dissolved solids (TDS) determined from the island-wide reconnaissance survey in 1990 range between around 150 and 1400 mg l^{-1} (Figure 9). Values are generally lowest in groundwaters from the north of the island and increase further south. This partly reflects geological variations, dissolved solutes being lowest in groundwaters from the Rozel Conglomerate and the Jersey Volcanic Group. However, the regional trend is also considered to be a function of increasing residence time of groundwater in the aquifers towards the south along regional groundwater-flow paths (Figure 5). Groundwaters from the south have had longer periods to accumulate solutes by reaction with silicate and other minerals in the aquifers.

Highest TDS concentrations are found in coastal areas, particularly the low-lying parts of Grouville and St Clement. This reflects localised saline intrusion as a result of low groundwater heads, although the effect at present rates of pumping is minor: major-ion and isotopic compositions of near-coastal groundwaters from the Grouville and St Clement areas suggest that a seawater component amounts to less than 1% of the pumped groundwater (Robins et al., 1992). In most areas, the groundwater head is too great for saline intrusion to be a major influence on groundwater chemistry.

Around 80% of the groundwaters investigated are acidic (pH<7) and almost all samples are undersaturated with respect to calcite. The pH values are lowest in the north of the island and increase southwards (Figure 10). This reflects the paucity of carbonate minerals in the aquifers, particularly in the Northwest Granite and the Jersey Volcanic Group, but is also related to increasing water-rock reaction along the groundwater-flow paths.

Most of the groundwaters are oxidising with high redox potentials and dissolved-oxygen concentrations. This reflects the shallow flow and hence ready access of air to the aquifers. However, a few groundwaters investigated are reducing with redox-potential values of 250 mV or less and low concentrations of, or undetectable, dissolved-oxygen. These are typically found in the low-lying south and south-east coastal areas as well as in valley locations around St Saviour (Robins and Smedley, 1991, 1994). Concentrations of Fe and Mn are often high in the reducing groundwaters. The regional patterns of groundwater flow in Jersey suggest that groundwaters welling up at the south and south-east coasts, albeit of small volume, have had longer flow paths, largely along north-south flow lines, and deeper circulation below the surface than in the more elevated parts of the island. Restriction of oxygen input from the surface and longer residence times is considered to be the most likely explanation for the occurrence of reducing waters in the low-lying coastal areas.

The shallow aquifers of Jersey are vulnerable to surface pollution inputs and many of the groundwaters show prominent evidence of such inputs, mainly from agricultural sources. Nitrate is an additional major anion in many of the groundwaters. Around 60–70% of groundwaters sampled throughout the seven years of investigation have concentrations of nitrate in excess of the EC maximum admissible concentration (MAC) for drinking water. Many sources also periodically exceed the limit for K and NH_4. Some of the K derives from natural mineral reaction, concentrations being particularly high in groundwaters from the Northwest Granite, possibly as a result of reaction of alkali feldspar. However, much is likely to be derived from agricultural sources. Of increasing concern is the evidence for detectable organic compounds (pesticides and non-aqueous-phase liquids) in many of the sources monitored.

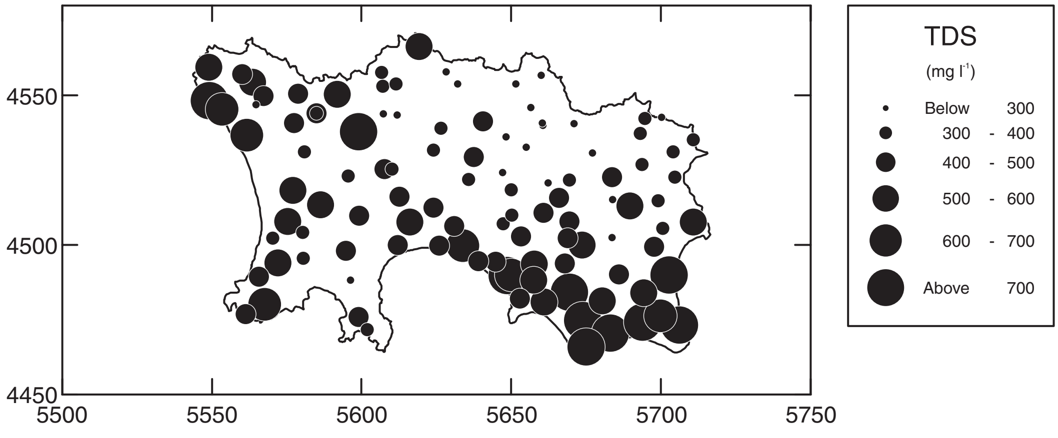
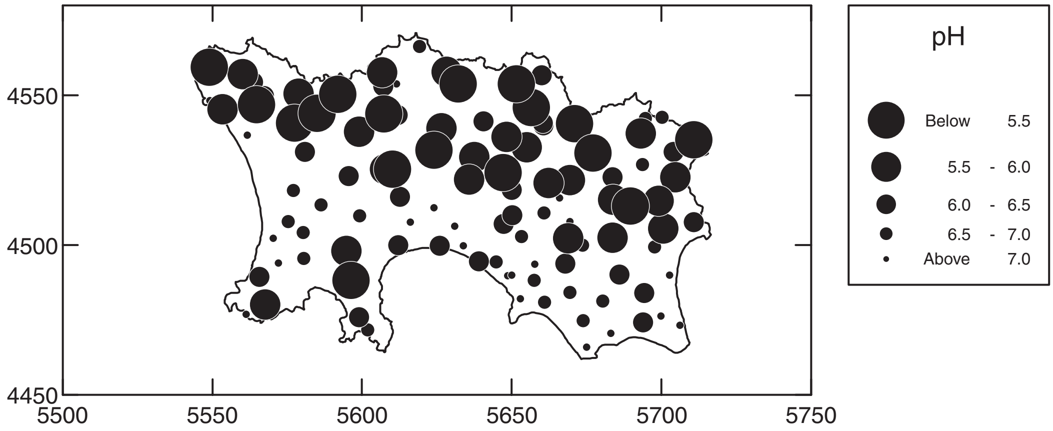


Figure 9 Regional distribution of TDS concentrations in groundwater, from the Spring 1990 survey.

Figure 10 Regional distribution of pH in shallow groundwater, from the Spring 1990 survey.



3.1.2 Groundwater residence time

Combined chemical and isotopic evidence suggests that the groundwaters represent predominantly recent recharge. Low TDS concentrations in the northern part of the island, acidic groundwater, dominance of oxygenated water and frequent presence of pollutants all point towards recent inputs to the aquifers. Stable-oxygen and hydrogen isotope ratios ($\delta^{18}O$ in the range -5.6 to -6.1 ‰ and $\delta^{2}H$ in the range -34 to -39 ‰) are also comparable to values for modern recharge determined from other areas under similar climatic conditions (e.g. UK; Smedley et al., 1989).

The most compelling evidence for dominance of modern recharge is observed tritium data. Tritium (^{3}H) is produced naturally by cosmic-ray bombardment in the upper atmosphere, but enhanced greatly in the environment in the 1950s and 1960s following development of the atomic weapons industry. With a half life of 12.3 years, much of the bomb-derived tritium in the environment has decayed since the 1960s peak but levels in rainfall in the northern hemisphere are still above natural background values. Weighted mean tritium concentrations in rainfall at Valentia Observatory in western Ireland were 6.1 TU in 1987. Values for continental stations were higher at between 20 and 40 TU in the same year (Robins and Smedley, 1994). Detectable concentrations of tritium in groundwaters indicate that they derive from, or at least contain a component of, recent post-bomb recharge.

Tritium concentrations for groundwater samples analysed from Jersey range between 2 and 22 TU. The lowest value was found in a groundwater from St Saviour and may indicate the presence of an older groundwater locally, though the value suggests that the age is unlikely to be more than a few decades. Most groundwaters have >7 TU. Such values are higher than would be expected for old groundwater having had no input of modern rainfall since the 1950s or 1960s and hence suggest a dominance of modern recharge.

The highest tritium concentration (22 TU) was found in a reducing groundwater from the coastal area of St Clement. The salinity of this groundwater (TDS 1440 mg l^{-1}, SEC 1800 μS cm^{-1}) suggests that it contains a small component of seawater although, as noted above, this amounts to less than 1% of the total and would therefore have a negligible effect on the tritium concentration. The implication is that the freshwater component derives mainly from modern recharge. The data indicate that even groundwaters from the low-lying south-east which have had longer flow paths (north-south) and possibly deeper routes of circulation do not represent old groundwater and are, therefore, still potentially vulnerable to surface-derived pollution.

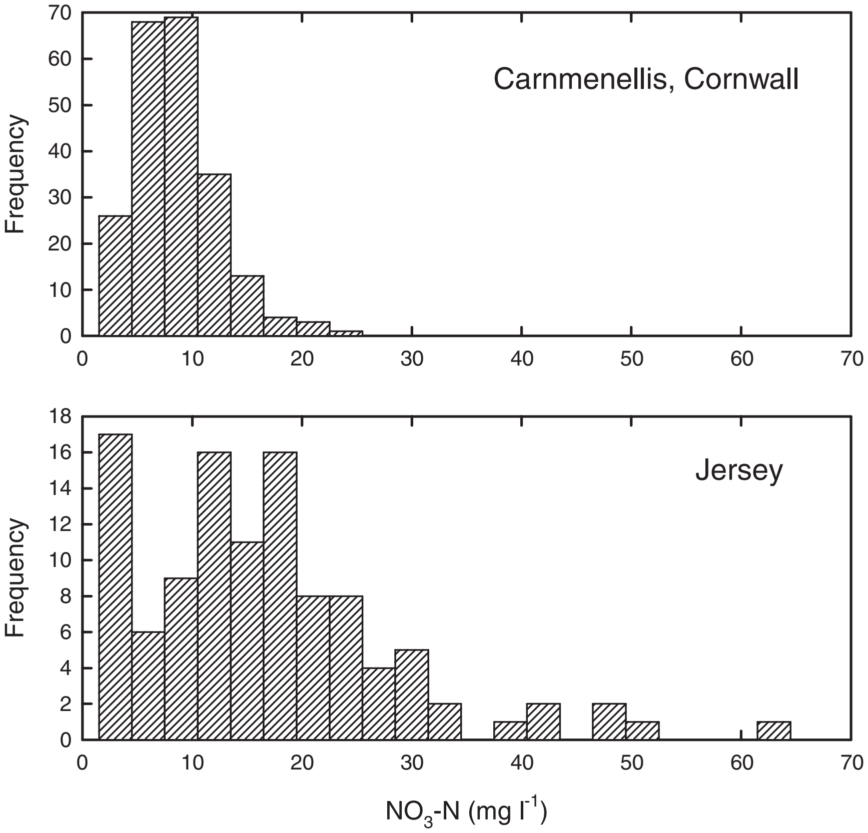
3.2 GROUNDWATER POLLUTION

3.2.1 Distribution of nitrate in the groundwater

Nitrate has long been identified as a prominent pollutant in water on Jersey. Foster et al. (1989) identified high concentrations and distinct seasonal fluctuations in streamwaters on the island. Monitoring of streamwaters in Trinity during 1994 for the IH catchment study also revealed high NO_3-N concentrations of between 6 and 19 mg l^{-1}, with marked

Photograph 5 Collecting a groundwater sample for chemical analysis at a St Helier Hotel [GS 466].

Figure 11 Histograms of NO$_3$-N concentration in groundwaters from Carnmenellis, Cornwall (from Smedley et al., 1989) and Jersey (Spring 1990 survey).



maxima during the autumn months when rapid runoff and leaching of nitrate from soil is greatest and minima during the summer when baseflow to streams and biomass uptake is highest (McCartney et al., 1995). High concentrations have also been found repeatedly in groundwaters from the BGS-PSD monitoring since 1990.

The EC health-based MAC for NO$_3$-N in drinking water is 11.3 mg l^{-1}. Although the EC regulations do not apply in Jersey, this limit serves as a useful guide to the degree of pollution of the groundwaters. Adherence to the limit would also be a safeguard for public health. Six-monthly surveys of the groundwater quality across the island have shown repeatedly that around 60–70% of the sources sampled exceed the EC limit, some significantly. A histogram of NO$_3$-N concentrations is given for Jersey (Spring 1990) in Figure 11. Concentrations in shallow groundwaters from the Carnmenellis area of Cornwall are given for comparison (Smedley et al., 1989). The Carnmenellis area has been chosen because of its very similar geology, climate and maritime aspect. Although many groundwater sources in Cornwall have NO$_3$-N concentrations close to 10 mg l^{-1}, water quality with respect to nitrate is worse in Jersey.

Under the UK Environment Agency's classification, all aquifers in Jersey would be classified as 'highly vulnerable' because of the importance of fracturing (by-pass flow), lack of impermeable cover and the shallow depth to the water table.

There is no clear geographical trend in the distribution of nitrate in Jersey groundwater, apart from in reducing groundwaters from the south coast (St Aubin's Bay) and south-east coastal areas where concentrations are usually below detection limits. A map of the regional distribution is given in Figure 12. In the oxidising groundwaters, the concentrations are considered to relate to local farming practice and to a less extent, inputs from local domestic sources (soakaways, septic tanks).

3.2.2 Nitrate in the unsaturated zone

Chilton and Bird (1994) investigated the chemical quality of porewaters from the shallow unsaturated zone in Jersey to assess the impact of land-use on the regional groundwater quality. The investigation focussed in particular on the distribution of nitrate, Cl and SO$_4$ in soil porewaters, and the influence of agricultural fertilisers on the chemical composition of unsaturated-zone profiles. Fourteen bore-

Figure 12 Regional distribution of nitrate in Jersey groundwater (from the Spring 1990 survey).

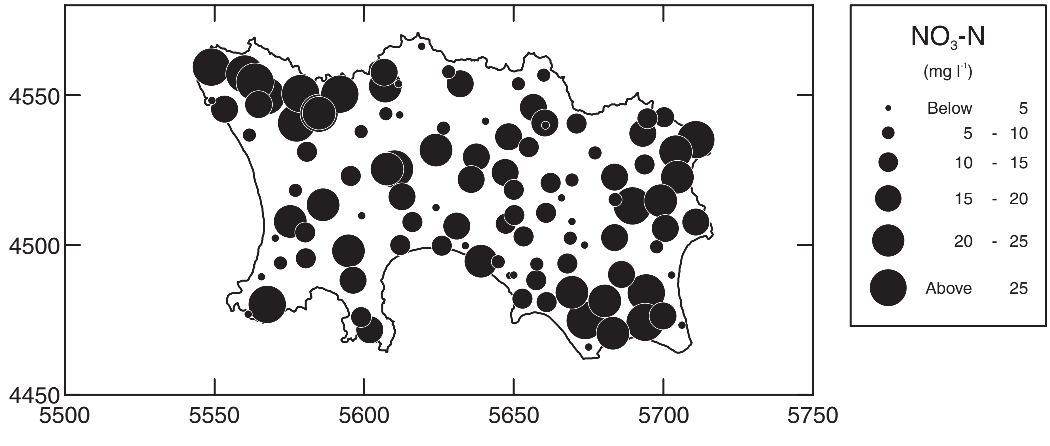
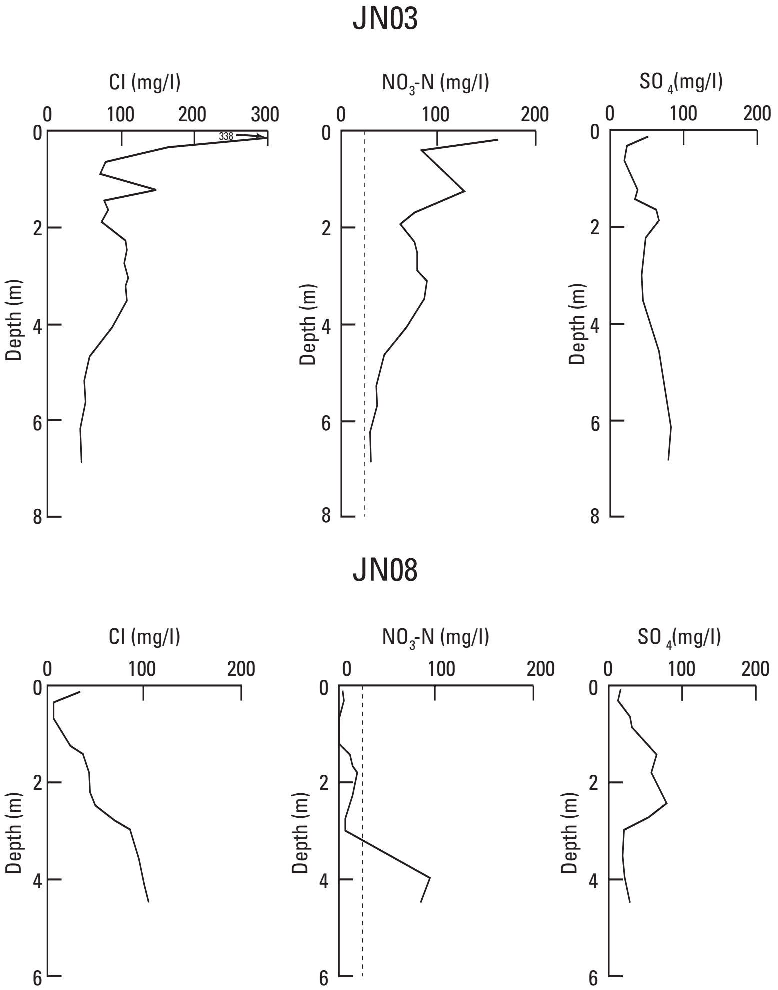


Figure 13 Profiles of solutes in the unsaturated zone, boreholes JN03 and JN08, from Chilton and Bird (1994).

Borehole JN03 was drilled in a field used for early potatoes followed by summer grass with applications of inorganic N fertiliser and cow manure. Borehole JN08 was drilled on fallow land, not fertilised since 1989. Before that, the field was used for early potato cultivation and was fertilised with inorganic N. The dashed lines on the NO_3-N plots indicate the EC MAC of 11.3 mg l^{-1}.



holes were drilled down to a maximum depth of 8 m below surface in field locations with variable cropping histories.

Results indicated a clear correlation between nitrate (and to some extent Cl and SO_4) concentrations in the porewater profiles and surface applications of fertiliser (Figure 13). Nitrate concentrations up to 140 mg l^{-1} were observed in porewaters beneath heavily cultivated fields and some profiles showed evidence for changes in land-use in the recent past. Borehole JN8 for example, had low NO_3-N concentrations in the top 2.5 m of the profile but higher concentrations below. The area was used for potato cultivation prior to 1989 but fallowed thereafter (Figure 13).

Inexplicably, some sites chosen as controls also had high porewater-nitrate as well as Cl and SO_4 concentrations at depth. Lack of detailed information about the land-use history of some sites has led to difficulties in interpretation of these data. Nonetheless, the high nitrate concentrations in porewaters below cultivated fields indicate that downward movement by piston flow will ultimately lead to nitrate and other dissolved pollutants entering the groundwater at the water table and impacting the regional groundwater quality. The possibilities for denitrification in the unsaturated zone are considered to be minimal as the unsaturated-zone environment is predominantly aerobic. This conclusion was also reached from investigations of denitrification in the unsaturated zone of Chalk and Triassic Sandstone aquifers in England (Kinniburgh et al., 1996).

Chilton and Bird (1994) estimated nitrogen leaching losses to groundwater from the nitrate profiles assuming an average annual infiltration figure of 60 mm. Losses of between about 11 and 25 kg N ha^{-1} a^{-1} were estimated for cultivated land. Subsequent refined long-term average infiltration estimates given by Blackie et al. (1996) of about 130 mm a^{-1} provide revised leaching-loss estimates of between 23 and 52 kg N ha^{-1} a^{-1} from the Jersey profiles. Such values are in line with leaching losses determined for cropped areas in the UK (cereals, legumes, fertilised grass; Chilton and Bird, 1994). Given the slow infiltration rates, this allows a significant concentration of nitrate to leach down to the water table.

Results of the unsaturated-zone profiling suggest that the rate of downward movement of water through the unsaturated zone is of the order of 1 m per 2–3 years. Even though the unsaturated zone is typically thin across much of the island, this slow rate implies that it would take a variable interval of between 5 and 18 years for diminution in surface N inputs to be reflected in reduction of nitrate concentrations at the water table. The high concentrations of nitrate in some of the porewater profiles from cultivated sites studied by Chilton and Bird (1994) suggest that groundwater quality may even deteriorate further as the porewater moves downwards and reaches the water table. Such a conclusion was also reached by Lawrence et al. (1983) for the Yorkshire Chalk aquifer where nitrate concentrations of 20–40 mg l^{-1} were found in unsaturated-zone porewaters. Nitrate concentrations have been increasing steadily in some groundwaters from the Yorkshire Chalk since the 1970s.

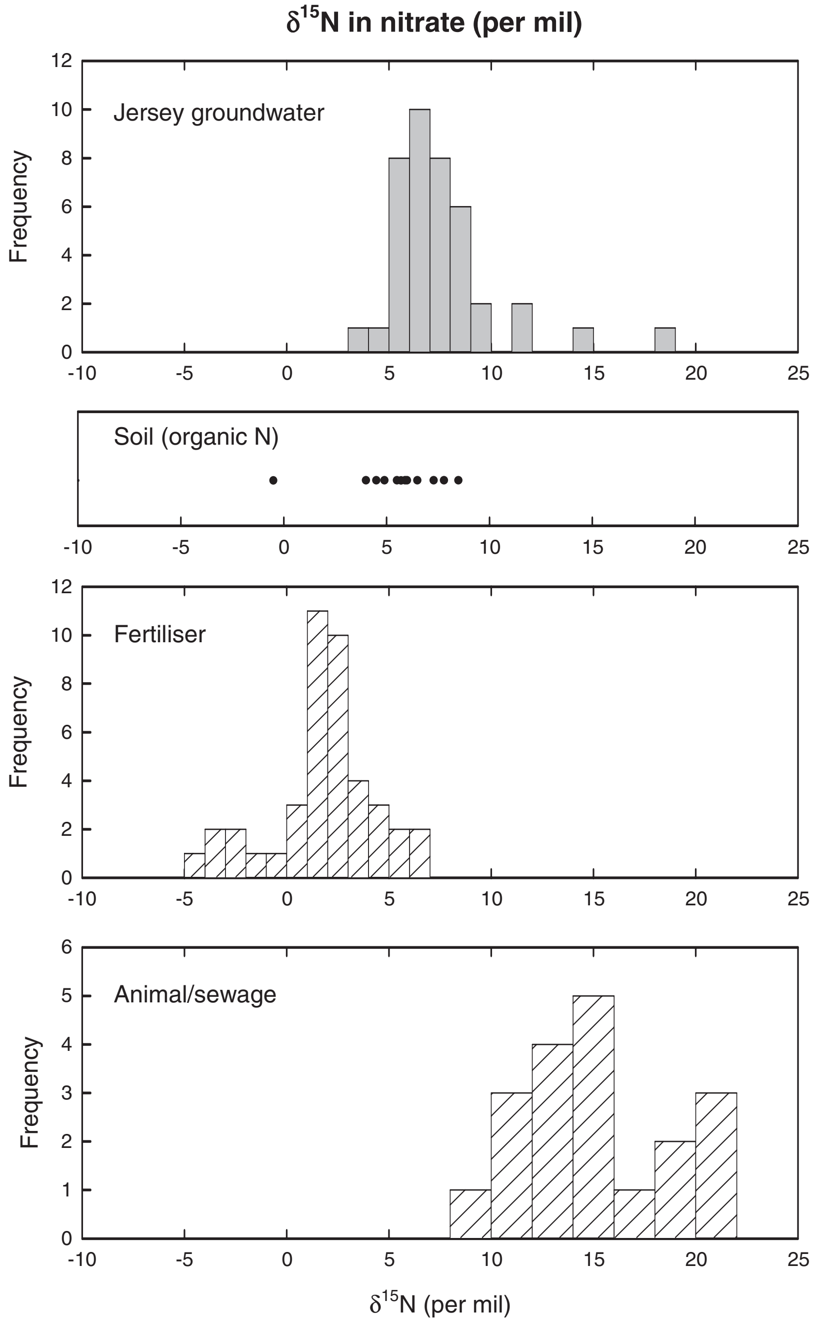
3.2.3 Nitrogen-isotope evidence

Green et al. (1998) carried out an investigation of the N-isotopic composition of Jersey groundwaters during Summer 1995 to determine the relative contributions of nitrate from fertilisers and domestic sources (soakaways, septic tanks) and to assess the importance of denitrification. They found $\delta^{15}N$ values (normalised $^{15}N/^{14}N$ ratios) ranging between +3.6 and +18.4 ‰ with a mean of +7.7 ‰ (40 samples) in groundwaters taken from monitoring sites across the island. Most values fell in the range +4 to +9 ‰ (Figure 14). Typical $\delta^{15}N$ ranges for NO_3 from fertilisers, animal wastes and sewage and from mineralisation of soil organic nitrogen are given for comparison (from Heaton, 1986). The values for Jersey groundwaters are similar to the values found for nitrate derived from mineralisation of soil organic N, and imply that this is the dominant source of the nitrate.

The production of nitrate by mineralisation of soil organic nitrogen can be described by the steps:

organic N Æ NH_4^+ Æ NO_2^- Æ NO_3^-.

Figure 14 Histograms of $\delta^{15}N$ of nitrate in Jersey groundwater (from Green et a., 1998) compared to values of nitrate from soil organic N, fertiliser and animal waste/sewage (from Heaton, 1986).



The degree of isotopic fractionation during this process varies according to the rates of each step and the relative amounts of the species available. In normal, recently undisturbed field environments, where there is not a great excess of NH_4, the nitrate formed by mineralisation has a $\delta^{15}N$ value close to that of the soil organic nitrogen, and values are typically in the range +4 to +9 ‰ (Heaton, 1986; Figure 14).

The similarity of the $\delta^{15}N$ values of Jersey groundwaters to those of soil organic nitrogen implies that the nitrate is derived by leaching from soil rather than from direct inputs of fertiliser or animal waste. However, following its application to the land, fertiliser and manure becomes heavily involved in biological transformations in the soil-vegetation system and its isotopic signature may be lost by exchange with the large volume of organic N present in the soil. Isotopic signatures of dissolved NO_3 in water may, therefore, resemble natural soil N, even though they are derived ultimately from fertiliser sources. Indeed, nitrate in groundwater derived by recharge from heavily cultivated soils often has isotopic compositions similar to those found in most of the Jersey samples (ca. +4 to +9 ‰).

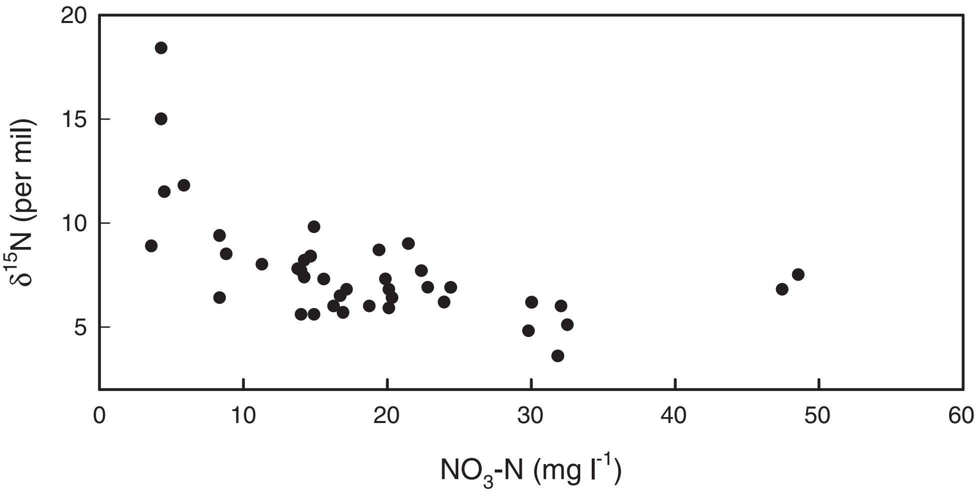
3.2.4 Denitrification

Green et al. (1998) found that reducing groundwaters from the south and south-east coasts of Jersey had heavier N-isotopic signatures (more positive) than most of the samples analysed. Heavy $\delta^{15}N$ compositions may result from direct inputs from sewage or animal waste (Figure 14) or from denitrification. As Green et al. (1998) argued, the former is unlikely since it would imply sewer leakage only from the southern part of the island in an area where the sewer system is relatively new and maintained under a negative pressure. Given the correlation between $\delta^{15}N$ and the NO_3-N concentration of the Jersey groundwaters (Figure 15), denitrification in the zone of reducing groundwaters appears much more likely.

Denitrification involves reduction of NO_3 to N_2 gas and requires the availability of suitable electron donors, such as sulphide, organic carbon or ferrous iron, to drive the process (Robins and Smedley, 1994). Organic carbon is present in the soil and in small concentrations dissolved in water. Sulphide may be present in small amounts in the aquifer as pyrite. Ferrous iron is ubiquitous in aquifers and is present in concentrations of several mg l^{-1} in the reducing Jersey groundwaters from the south and south-east coasts. It is, therefore, considered that electron acceptors are available to allow denitrification to take place. Additional evidence for denitrification derives from the fact that one of the most reducing groundwaters investigated (Sefton Nursery) has a tritium concentration of 22 TU, indicative of dominantly modern recharge. The implication is that the recharge water would have been initially high in nitrate and that this has subsequently been lost in the aquifer by reduction to gaseous N_2.

The denitrification process may be catalysed greatly by microbiological activity. Microbiological analysis (Robins and Smedley, 1991) identified several microbial groups, including denitrifying and sulphate-reducing bacteria, in groundwaters at several of the Jersey monitoring sites. They were absent however, from some of the most reducing groundwaters investigated. The presence of bacteria in some sources suggests that the denitrification process is microbially catalysed, but absence in the most reducing groundwaters suggests that the process may also be taking place by inorganic reduction.

Figure 15 Variations of $\delta^{15}N$ with NO_3-N in Jersey groundwaters (data from Green et al., 1998).



Some of the groundwaters with $\delta^{15}N$ compositions and nitrate concentrations intermediate between the two observed extremes (Figure 15) may result from mixing between isotopically-distinct oxidised and reducing (denitrified) groundwaters.

The denitrification process is considered to be minor and only important in the southern parts of the island where longer-flow-path groundwaters well up from depth and discharge to the sea. Since most groundwaters in Jersey are oxidising, there is little potential for natural remediation of the groundwater quality by denitrification.

Although groundwaters in the south and south-east have low nitrate concentrations, this cannot be taken as an indication that these have not been contaminated by other pollutants since the limited tritium evidence suggests that a major component comprises recent recharge.

3.2.5 Other inorganic pollutants

Application of fertilisers as well as leakage from septic tanks and soakaways can add other inorganic contaminants besides nitrate to the groundwater. The most important include Cl, SO_4, K, P, NO_2, NH_4 and possibly B. However, many of these determinands have less clearly-defined origins than nitrate as additional sources include water-rock reaction and seawater. Chloride and SO_4 concentrations have high baseline concentrations in Jersey groundwaters due to the influence of maritime recharge, potential for marine aerosol influences close to the coast and saline intrusion in low-lying areas. Porewater profiles showed generally good correlations between NO_3-N and Cl in the unsaturated zone (Chilton and Bird, 1994) and suggest that Cl is an additional pollutant applied with N-based fertiliser to the land surface (e.g. KCl, manure). The correlation with SO_4 is typically less good in the profiles, indicating either that SO_4 has a different transport behaviour in the unsaturated zone or that fertilisers are not always SO_4-rich (e.g. NPK fertiliser).

Potassium is an important component of fertiliser but has an important additional source from aquifer minerals. It is particularly high in the Northwest Granite (>10 mg l^{-1}), most likely due to dissolution of K-feldspar. Separation of the two influences is, therefore, difficult. Nonetheless, the observed correlation between K and nitrate in groundwaters collected in 1990 (Robins and Smedley, 1991) suggests that

Photograph 6 Nitrogen isotope sampling at a farmyard borehole [GS 464].

agricultural pollution is an important source of K regionally. Some groundwaters from Jersey exceed the EC MAC for K in drinking water of 12 mg l^{-1}.

Concentrations of NO_2 were only determined at a few sites during the seven years of investigation. Most analyses were below detection limits. The low values reflect the oxidising nature of most of the groundwaters. Nitrite is therefore not likely to be a problem in the Jersey groundwaters (Appendix 2).

Ammonium concentrations are likewise usually low (<0.1 mg l^{-1}) but occasional high values, above the EC MAC of 0.39 mg l^{-1} as N have been determined. Of samples collected during the Spring 1991 survey, 2.6% exceeded the EC MAC. The highest concentration was from a source heavily polluted with nitrate (and pesticides) and the source of the NH_4 is therefore most likely to be surface-derived pollution, where the NH_4 infiltrated to the groundwater directly has insufficient time to oxidise to nitrate. Some other sites with reducing groundwater also have relatively high concentrations (e.g. Sefton Nursery). This is likely to be a function of partial reduction of nitrate in the aquifer but some NH_4 may also derive naturally in this zone from desorption of the NH_4^+ cation from clay-mineral surfaces.

Phosphorus is generally present in only low concentrations in the Jersey groundwaters and is not typically a highly mobile element. Boron concentrations are variable across the island but are generally highest in the south-east coastal area (Robins and Smedley, 1991). The distribution is believed to be related closely to the influence of saline intrusion. Boron concentrations in seawater are around 4.5 mg l^{-1} (Hem, 1985), a value much higher than observed in any of the Jersey groundwaters.

3.2.6 Organic compounds (pesticides, NAPLs)

Monitoring of groundwater quality over the seven years has also included analysis of a large range of organic compounds. A summary of median values for monitored sites is given in Appendix 4. Most analyses give concentrations of these compounds below detection limits. However, relatively high concentrations, were detected of some compounds, notably some pesticides, as well as a few non-aqueous-phase liquids (NAPLs).

PESTICIDES

The presence of pesticides in drinking water can pose a significant threat to health since they are designed to be toxic, although toxicity of individual compounds to humans varies greatly. Pesticides include herbicides, insecticides, fungicides, growth regulators and crop desiccants. Among these, insecticides are often among the most toxic to humans. Commonly-used compounds include urea herbicides (e.g. isoproturon, chlortoluron, methabenzthiazuron, carbetamide, linuron, diuron), phenoxyalkanoic acid herbicides (e.g. mecoprop), triazines (e.g. atrazine, simazine, propazine, trietazine, terbutryn) and organophosphorus compounds (e.g. triazophos, ethyl parathion). The current EC Drinking-Water Directive imposes a maximum admissible concentration for any individual pesticide compound of 0.1 µg l^{-1} and a total-pesticide limit of 0.5 µg l^{-1}. Whilst this is not directly applicable to drinking water on Jersey, it serves as a useful guideline for water quality. Also, statutory regulations exist for pesticide concentrations in agricultural produce imported to EC countries.

Transport of pesticides to groundwater from the surface depends largely on depth of soil cover, soil permeability and potential for by-pass flow (allowing rapid access to the water table), as well as timing of application to crops. Pesticides applied at pre-emergence or in early plant development have greatest potential to leach into groundwater as they are more likely to come into contact with the soil.

Pesticides degrade in the soil environment, the rates dependent on factors such as soil temperature, moisture content, pH, organic matter, clay content, oxygen and microbial activity (e.g. Chilton et al., 1995). The potential for degradation is much lower below the soil horizon.

The most commonly detected pesticides in Jersey groundwater over the study period were chlorthal (a daughter product), atrazine and simazine. Chlorthal in particular has relatively high concentrations (notably detected at Atlantic Hotel, La Chenée, Geranium Farm, La Haute, La Mare Vineyards, Meadow Springs, Norwood, Priory Inn, States Farm well, St Peter's Nursery), occasionally in excess of the EC MAC (0.1 µg l^{-1}; section 3.2.7). Chlorthal is a horticultural herbicide used especially for brassicas, beans, onions and soft fruits. It is an important component of 'Decimate', a compound used regularly on Jersey and applied to crops at relatively high rates (chlorthal-dimethyl at typically around 4500 g ha^{-1}; Robins et al., 1993).

Detectable concentrations of atrazine and simazine were found at Atlantic Hotel, Chateau la Chaire, Geranium Farm, La Chenée, Oakbank, State Farm well, St Helier Nurseries) and atrazine has been detected repeatedly at Grouville Spring at up to 0.05 µg l^{-1}. Atrazine and simazine are more likely to have been used as general weedkillers for amenity purposes rather than for agricultural activities. Other pesticides detected periodically in the groundwaters include linuron, diuron, MCPA, mecoprop, carbetamide, methabenzthiazuron and trietazine, albeit at concentrations below the EC MAC.

NAPLs

Many of the organic compounds in common use are insoluble or sparingly soluble in water. These are classed as non-aqueous-phase liquids (NAPLs) and can be divided into dense liquids (DNAPLs) and light compounds (LNAPLs). Dense compounds include many of the chlorinated solvents and di- or tri-halomethanes (commonly termed THMs).

DNAPLs: these are denser and less viscous than water. They have a tendency to penetrate rapidly and deeply into aquifers as a result of density differences. Once present in groundwater, they may persist for long periods of time. The chlorinated solvents include dichloromethane (DCM), trichloromethane (TCM) and tetrachloroethene (PCE), which are commonly used in paint strippers and aerosols. They have several breakdown products which are occasionally detectable in polluted groundwaters. Di- and trihalomethanes are by-products of water chlorination and presence in groundwater can result from leaking water mains. They are often generated from competitive bromine substitution on chlorinated hydrocarbon compounds, resulting in compounds such as bromochloromethane, bromodichloromethane and bromoform.

LNAPLs: many light non-aqueous-phase liquids are used as fuels and fuel additives. They are less dense than water and hence have a tendency to float rather than sink to the base of an aquifer. Their transport is therefore determined by the regional hydraulic gradient. LNAPLs can derive from car exhausts and petrol spillages. Compounds include benzene, toluene, ethylbenzene, xylene (BTEX components of fuel) as well as methyl-*t*-butylether (MTBE), present at concentrations up to 10% in unleaded petrol. MTBE has a much lower toxicity than the BTEX additives but is considered to be non-biodegradable and hence persistent in the groundwater environment.

Photograph 7 The Grouville Spring [GS 465].

The current EC Drinking-Water Directive has set a guideline value for individual compounds in this group of 1 µg l^{-1}, although MACs are assigned to only three compounds: tetrachloromethane (CCl_4, 3 µg l^{-1}), trichloroethene 30 µg l^{-1}) and tetrachloroethene (10 µg l^{-1}). The limits are an order of magnitude higher than for pesticide compounds.

Concentrations of investigated DNAPLs are often detectable in the Jersey groundwaters although individual compounds are usually <0.5 µg l^{-1}. Detected compounds include tetrachloroethene, trichloroethene, 1,1,1-trichloroethane, 1,3-dichlorobenzene, 1,2,4-trichlorobenzene, 1,2,3-trichlorobenzene and hexachlorobutadiene. Of the compounds with assigned EC MACs, the only observed exceedance was for tetrachloroethene, with a concentration of 12 µg l^{-1} at one site (Besco Laundry, median 10 µg l^{-1}, Appendix 4). It is likely that this derives from local leakage from dry-cleaning operations. Low concentrations of this compound were also detected at La Mare Vineyards (up to 0.4 µg l^{-1}) and Priory Inn (up to 0.7 µg l^{-1}). These sites either have shallow water tables or are open wells, and are, therefore, vulnerable to pollution inputs from the surface. Concentrations of trichloroethene were usually <0.5 µg l^{-1} and tetrachloromethane was everywhere <0.1 µg l^{-1}.

The only monitoring site showing evidence of detectable concentrations of di- and tri-halomethanes is Atlantic Hotel, where concentrations up to 20 µg l^{-1} have been found for total analysed compounds of this type. The borehole is used for supplying a swimming pool and the high concentrations locally are probably related to leakage from the system. The fact that halomethane compounds have not been found elsewhere in Jersey groundwaters suggests that leakage of chlorinated water from public-supply mains is not a significant problem.

Detectable concentrations have also been found of the LNAPLs at various sites across the island but fewer determinations have been made for these compounds. They include benzene, toluene and *n*-butylbenzene, although concentrations are usually <0.5 µg l^{-1}.

The fact that so many organic compounds are detected, albeit at low concentrations, in Jersey groundwaters is of environmental concern. The poor groundwater quality warrants the implementation of measures to protect the resource from agricultural, industrial and domestic pollution. Even with immediate improvements in practices related to the use of organic compounds, it is likely to take many years for the quality of Jersey groundwaters to reflect the changes.

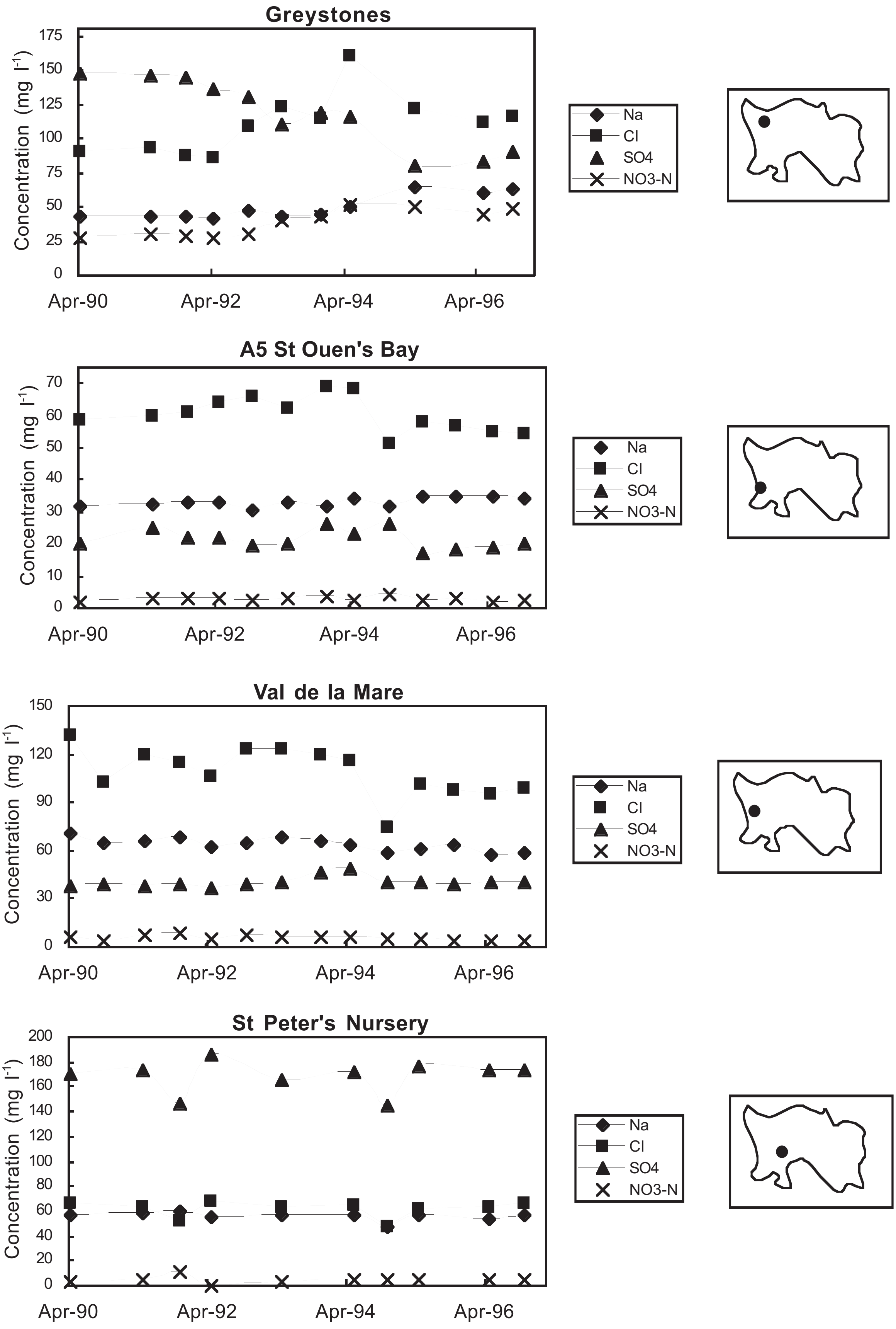


Figure 16 Temporal trends in Na, Cl, SO_4 and NO_3-N in groundwaters from selected sites.

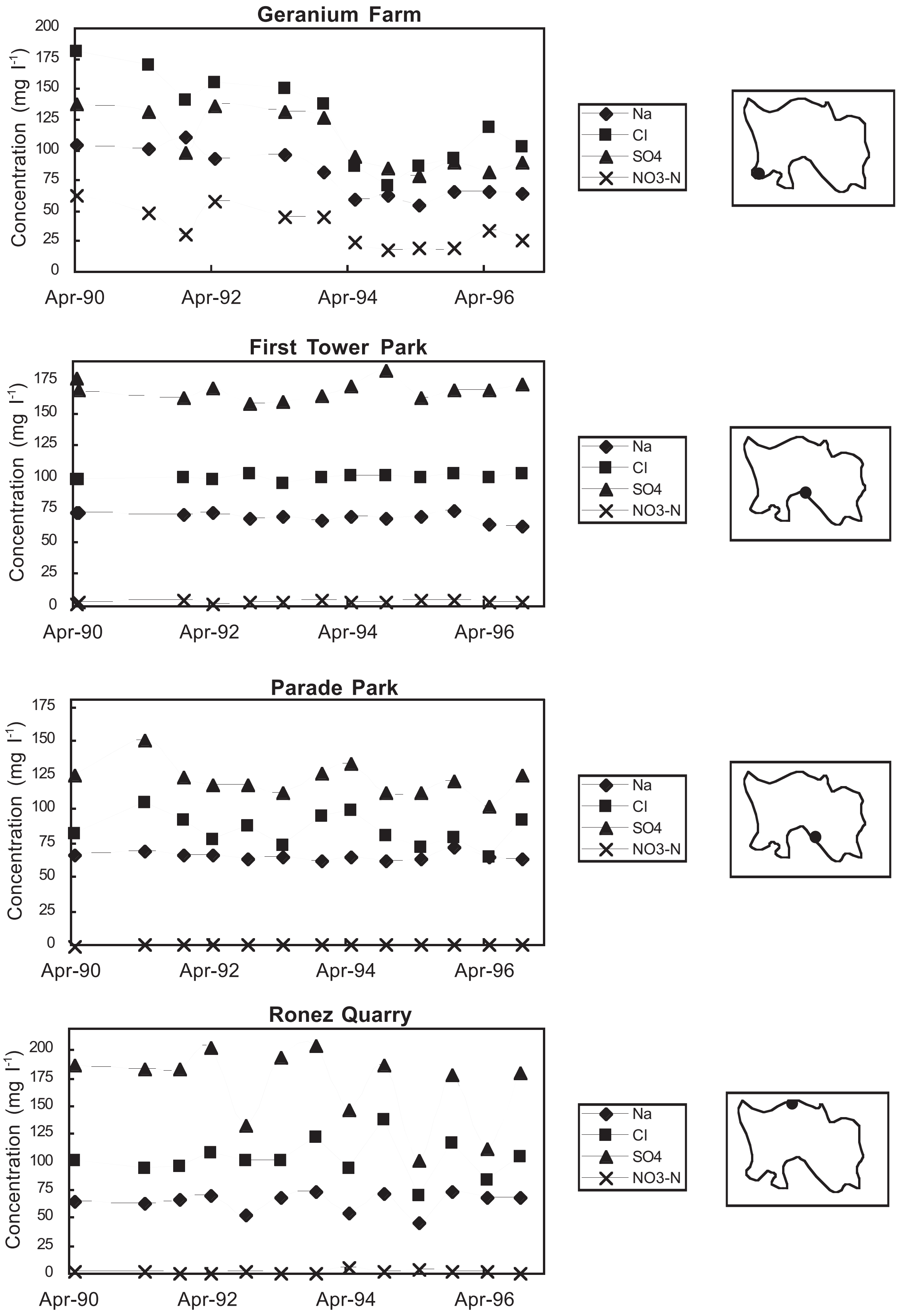


Figure 17 Temporal trends in Na, Cl, SO_4 and NO_3-N in groundwaters from selected sites.

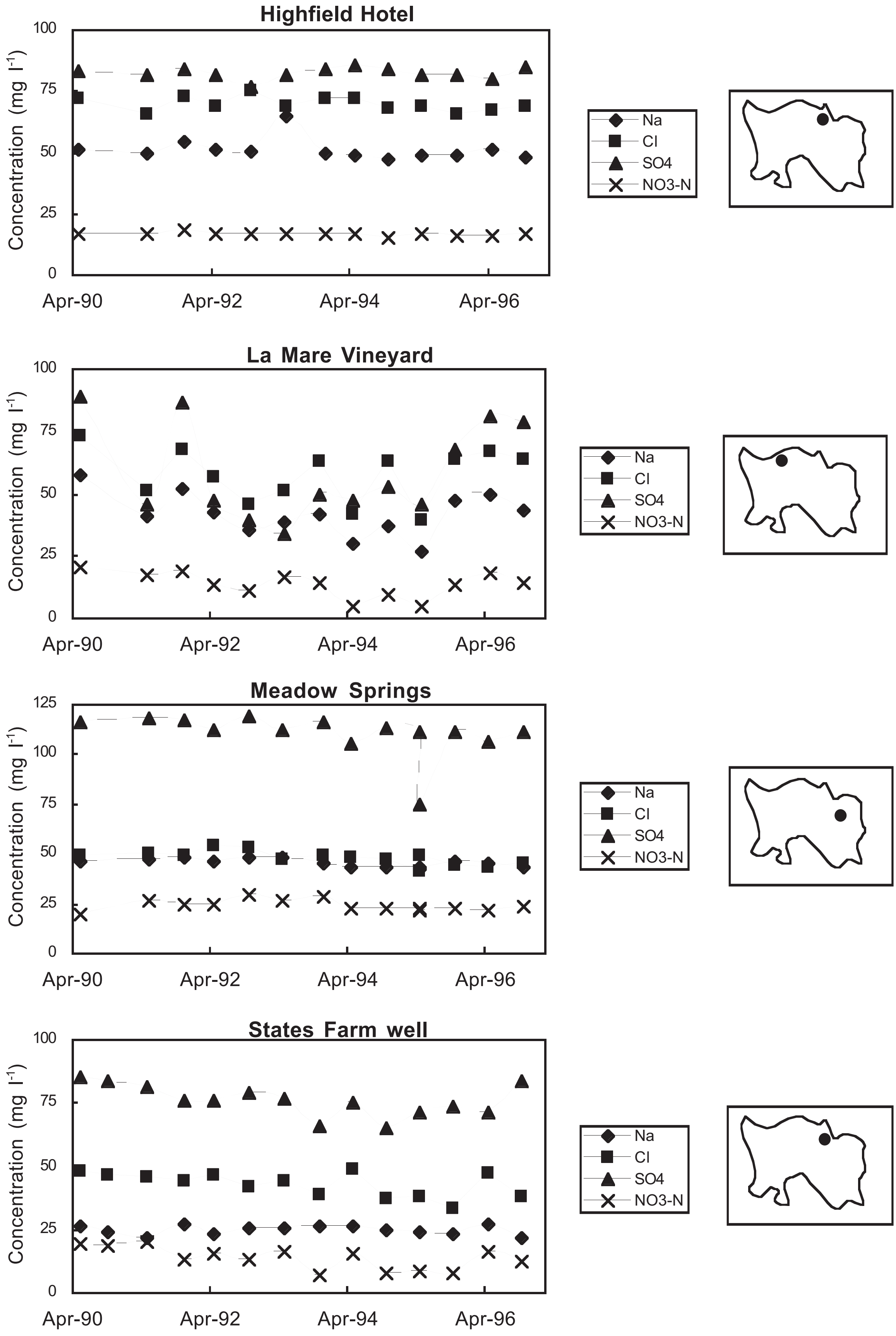


Figure 18 Temporal trends in Na, Cl, SO_4 and NO_3-N in groundwaters from selected sites.

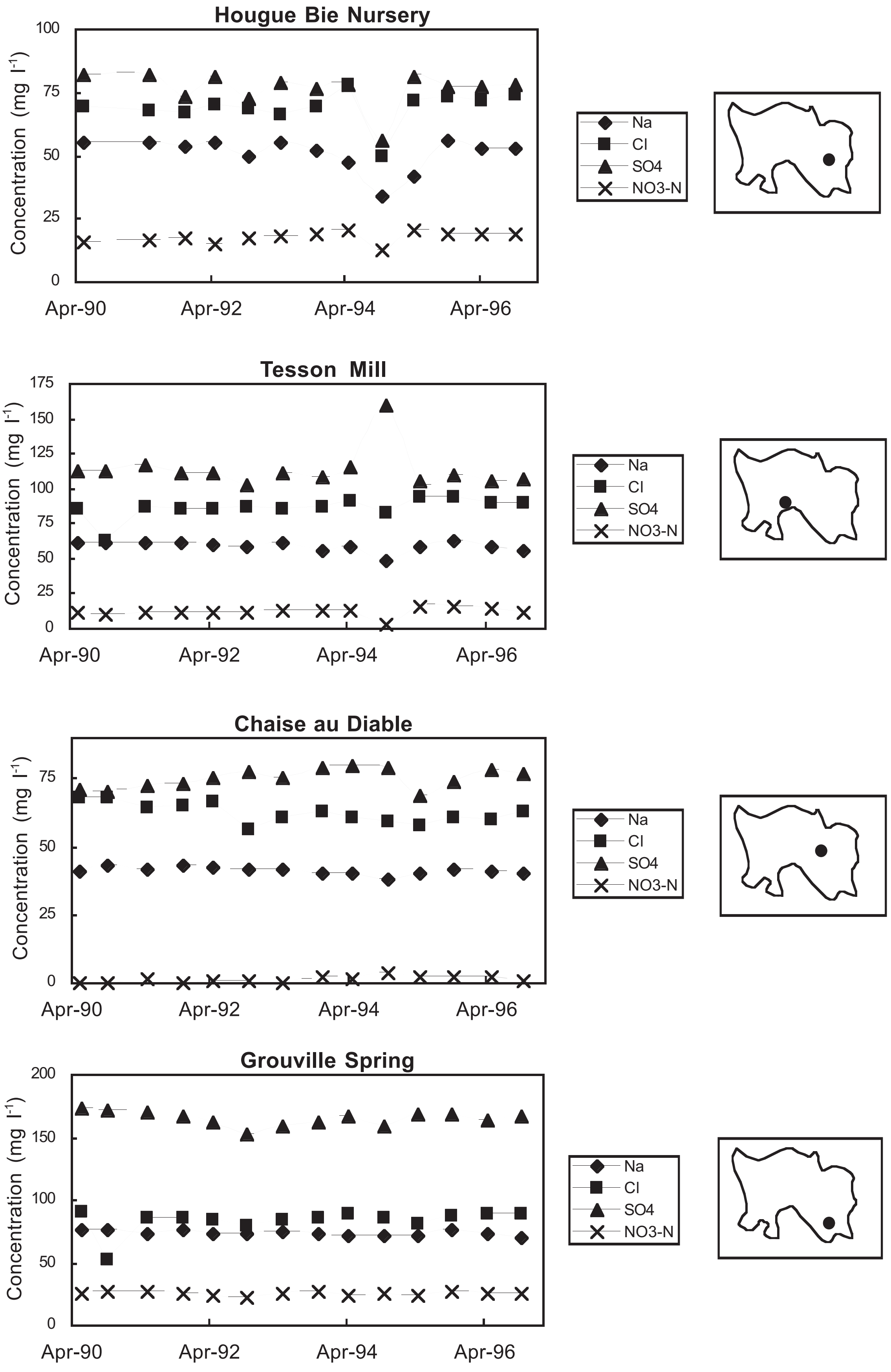


Figure 19 Temporal trends in Na, Cl, SO_4 and NO_3-N in groundwaters from selected sites.

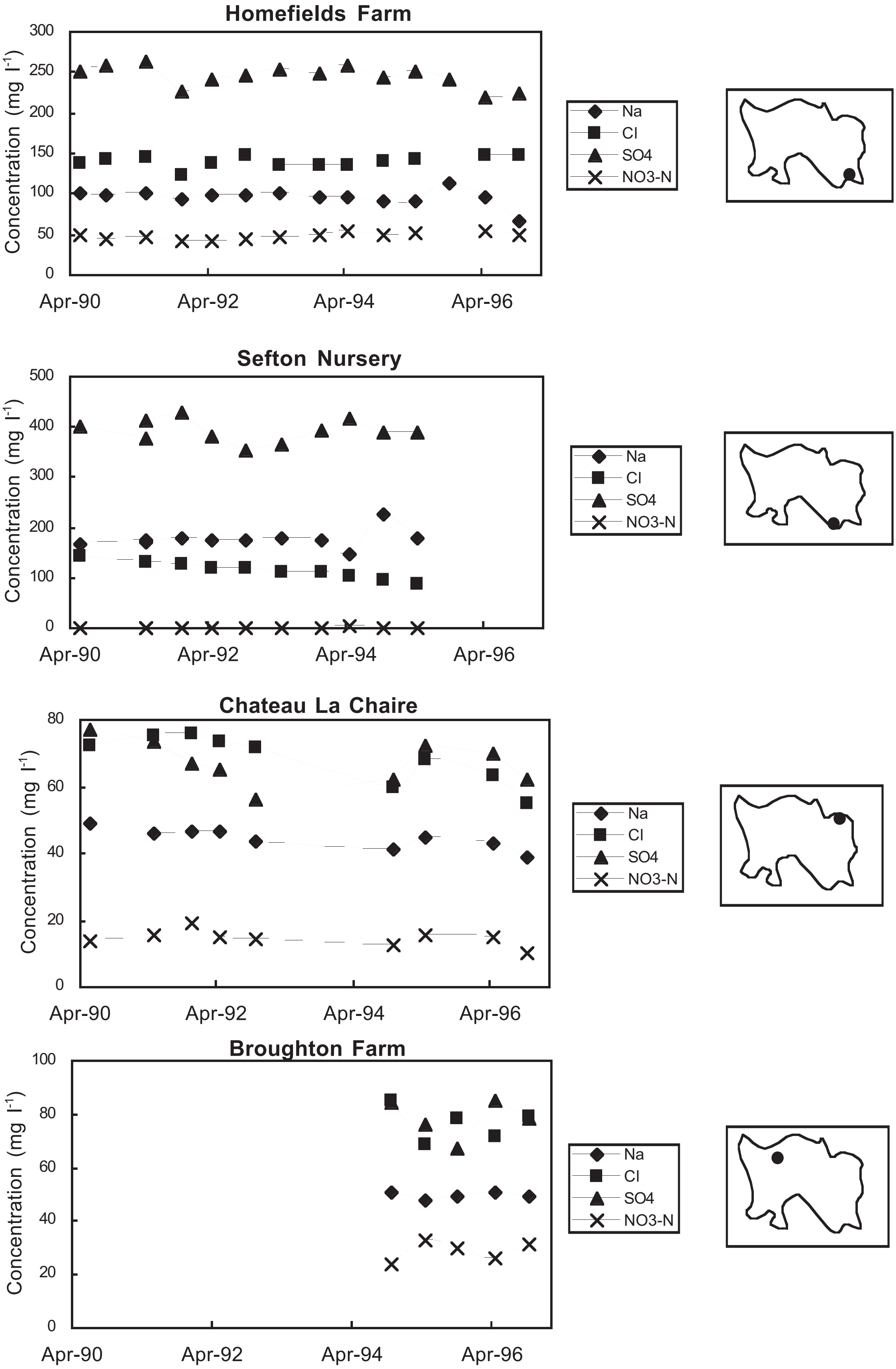


Figure 20 Temporal trends in Na, Cl, SO_4 and NO_3-N in groundwaters from selected sites.

Table 5 Summary of linear-regression analysis (slope, mg l^{-1} a^{-1}, and coefficient of determination, r^2) for monitored NO_3-N concentrations in Jersey groundwaters.

Locality	Slope (rate of change of a^{-1})	r^2	Locality	Slope (rate of change of a^{-1})	r^2
Greystones	4.02	0.720	Apple Barn	1.10	0.789
Les Mauves	-1.46	0.068	Ronez Quarry	0.15	0.054
A5 St Ouen's Bay	0.01	0.002	Highfield Hotel	-0.15	0.217
Val de la Mare	-0.37	0.297	States Farm Well	-1.35	0.402
Val de la Mare Farm	0.07	0.001	La Mare Vineyard	-1.11	0.205
St Peter's Nursery	-0.10	0.007	Meadow Springs	-0.25	0.033
Geranium Farm	-5.73	0.589	Manor Farm	-1.44	0.213
Quennavais Campsite	-0.26	0.343	Oakbank	-1.79	0.174
Priory Inn	-0.24	0.083	Hougue Bie Nursery	0.53	0.201
Les Bourgeons	0.32	0.092	Tesson Mill	0.29	0.043
St Helier Nursery	0.66	0.414	Chaise au Diable	0.28	0.302
Stonewall Farm	0.56	0.210	Grouville Spring	0.07	0.012
First Tower Park	0.08	0.036	Le Coie Hotel	0.04	0.026
Coronation Park	-0.53	0.203	Homefields Farm	1.03	0.367
Greywings	0.11	0.011	Sefton Nursery	0.27	0.080
L'Auberge du Nord	1.72	0.235	Chateau la Chaire	-0.49	0.232

3.2.7 Temporal trends in water quality

Monitoring of inorganic water quality since 1990 has provided up to 14 sets of analyses for selected sites across the island. Analytical details are listed in Appendix 1. Results for Na, Cl, SO_4 and NO_3-N are given for some sites in Figures 16 to 20. These determinands encompass the major-ion composition of the groundwaters and NO_3-N, Cl and SO_4 are indicators of temporal changes in pollutant inputs. In low-lying coastal areas, Na, Cl and SO_4 are also indicators of the saline intrusion.

The chemical quality of many of the sites has varied little over the monitoring interval (e.g. First Tower Park, Highfield Hotel, Meadow Springs, Chaise au Diable, Grouville Spring, Homefields Farm, Chateau la Chaire). Many of these sources have high concentrations of nitrate, Cl and SO_4, derived at least in part from agricultural sources. However, the stable compositions of most suggest that water quality with respect to surface pollutants is not deteriorating with time.

Table 5 shows a summary of the results of linear-regression analysis of NO_3-N concentrations with time in selected monitored sites. Values for the slope indicate the rate of change of NO_3-N concentrations per year and r^2 is the coefficient of determination which indicates the goodness of fit of the data to a straight line. Few of the sites show evidence of a pronounced change in NO_3-N concentration with time, with a good coefficient of determination. Exceptions are Greystones with an apparent increase of 4 mg l^{-1} per year, Apple Barn with an apparent increase of 1.1 mg l^{-1} per year and Geranium Farm with an apparent annual decrease of 5.7 mg l^{-1} (Figures 16, 18).

Geranium Farm is the only site monitored with a clear improvement in water quality with time. Concentrations of Na, Cl, SO_4 and NO_3-N have all decreased progressively (Figure 13). This site is a shallow well in a local depression with a near-surface water table. Response to surface pollution inputs is rapid and the site is, therefore, highly vulnerable. Slurry was applied periodically to an adjacent field upgradient of the well until 1990. Improvements in water quality with time probably reflect the cessation of this practice.

In the low-lying coastal areas, although there is evidence of higher salinity derived from mixing with a minor proportion of seawater, there is no evidence for increasing salinity resulting from pumping-induced saline intrusion. One of the sites monitored (Sefton Nursery) shows a slight decline of Cl concentrations with time (Figure 20). Pumping no longer occurs regularly at this site and it is probable that the groundwater quality is improving slightly as a result of influxes of a greater proportion of fresh recharge water.

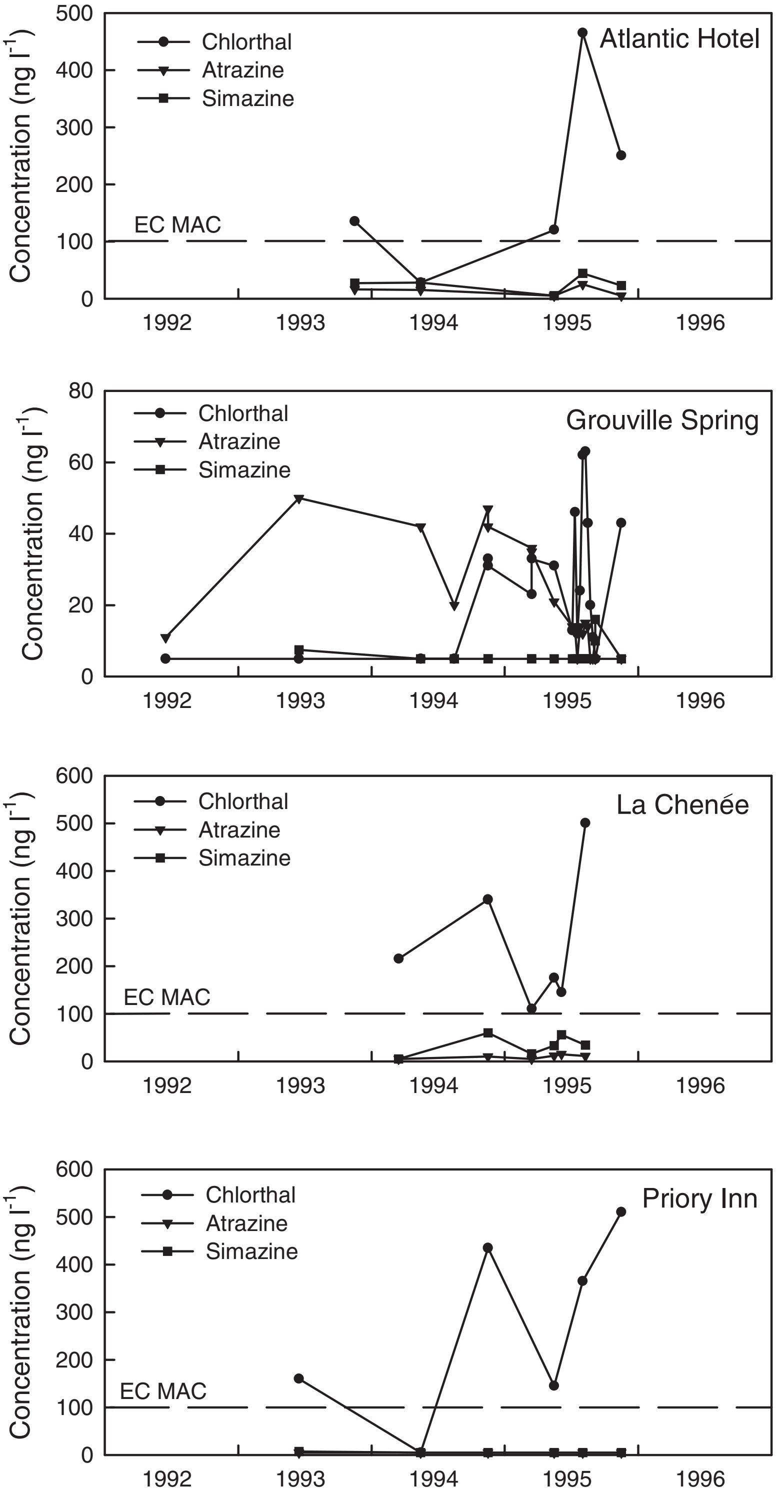
Some sites show distinct seasonal fluctuations in water quality. Ronez Quarry, on the high north coast (Figure 17), shows variations in Na, Cl and SO_4 in particular. Here groundwater heads are too high for the effect to be derived from saline intrusion. Seasonal variations in the input of solutes from marine-derived aerosols may be responsible. Alternatively, the poor degree of buffering of the water quality may result from rapid inputs of recharge to the water table and short residence time such that the groundwaters have insufficient time to equilibrate with aquifer minerals. Temporal fluctuations are also found in many of the open shallow wells (La Mare Vineyard, States Farm well, Hougue Bie Nursery), presumably also related to the rapid response of such sources to rainfall inputs.

Few sites show clear evidence for long-term increases in major-element concentration and hence deterioration of regional groundwater quality. Increases in NO_3-N concentration at Greystones and Apple Barn (Table 5) may be due to local changes in fertiliser application rather than reflecting an island-wide deterioration in groundwater quality.

Monitoring for organic compounds indicates that concentrations of detectable compounds have varied significantly over the study period. Of the pesticides, chlorthal has consistently the highest concentrations at sites where it is detected. There is some evidence that, at a few sites, the concentrations may be increasing slightly (e.g. Figure 21), although the time-series data are rather limited for trends to be assessed. Concentrations of atrazine and simazine do not appear to have increased at monitoring sites.

Monitoring of surface water and groundwater for aldicarb and oxamyl (nematicides) has been carried out by the Department of Agriculture and Fisheries since 1987. Few positive determinations have been made during this period, and concentrations appear to have decreased during the 1990s, presumably as a result of more careful and restricted use.

Figure 21 Temporal trends in concentrations of chlorthal, atrazine and simazine herbicides in selected Jersey groundwaters.



Detectable concentrations of some of the chlorinated solvents and di- and trihalomethanes have also been found but there are too few data at this stage to assess temporal trends.

Nonetheless, concentrations of nitrate, some pesticides (chlorthal, atrazine, simazine) and non-aqueous-phase liquids at many sites indicate that some of the groundwaters are already significantly polluted. There has been little if any improvement in the quality of water at most sites over the seven years of monitoring. Any remediation of the groundwater quality following changes in farming or industrial practice is likely to be a slow process. Indeed, atrazine and simazine remain detectable in Jersey groundwaters despite the fact that their use on the island has not been approved since January 1993.

4 Present day situation

4.1 REGULATION

4.1.1 Norman Law and existing Statutes

There is currently no Jersey law which allows for the management of groundwater. Ancient concepts of Norman Law state that landowners own the water under their land. These are reinforced by Roman Law and by the current and long-standing practice of unregulated abstraction of groundwater and a lack of provision for the protection of groundwater. There are a number of minor pieces of related legislation and these include:

- The Water (Prevention of Pollution) Byelaws for Jersey (1975) which prevents certain activities in selected surface water catchments;
- The Sewerage (Miscellaneous Provisions) (Jersey) Law (1979) which protects the marine environment from any land-based pollution source;
- The Drainage (Jersey) Law (1962) which provides for the repair, maintenance and control of water courses.

Recognition of the need to manage groundwater resources has begun and a Water Pollution Law is in preparation. This will make it an offence to pollute controlled waters (which include groundwater). The storage and handling of potential pollutants will also be controlled so allowing a policy of pollution prevention. As yet, there is no commitment to manage groundwater quantity through, for example, groundwater abstraction licensing. However, this is an inevitable development that will bring Jersey into line with all the other developed groundwater-dependent communities of the world.

4.2 RESOURCES

Since half the long-term mean renewable resource is used, water supplies are secure except in years with below-average rainfall. Houghton-Carr et al. (1998) suggest that such a shortfall has occurred with a frequency of less than one year in five over the last 28 years. Climate change may increase this frequency.

The continuation of intensive land use practice places both surface water and groundwater at risk of pollution. Denitrification of mains water supplies may safeguard some of the community from part of the threat, but the only sensible way forward is to manage the application of chemicals for agricultural purposes. This policy is now universally adopted throughout the European Community.

Jersey is not obliged to meet the standards set by the European Community. It does, however, acknowledge the benefits of so doing and recognises that visitors from the remainder of Europe expect the same high standards of water supply that they enjoy at home.

The same pollution problems are also apparent in the adjacent mainland of France. In the Cotentin Peninsula, where the geology and climate are broadly similar to those of Jersey, groundwater pollution by nitrate and pesticides is an increasing problem. The availability of surface water from rivers and streams allows a much greater level of crop irrigation to be carried out and this, in turn, promotes additional leaching of chemicals to groundwater. The difference in France, however, is that the groundwater and its consequent baseflow to surface waters is not the source of public drinking water, and the pollution of a controlled water, although in conflict with European Community policy is not critical to society.

Although comparisons can be made between Jersey and other islands these may be confusing unless similar geology, climate and demand can be demonstrated. The situation on Guernsey is probably the best example. Here the average nitrate concentration was found, in a survey of 70 groundwater sources, to be 15.2 mg l^{-1} (Jehan, 1993). Groundwater is not normally put into the public supply in Guernsey except at times of acute water scarcity, but there are about 1000 private boreholes and well sources on the island. Even in Alderney the groundwater is polluted, perhaps more by septic tanks than other sources, and the average nitrate concentration is 10 mg l^{-1} in the 30 sources on the island (Hodgson, 1992).

4.3 CONCLUSIONS

4.3.1 A delicate balance

The availability of groundwater in Jersey is sufficient to satisfy demand in most years. Although the abstraction of groundwater is reaching a level across the whole island beyond which permanent reduction in water levels will occur with consequent derogation of some sources. Temporary reduction in groundwater levels, particularly in the north of the island, already occurs during summer periods following winters of below-average rainfall. In recent years these have occurred in less than one in five years. Consequent loss of sources has induced some operators to deepen their boreholes in the past, but this may cause a further temporary lowering of water level until the onset of the next good rain season. Deepening can only be beneficial if the borehole or well stays within the shallow productive zone of weathering; for the most part deeper boreholes are not efficient.

The main palliative effect is the thin nature of the aquifer. At greater than 25 m below the water table, most fractures are insufficiently dilated to store or transmit water. Consequently, if the water table falls within this zone, in which the hydraulic properties are generally inadequate to sustain a significant level of pumping, little further damage will be caused to the aquifer. It is this natural process of groundwater management that has undoubtedly saved the island aquifer from failure in the past.

Currently about half the long-term renewable resource (either direct groundwater abstraction or available groundwater baseflow into streams and reservoirs) is used. It is probable that a large part of the groundwater available for direct abstraction from boreholes and wells is already taken, and that there is little room for further development before permanent derogation of baseflow and reduction in water

Photograph 8 Wetland on the St Ouen's sand aquifer — the North Canal [Tourism Department].

levels will occur in some areas of the island. Return flow to groundwater from irrigation and septic tanks is insufficient to repair this situation.

4.3.2 Chemical hazards

Groundwater quality in Jersey exhibits the influence of many processes, including inputs of maritime-influenced recharge, water-rock reaction, seawater influences in low-lying coastal areas and redox processes, all of which occur naturally. Superimposed on this is the influence of pollution from agricultural, industrial and domestic operations which are input at the surface from either point or diffuse sources. Pollution has had a notable impact on Jersey groundwaters because of the generally thin unsaturated zone and soil cover, lack of protection from surface impermeable strata (e.g. superficial deposits), fractured bedrock and widespread use of fertilisers and pesticides.

Whilst Jersey does not have a statutory obligation to follow EC guidelines for drinking-water quality, it does have a commitment to the concept of sustainability[1]. Consequently, the EC limits imposed for various determinands give a useful yardstick for safeguarding groundwater quality and public health even on Jersey. EC guidelines and MACs for drinking water are currently under European Parliamentary review and modifications are as yet uncertain. However, proposed modifications include removal of many of the frequently-determined parameters such as temperature, dry residues, kjeldahl-N, and hydrogen sulphide, together with many of the major elements which are seldom toxic (Cl, Na, K, Ca, Mg, Si) and some trace elements (Zn, Co, P, Ba, Ag, Be, V). The EC MACs for As and Pb are likely to be reduced from 50 µg l^{-1} to something close to 10 µg l^{-1} in recognition of their toxicity. The guide limit for B is also under review and may be reduced to 0.3 mg l^{-1}. Limits for NO_3-N, NO_2-N and NH_4-N are unlikely to change. Of the organic compounds, a limit of 1 µg l^{-1} is likely to be imposed for benzene, although standards for trichloroethene and tetrachloroethene may be relaxed (to ca. 70 µg l^{-1} and 40 µg l^{-1} respectively). Pesticide limits are unlikely to be relaxed although there is uncertainty over whether the 0.5 µg l^{-1} limit for total pesticides will be retained.

Bearing in mind these new proposed standards, the main threats to the quality of Jersey groundwater for future years are from the N species (nitrate and ammonium) and from pesticides. At present concentrations, NAPLs are not a major problem regionally, although their detection even at low concentrations is an indication of the vulnerability of the groundwater resource. Closer monitoring of elements such as benzene should be carried out, although most detected concentrations over the monitoring period have been about 0.2 µg l^{-1} or less.

Major-element concentrations of Jersey groundwaters in general do not pose a serious water-quality problem, apart from on aesthetic and practical grounds (salinity, Fe, Mn). Concentrations of As and Pb have not been monitored in the groundwaters but given the local geology and physicochemical condition of the groundwaters, these are unlikely to be high. Lead may only be a problem where Pb pipeworks are installed.

There is value in continuing to sample and analyse groundwaters for NO_3-N, NO_2-N and NH_4-N, as well as commonly-used pesticides and their breakdown products in particular, to monitor trends in pollution. Elements such as Cl and SO_4 can also act as important tracers for pollution inputs as they often derive from similar sources. Only with long-term time-series data can reliable information be gained concerning changes in groundwater quality and impacts of any improvements in farming and industrial practices.

4.3.3 The legacy

The environmental balance of a small island is delicate. Anthropogenic influence can have an adverse effect on that balance, particularly if activities which can be shown to be putting the environment under stress are left unchecked.

In Jersey, the quality of the groundwater and groundwater baseflow is poor, being polluted principally by the application of fertilizer and pesticide to land and crops. Although there are other pollution hazards, none is as great as that posed by current agricultural practice. Conversion to organic farming could in the long-term rectify the situation, but it is unlikely that any significant change would occur in the short-term, and it could take some tens of years to flush the groundwater system of its current pollutant load. The proposed Pollution Control Law addresses this issue.

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[1] States Strategic Policy Document for 1995 and 1996.

Physical stress to the Jersey aquifer has not as yet caused any irrevocable damage. Nevertheless, any shortfall in annual recharge is seen immediately in reduced yields and loss of supply in some of the shallower and coastal boreholes and springs at the northern recharge end of the island. However, as the groundwater is young, a few tens of years in age, these sources quickly recover given the onset of the next rains. Total use of groundwater and baseflow represents just over half the available annual renewable resource. This should not be used as a basis for complacency because recharge is not always sufficient to sustain demand; there were four years with less than 30 mm recharge in the period 1988–1996. Any further increase abstraction may start to erode baseflow and so permanently damage the resource potential of the aquifer. This fact is a compelling reason for the States to urgently review the need for regulation of groundwater abstraction as a component of a sensible groundwater management policy. This is a necessary step towards safeguarding the island's water resources for future generations.

ACKNOWLEDGEMENTS

The Jersey groundwater study encompasses the combined efforts of people from a number of different organisations and disciplines. Contributors include field workers, analysts, modellers, agronomists, environmentalists, sociologists, economists, engineers and lawyers, as well as hydrologists, hydrogeologists and hydrogeochemists. The authors of this report are grateful to all of them, not least for the unstinting interest and encouragement provided by staff at all levels within the Public Services Department, and to colleagues within BGS and IH for direct contributions to the study as well as for discussion and periodic scientific review. In addition, the significant role of the Groundwater Review Group in guiding the study towards a sensible conclusion has been extremely valuable. But above all, the authors thank the people of Jersey for providing access to wells, boreholes and springs, for their hospitality and good-humoured tolerance of our enquiries.

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Glossary

annual renewable resource the amount of water that can be taken from a groundwater system without damaging that system in the long term

aquifer permeable strata that can transmit and store water in significant quantities

baseflow natural discharge of groundwater from an aquifer to rivers and the sea

denitrification the process of reduction of nitrate to nitrogen gas which may then discharge to the atmosphere, a process usually assisted by bacteria

drawdown the difference between the rest water level or static water level and the level caused by pumping a borehole or well

evapotranspiration loss of water from the land surface through the transpiration of plants and evaporation from the soil

field capacity the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased

flow-path the line that defines the direction of flow in an aquifer from a recharge area to a discharge area

fractures/fissures natural cracks in rocks that enhance relatively rapid water movement

hydraulic conductivity the rate of flow of groundwater through a cross-sectional area of an aquifer under unit hydraulic gradient

hydraulic gradient the prevailing inclination of the water table which provides the driving force to transmit groundwater through an aquifer

major-ion chemistry the concentrations of the cations: Na, K, Ca and Mg and the anions: HCO_3, SO_4, Cl and NO_3-N which are the most abundant ions in groundwater

permeability a measure of the relative ease with which a porous aquifer can transmit groundwater under a potential gradient, it takes no account of fissure flow

redox reducing or oxidising potential of groundwater

residence time the average length of time groundwater has been stored in an aquifer, although waters may be mixed and have different ages

saline intrusion the entry of sea water into a coastal aquifer

specific capacity the pumping rate of a borehole or well divided by the drawdown

storativity the amount of water held in storage within an aquifer expressed as volume per unit volume of aquifer

transmissivity the product of the hydraulic conductivity of an aquifer and its thickness

vadose or unsaturated zone the unsaturated zone above the water table through which percolating recharging water falls vertically under gravity

water table the level beneath which the aquifer is saturated

Appendix 1 Analytical methods for analysis of Jersey groundwater

A1.1 BGS SAMPLING AND ANALYSIS

Collection and analysis of groundwater samples from Jersey was initiated by BGS in May 1990. During the first reconnaissance sampling campaign, 109 samples were collected island-wide from shallow wells, springs and boreholes. Where possible, measurements at these sites included redox potential (Eh) and dissolved oxygen. Sources were pumped as long as possible to allow stable readings of these measurements to be made and to purge standing water prior to sample collection. Following the reconnaissance survey, suitable sites were selected for further monitoring and were visited subsequently at six-monthly intervals (Spring and Autumn). At subsequent visits, Eh and dissolved oxygen were not measured and continuous flow of water was therefore not required. However, sources were pre-purged wherever possible to enable collection of representative groundwater.

Sampling and analysis of water was the responsibility of BGS until Autumn 1993. Chemical analysis of samples collected up to this point was carried out at the BGS laboratories in Wallingford. Measurements of pH, temperature, electrical conductivity and HCO_3 as well as Eh and dissolved oxygen were carried out on site. Major cations, SO_4 and trace metals were analysed on filtered (0.45 µm) and acidified (1% HNO_3) samples by inductively-coupled-plasma atomic emission spectrometry (ICP-AES). Analysis of NO_3, NO_2, NH_4 and Cl was by automated colorimetry on filtered but unacidified samples.

A1.2 STATES OF JERSEY SAMPLING AND ANALYSIS

Responsibility for monitoring of Jersey groundwater passed to PSD in Autumn 1993. Sampling has continued at six-monthly intervals subsequently. Sampling protocol has been similar to that carried out earlier by BGS, including purging of sources where possible prior to collection, on-site measurement of pH, temperature, electrical conductivity and HCO_3 and collection of separate filtered acidified and unacidified aliquots for chemical analysis. Analysis has been carried out by the States of Jersey Official Analyst. Acidified aliquots have been analysed in duplicate for Ca, Mg, Na, K, Mn, and Fe by atomic absorption spectrometry (AAS) and unacidified aliquots in duplicate for Cl, NO_3 and SO_4 by ion chromatography (IC).

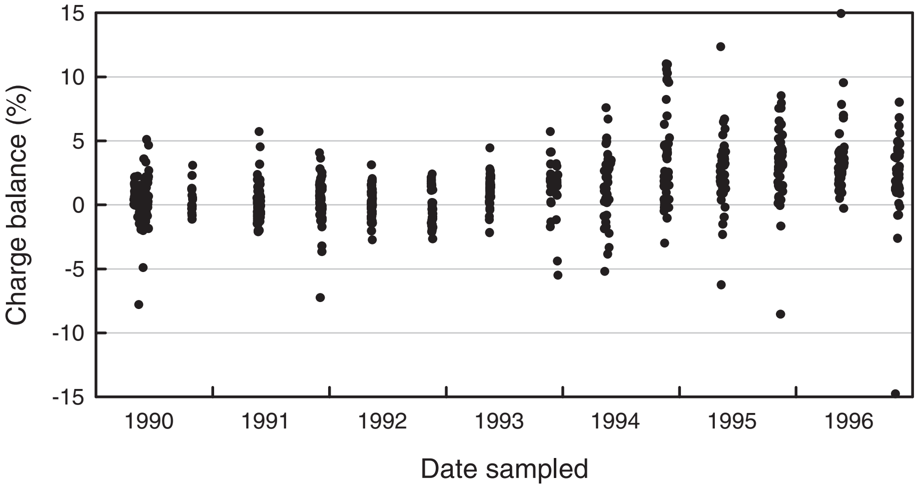
Throughout the period 1990–1996, samples have also been collected biannually for analysis of organic compounds. Samples are collected in prepared glass containers by PSD staff and delivered overnight for analysis by a NAMAS-accredited UK laboratory. Current sampling and analysis includes urea herbicides (analysis by HPLC), phenoxyalkanoic-acid herbicides (analysis by GC-MS), triazine herbicides (analysis by GC-NPD), trihalomethanes (analysis by GC-EC) and volatile organic compounds (collection in glass vials to exclude air, concentration by purge-and-trap procedure and analysis by GC-MS).

Microbiological samples are also collected from selected sites at intervals by PSD staff. Samples are taken aseptically in 1-litre sterile plastic bottles and stored in cool, dark conditions. Analysis for faecal streptococci, faecal coliforms and total coliforms is carried out using membrane filtration. Samples are analysed by the States of Jersey Official Analyst.

During the Autumn 1993 sampling campaign, samples from six sites were analysed by both BGS and the States Analyst. Results for most determinands compared to within about 5% although some (Ca, Na and Cl) revealed laboratory bias. Results for Mg showed poorer agreement, to only around 20%.

Analytical charge balances for the chemical analyses throughout the 1990–1996 monitoring period are given in Figure A1.1.

Figure A1.1 Analytical charge balance for groundwater samples collected from Jersey during 1990 to 1996.



Appendix 2 Median values for major-element concentrations in Jersey groundwaters (data from BGS and the States of Jersey Official Analyst).

No.	Locality	Grid Reference	Temp °C	pH	SEC µS cm^{-1}	Na mg l^{-1}	K mg l^{-1}	Ca mg l^{-1}	Mg mg l^{-1}	Cl mg l^{-1}	SO$_4$ mg l^{-1}	HCO$_3$ mg l^{-1}	NO$_3$-N mg l^{-1}	NO$_2$-N mg l^{-1}	NH$_4$-N mg l^{-1}	Si mg l^{-1}
1	Greystones	55774 45408	12.8	5.41	920	44.0	20.5	60.7	28.8	112	118	6.8	40.5	—	<0.01	5.87
2	Les Mauves	55672 45499	12.9	6.02	700	48.9	17.1	62.2	17.5	74.3	125	32.5	24.9	—	<0.01	2.58
3	Jersey Racecourse	55490 45595	11.5	4.95	940	94.6	29.2	60.3	23.8	170	96.1	3.0	40.2	—	—	5.56
4	A5 St Ouen's Bay	55702 45023	12.9	7.41	410	32.0	1.50	67.6	5.8	58.4	19.8	179	1.7	—	—	3.52
5	Val de la Mare	55770 45184	13.4	6.71	769	64.3	3.06	75.6	17.3	111	39.8	192	5.6	<0.005	0.01	7.30
6	Lobster Pot	55492 45484	13.5	7.14	948	83.3	4.69	73.7	12.5	169	40.7	177	1.8	—	0.10	7.95
7	La Pointe	55600 45572	12.7	5.52	800	66.2	23.4	43.7	29.1	98.9	139	15	27.3	—	—	5.99
8	Le Bas de l'Etaque	55534 45454	13.5	5.79	960	109.3	45.7	60.5	21.0	230	116	25	19.2	—	—	4.07
9	Atlantic Hotel	55656 44894	13.7	6.42	597	67.4	2.10	40.0	8.2	78.5	67.3	96	1.2	<0.005	0.01	11.3
10	La Moye Golf Course	55720 44940	13.1	7.17	685	40.2	2.93	92.5	8.9	72.9	43.1	224.	8.3	—	0.02	4.20
11	Villa Martinique	55616 45367	16.1	7.40	820	69.7	3.21	97.0	20.6	159	49.5	200	8.1	—	—	6.04
12	Radar Station	55613 44770	13.4	7.09	650	61.2	1.59	60.0	11.2	119	18.4	173	<1.0	—	—	10.0
13	Val de la Mare Farm	55752 45079	13.1	6.26	1053	85.0	10.62	86.2	26.6	152	130	50	31.4	—	0.01	6.97
14	Les Quennevais	55805 44956	12.9	6.51	425	47.1	1.63	42.1	9.4	53.6	20.7	129	11.7	—	—	9.64
15	St Peter's Nursery	55992 45098	13.0	6.72	638	56.3	2.22	45.3	21.3	63.1	172	44	4.4	—	<0.01	8.61
16	Geranium Farm	55676 44802	11.7	5.71	960	74.0	30.5	64.0	18.0	128	96.5	25	31.9	—	3.66	5.59
17	Holiday Village	56018 44718	15.6	6.61	735	59.2	18.2	55.5	14.0	132	62.5	32	19.8	—	—	5.58
18	Emahroo	55948 44982	12.9	5.86	780	78.6	8.88	45.1	18.2	95.2	125	27	23.4	—	—	9.05
19	Quennevais Campsite	55802 45042	13.3	6.79	583	58.0	1.79	40.3	12.1	69.5	70.8	65	11.7	—	<0.01	8.04
20	Priory Inn	56066 45578	12.9	5.66	625	57.0	5.69	34.9	19.1	82.0	87.3	19	19.5	—	<0.01	10.0
21	Mushroom Farm	56126 45163	16.8	6.31	850	86.1	3.54	60.4	18.4	118	131	59	16.1	0.036	0.02	9.74
22	West View Hotel	56072 45440	13.3	5.54	427	31.4	2.68	21.7	16.2	44.0	76.0	12	9.4	—	<0.01	10.2
23	Besco Laundry	56120 45000	14.4	6.57	864	69.0	5.00	83.0	20.4	97.0	134	132	2.7	—	<0.01	7.62
24	Portelet Hotel	55990 44760	13.9	6.46	730	84.5	2.92	60.6	14.1	152	63.2	88	11.1	—	—	8.14
25	Les Bourgeons	56240 45126	13.1	7.49	655	36.7	2.10	69.0	18.8	78.0	118	91	3.8	—	<0.01	5.99
26	Ville Bagot	55787 45506	12.1	5.93	880	64.9	23.8	53.7	29.6	99.6	102	32	40.2	—	<0.01	8.16
27	Warwick Farm	56499 45186	13.2	6.23	550	55.7	5.73	34.4	14.3	56.3	98.9	69	10.7	—	0.10	10.8
28	St George's Estate	55630 45545	16.4	6.20	860	86.2	15.1	55.7	29.4	116	126.	57	32.4	—	—	5.60
29	Overdale Hospital	56447 44945	13.8	6.93	709	58.1	1.54	57.9	16.5	74.1	84.3	144	9.1	—	—	8.73
30	St Helier Nursery	56472 45071	13.2	6.04	450	52.1	1.78	28.0	6.0	41.0	75.2	27	11.1	<0.005	0.01	11.5
31	Stonewall Farm	56607 45108	13.1	6.54	714	52.8	3.00	77.5	11.0	74.8	70.0	131	17.0	0.009	<0.01	11.9
32	First Tower Laundry	56390 44947	13.6	6.35	780	67.8	7.60	62.3	24.1	105	117	61	22.8	<0.005	<0.01	6.86
33	Glen Hotel	56532 45030	12.4	5.65	480	45.2	9.06	30.5	10.5	58.3	78.0	18	13.5	—	—	13.5
34	Harvest Barn	56501 45101	17.2	7.02	770	72.8	2.35	81.0	25.3	97.6	177	152	2.2	—	—	4.33
35	Trinity Manor	56550 45328	13.4	7.20	770	71.9	2.73	82.3	24.5	97.5	168	182	3.7	—	0.16	4.50
36	First Tower Park	56338 44999	13.5	7.01	904	69.9	2.50	82.3	24.1	100	167	136	3.0	—	0.16	4.30
37	Parade Park	56487 44898	14.0	7.06	940	64.2	6.40	104.5	22.4	81.7	120	274	<0.3	—	0.11	8.26
38	Mon Bijou	55808 45312	13.0	6.11	553	50.1	5.15	29.7	16.0	75.0	62.4	34	12.2	—	0.10	6.92
39	Creaux Cottage	55849 45441	12.9	5.42	820	63.4	25.3	59.7	15.2	118	93.3	14	28.8	—	—	7.00
40	Creaux Cottage	55849 45441	14.5	5.87	715	75.1	3.83	47.7	14.0	102	106	26	20.2	—	—	12.4
41	Greenhills Hotel	56076 45254	13.3	5.76	753	50.4	8.13	50.9	31.0	94.8	102	42	28.3	—	0.02	5.74

Appendix 3 Median values for trace-element concentrations in Jersey groundwaters (data from BGS and the States of Jersey Official Analyst).

No.	Locality	Grid Reference	Al $\mu g\ l^{-1}$	Sr $\mu g\ l^{-1}$	Ba $\mu g\ l^{-1}$	Li $\mu g\ l^{-1}$	B $\mu g\ l^{-1}$	Fe $\mu g\ l^{-1}$	Mn $\mu g\ l^{-1}$	Cu $\mu g\ l^{-1}$	Zn $\mu g\ l^{-1}$
1	Greystones	55774 45408	<50	1140	34	4	84	21	80	4	32
2	Les Mauves	55672 45499	<50	1226	73	3	171	41	<2	13	31
3	Jersey Racecourse	55490 45595	714	1281	176	2	121	60	186	5	17
4	A5 St Ouen’s Bay	55702 45023	<50	321	14	<2	20	31	9	<4	13
5	Val de la Mare	55770 45184	<50	287	163	8	45	13	156	4	10
6	Lobster Pot	55492 45484	<50	228	69	18	94	6	1566	10	22
7	La Pointe	55600 45572	<50	908	92	7	239	27	627	49	89
8	Le Bas de l’Etaque	55534 45454	<50	820	65	<2	203	32	462	5	105
9	Atlantic Hotel	55656 44894	<50	151	29	6	87	64	463	70	90
10	La Moye Golf Course	55720 44940	<50	362	47	3	67	9	3	<4	<8
11	Villa Martinique	55616 45367	<50	360	50	<2	35	22	20	<4	22
12	Radar Station	55613 44770	<50	162	228	12	38	11	1609	<4	<8
13	Val de la Mare Farm	55752 45079	<50	424	21	7	112	<5	<2	<4	10
14	Les Quennevais	55805 44956	<50	181	3	4	30	<5	<2	<4	<8
15	St Peter’s Nursery	55992 45098	<50	191	4	8	35	40	51	4	78
16	Geranium Farm	55676 44802	139	1852	153	<2	330	94	120	17	83
17	Holiday Village	56018 44718	<50	685	57	<2	118	23	166	<4	16
18	Emahroo	55948 44982	<50	257	45	4	141	29	4	7	26
19	Quennevais Campsite	55802 45042	<50	198	6	11	37	8	5	<4	9
20	Priory Inn	56066 45578	<50	236	83	8	95	15	<2	35	41
21	Mushroom Farm	56126 45163	<50	252	33	8	115	17	6	13	62
22	West View Hotel	56072 45440	<50	159	29	5	75	122	5	33	1149
23	Besco Laundry	56120 45000	<50	231	42	3	307	10	49	<4	23
24	Portelet Hotel	55990 44760	78	210	26	4	82	70	1545	<4	2847
25	Les Bourgeons	56240 45126	<50	242	24	5	22	<5	7	<4	<8
26	Ville Bagot	55787 45506	<50	373	39	4	115	13	4	25	27
27	Warwick Farm	56499 45186	<50	133	26	7	121	52	7	14	289
28	St George’s Estate	55630 45545	<50	923	101	8	486	8	1327	<4	578
29	Overdale Hospital	56447 44945	<50	242	45	5	67	5	3	<4	156
30	St Helier Nursery	56472 45071	<50	128	6	4	116	17	2	28	39
31	Stonewall Farm	56607 45108	<50	218	165	7	55	<5	235	9	16
32	First Tower Laundry	56390 44947	<50	299	40	2	160	5	4	15	9
33	Glen Hotel	56532 45030	<50	173	65	<2	60	13	11	<4	40
34	Harvest Barn	56501 45101	<50	228	38	<2	80	18	132	<4	<8
35	Trinity Manor	56550 45328	<50	219	37	6	101	9	153	<4	26
36	First Tower Park	56338 44999	<50	226	38	5	93	79	166	<4	13
37	Parade Park	56487 44898	<50	343	161	4	83	1583	538	<4	11
38	Mon Bijou	55808 45312	23	199	72	2	50	336	14	22	91
39	Creaux Cottage	55849 45441	<50	779	82	<2	124	15	68	<4	24
40	Creaux Cottage	55849 45441	<50	200	25	14	70	16	1233	11	33
41	Greenhills Hotel	56076 45254	<50	503	61	<2	108	11	35	183	134

Appendix 4 Median values for organic compounds analysed in Jersey groundwaters 1990 to 1996

No.	Locality	Chlortoluron ng l^{-1}	Isoproturon ng l^{-1}	Linuron ng l^{-1}	Diuron ng l^{-1}	Methabenz -thiazuron ng l^{-1}	Carbetamide ng l^{-1}	MCPA ng l^{-1}	MCPB ng l^{-1}	2,4-D ng l^{-1}	Mecoprop ng l^{-1}	Dichlorprop ng l^{-1}	2,4,5-Tric* ng l^{-1}	Dicamba ng l^{-1}	2,3,6-TBA ng l^{-1}
2	Les Mauves	—	<10	—	—	—	—	<10	—	10	<10	—	—	—	—
9	Atlantic Hotel	<10	<10	11	<10	<10	<10	<10	<10	<10	10	<10	<10	<10	<10
15	St Peter's Nursery	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
16	Geranium Farm	34	<10	<10	<10	29	<10	<10	<10	<10	<10	<10	<10	<10	<10
19	Quennevais Campsite	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
20	Priory Inn	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
23	Besco Laundry	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
30	St Helier Nursery	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
31	Stonewall Farm	—	<10	—	—	—	—	<10	—	<10	<10	—	—	—	—
45	Coronation Park	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
47	Greywings	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10.5	<10	<10	<10	<10
48	L'Auberge du Nord	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
58	Ronez Quarry	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
65A	States Farm borehole A	<10	16	<10	<13	<10	<33	<10	<10	<10	<10	<10	<10	<10	<10
65B	States Farm borehole B	<10	<10	<10	<11.5	<10	<16	<10	<10	<10	<10	<10	<10	<10	<10
66	States Farm well	—	<10	—	—	—	—	<10	—	20	180	—	—	—	—
67	La Mare Vineyard	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
70	Jersey Milk	—	—	—	—	—	—	—	—	—	—	—	—	—	—
76	Meadow Springs	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
80	Oakbank	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
81	Hougue Bie Nursery	<10	<10	<10	<10	30	22	<10	<10	<20	<10	<10	<10	<10	<10
86	La Chenée	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
100	Grouville Spring	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
108	Sefton Nursery	—	<10	—	—	—	—	—	—	—	—	—	—	—	—
109	Chateau la Chaire	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
112	La Villaise	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
114	Norwood	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
115	La Hauteur	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
165	Bellozanne borehole	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
No samples taken — total		121	131	121	121	121	121	130	121	130	130	121	121	113	121
No samples — analyte found		6	10	9	11	15	15	2	0	7	11	0	0	0	0
No sites — total		24	28	24	24	24	24	27	24	27	27	24	24	24	24
No sites — analyte found		5	9	6	8	14	11	2	0	7	7	0	0	0	0

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[*] 2,4,5-Tric: 2,4,5-Trichlorophenoxyacetic acid

Appendix 5 List of project reports

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

1990 St Ouen's Bay: numerical modelling of the groundwater resource of part of the sand aquifer. BGS Technical Report WD/90/40.

1991 Hydrogeological and hydrogeochemical survey of Jersey. BGS Technical Report WD/91/15.

1991 Microbial analysis of groundwater samples from Jersey. BGS Technical Report WE/91/1.

1992 Jersey groundwater Year 2 — further observations and groundwater model. BGS Technical Report WD/92/22.

1993 Jersey groundwater Year 3 — further observations and potential sources of pollution. BGS Technical Report WD/93/28.

1993 Estimates of open water evaporation and of potential transpiration for Jersey. IH Technical Report.

1994 Jersey groundwater Year 4 — monitoring and consolidation. BGS Technical Report WD/94/53.

1994 Nitrate in Jersey's groundwater: results of unsaturated zone porewater profiling, 1994. BGS Technical report WD/94/65.

1994 The Trinity catchment study Year 1. IH Technical Report.

1995 Jersey groundwater Year 5 — towards an end. BGS Technical Report WD/95/68.

1995 The Trinity catchment study Year 2. IH Technical Report.

1995 Source identification of nitrate contamination within groundwater of the Jersey bedrock aquifer using nitrogen stable isotopes. University of East Anglia MSc Thesis.

1996 Jersey groundwater Year 6 — an exceptionally dry year. BGS Technical report WD/96/70.

1996 The Trinity catchment study final report. IH Technical Report.

1996 Groundwater resources degradation in Jersey: socio-economic impacts and their mitigation*. NRI/BGS Technical Report WD/96/8.

1997 The landfill legacy in Jersey and the risk to surface and groundwater. BGS Technical Report WD/97/6C.

* This report was funded by the Economic and Social Research Council as part of the Global Environmental Change Initiative Phase III.

A number of papers have been published from time to time in the technical literature. These are cited in the text, and listed in the reference section at the end of this report. In addition, the Hydrogeological Map of Jersey (BGS, 1992) is available at a scale of 1:25 000.

BGS Research Report RR/98/5

The Jersey groundwater study

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