Baseline Report Series:
11. The Bridport Sands of Dorset and Somerset

Groundwater Systems and Water Quality
Commissioned Report CR/04/166N

Science Group: Air, Land & Water
Technical Report NC/99/74/11

The Natural Quality of Groundwater in England and Wales
A joint programme of research by the British Geological Survey and the Environment Agency

BRITISH GEOLOGICAL SURVEY
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& A R Lawrence

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Bridport Sands near Bridport, Dorset.

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FOREWORD

Groundwater issuing from springs has been regarded since the earliest recorded history as something pure, even sacred. In its natural state, it is generally of excellent quality and an essential natural resource. However, the natural quality of groundwater in our aquifers is continually being modified by the influence of man. This occurs due to groundwater abstraction and the consequent change in groundwater flow, artificial recharge and direct inputs of anthropogenic substances. A thorough knowledge of the quantity and quality of groundwaters in our aquifers, including a good understanding of the physical and chemical processes that control these, is therefore essential for effective management of this valuable resource.

About 35 per cent of public water supply in England and Wales is provided by groundwater resources, this figure being higher in the south and east of England where the figure exceeds 70 per cent. Groundwater is also extremely important for private water supplies and in some areas, often those with the highest concentration of private abstractions, alternative supplies are generally not available. Groundwater flows and seepages are also vital for maintaining summer flows in rivers, streams and wetland habitats, some of which rely solely on groundwater, especially in eastern and southern England. The quantity and quality of groundwater is therefore extremely important to sustain both water supply and sensitive ecosystems.

Until now there has not been a common approach, either in the UK or across Europe, to define the natural "baseline" quality of groundwater. Such a standard is needed as the scientific basis for defining natural variations in groundwater quality and whether or not anthropogenic pollution is taking place. It is not uncommon for existing limits for drinking water quality to be breached by entirely natural processes. This means that it is essential to understand the natural quality of groundwater to enable the necessary protection, management and restoration measures for groundwater to be adopted.

One of the main problems pertinent to groundwater remediation issues concerns the background or baseline to which remedial measures must, or can, be taken. Naturally high concentrations of some elements in particular areas may make it impossible or uneconomic to remediate to levels below the natural background which may already breach certain environmental standards. The Baseline Reports Series assesses the controls on water quality which are responsible for causing the natural variations seen in groundwater and provides a background for assessing the likely outcomes and timescales for restoration.

This report builds on a scoping study of England and Wales, carried out in 1996 by the British Geological Survey for the Environment Agency, which reviewed the approach to be adopted in producing a series of reports on the principal aquifers in England and Wales. The initial phase of this work was completed in 1998 and comprised reports on seven aquifers. This report forms part of the second phase of the work that will extend coverage to all the important aquifers in England and Wales. The Baseline reports will be of use not only to regulatory agencies but also to all users of groundwater, including water companies, industry and agriculture, and all those involved in the protection and remediation of groundwater.

BACKGROUND TO THE BASELINE PROJECT

The baseline concentration of a substance in groundwater may be defined in several different ways. For the purpose of the project, the definition is given as

> **"*the range in concentration (within a specified system) of a given element, species or chemical substance present in solution which is derived from natural geological, biological, or atmospheric sources*"**

Terms such as background or threshold can have a similar meaning and have often been used to identify "anomalous" concentrations relative to typical values e.g. in mineral exploration. There may be additional definitions required for regulation purposes, for example when changes from the present day conditions of groundwater may represent the starting point of monitoring. This may be defined as background and such an initial condition may include some anthropogenic component in the water quality.

In order to interpret the water quality variations in terms of the baseline, some knowledge of the residence times of groundwater is required. For this purpose both inert and reactive chemical and isotopic tracers are essential. Measurement of the absolute age of groundwater presents many difficulties and radiocarbon dating is the most widely used technique. By investigating the evolution of water quality along flow lines it may be possible to establish relative timescales using a combination of geochemical and isotopic methods. Indicators such as the stable isotope composition of water may also provide indirect evidence of residence time. The identification (or absence) of marker species related to activities of the industrial era, such as total organic carbon (TOC), tritium (^{3}H), dissolved greenhouse gases - chlorofluorocarbons (CFCs) - and certain micro-organic pollutants may provide evidence of a recent component in the groundwater. The baseline has been modified by man since earliest times due to settlement and agricultural practices. However, for practical purposes, it is convenient to be able to distinguish water of different 'ages': (i) palaeowater - recharge originating during or before the last glacial era i.e. older than c.10 ka (ii) pre-industrial water (pre 1800s), (iii) water predating modern agricultural practices (pre 1940s) and (iv) modern post-nuclear testing era (post 1963).

Thus an ideal starting point is to locate waters where there are no traces of human impact, essentially those from the pre-industrial era, although this is not always easy for several reasons. Groundwater exploitation by means of drilling may penetrate water of different ages and/or quality with increasing depth as a result of the stratification that invariably develops. This stratification is a result of different flow paths and flow rates being established as a consequence of prevailing hydraulic gradients and the natural variation in the aquifer's physical and geochemical properties. The drilling and installation of boreholes may penetrate this stratified groundwater and pumped samples will therefore often represent mixtures of the stratified system. In dual porosity aquifers, such as the Chalk, the water contained in the fractures may be considerably different chemically from the water contained in the matrix because of differences in residence time. The determination of the natural baseline can be achieved by several means including the study of pristine (unaffected by anthropogenic influence) environments, the use historical records and the application of graphical procedures such as probability plots to discriminate different populations (Shand & Frengstad, 2001; Edmunds et al., 2003). The "baseline" refers to a *specified system* (e.g. aquifer, groundwater body or formation) and is represented by a range of concentrations within that system. This range can then be specified by the median and lower and upper limits of concentration.

The BASELINE objectives are:

1. to establish criteria for defining the baseline concentrations of a wide range of substances that occur naturally in groundwater, as well as their chemical controls, based on sound geochemical principles, as a basis for defining water quality status and standards in England and Wales (in the context of UK and Europe); also to assess anomalies due to geological conditions and to formulate a quantitative basis for the definition of groundwater pollution

2. to characterise a series of reference aquifers across England and Wales that can be used to illustrate the ranges in natural groundwater quality. The baseline conditions will be investigated as far as possible by cross-sections along the hydraulic gradient, in well characterised aquifers. Sequential changes in water-rock interaction (redox, dissolution-precipitation, surface reactions) as well as mixing, will be investigated. These results will then be extrapolated to the region surrounding each reference area. Lithofacies and mineralogical controls will also be taken into account. A wide range of inorganic constituents as well as organic carbon will be analysed to a common standard within the project. Although the focus will be on pristine groundwaters, the interface zone between unpolluted and polluted groundwaters will be investigated; this is because, even in polluted systems, the main constituents of the water are also controlled by geological factors, amount of recharge and natural climate variation

3. to establish long term trends in water quality at representative localities in the selected reference aquifers and to interpret these in relation to past changes due to natural geochemical as well as hydrogeological responses or anthropogenic effects

4. to provide a scientific foundation to underpin UK and EU water quality guideline policy, notably the Water Framework Directive, with an emphasis on the protection and sustainable development of high quality groundwater.

1. EXECUTIVE SUMMARY

The Jurassic Bridport Sands form an important aquifer in the south west of England, providing water to pumping stations as well as supplying industrial and farm water supplies and supporting baseflow to surface waters. The area covered by this study comprises the outcrop and areas of confined aquifer around Yeovil and north of Bridport.

The hydrogeology of this aquifer is poorly understood, but the complex geology, in particular the abundance of faults, make it likely that the aquifer is compartmentalised with distinct groundwater units and flow systems. The Bridport Sands are strongly interbedded due to alternating clay-rich sands and harder calcite cemented sands. This undoubtedly causes significant heterogeneity in terms of transmissivity and it is probable that horizontal hydraulic conductivity is much greater than vertical hydraulic conductivity. Fracture flow is likely to be important in the aquifer. To the east of Yeovil, some boreholes abstract from both the Bridport Sands and the overlying Inferior Oolite as both are treated as one aquifer unit. The base of the sequence, the Pennard Sands, is often separated from the Bridport Sands by the Junction Bed but may, in places, be in hydraulic continuity with the Bridport Sands.

With a few exceptions the chemistry of Bridport Sands waters is considered to be mainly a function of natural water-rock interaction. The groundwaters are mainly of Ca-HCO_3 type although Na-HCO_3 types occur around Yeovil. It is considered the latter is due to ion-exchange reactions of Ca for Na, and the waters are derived from waters in the Pennard Sands at depth. These Na-HCO_3 type waters are also enriched in B, and it is not clear whether this is due to natural or anthropogenic influences. Other important processes include redox reactions and reducing conditions have led to increased dissolved concentrations of Fe and Mn in some waters. The range in Cl concentrations in the groundwaters indicates that mixing with formation water has occurred but is less significant than water-rock interaction. Some Cl may be derived from anthropogenic influences. Several groundwater sources in the Bridport Sands contain relatively high nitrate concentrations which are the result of human activity. It is difficult to establish a baseline because long-term time series data for the Bridport Sands were not available.

The spatial variations in solute concentrations may be large over relatively short distances in the Bridport Sands and care should be taken extrapolating baseline concentrations across the aquifer. Such heterogeneity is caused by variations in geology (faulting), hydrogeology (different flow systems) and mineralogy throughout the aquifer.

2. PERSPECTIVE

Rocks of Jurassic age in England crop out mainly in a broad band trending south-west to north-east from Dorset to Cleveland and form important local aquifers (Jones et al., 2000). The Jurassic Sands in the vicinity of Bridport and Yeovil in Dorset form a good example of such important local aquifers in the south-west of England.

The Bridport and Yeovil Sands are essentially a sandy formation of Upper Liassic (Lower Jurassic) age. The Bridport Sands Formation has been known by a variety of names (Cox et al., 1999) depending on their location (Yeovil Sands, Midford Sands, Cotteswold Sands). The sands generally form an arc-shaped outcrop, producing a scarp broken by steep sided valleys, extending from Beaminster to Poorton and Powerstock. From there the outcrop turns southwards and westwards (Wilson et al., 1958). The scenery of this area is amongst the most attractive in the south-west of England with steep grassy slopes, rounded knolls and vertical cliffs, such as those seen at West Bay. To the north, the Yeovil Sands cover a significant area north and west of Crewkerne and to the south smaller areas such as at Drimpton. The main outcrop area however extends in a wide belt from around Shepton Beauchamp eastwards through Yeovil to the River Yeo before narrowing and finally swinging to the north east.

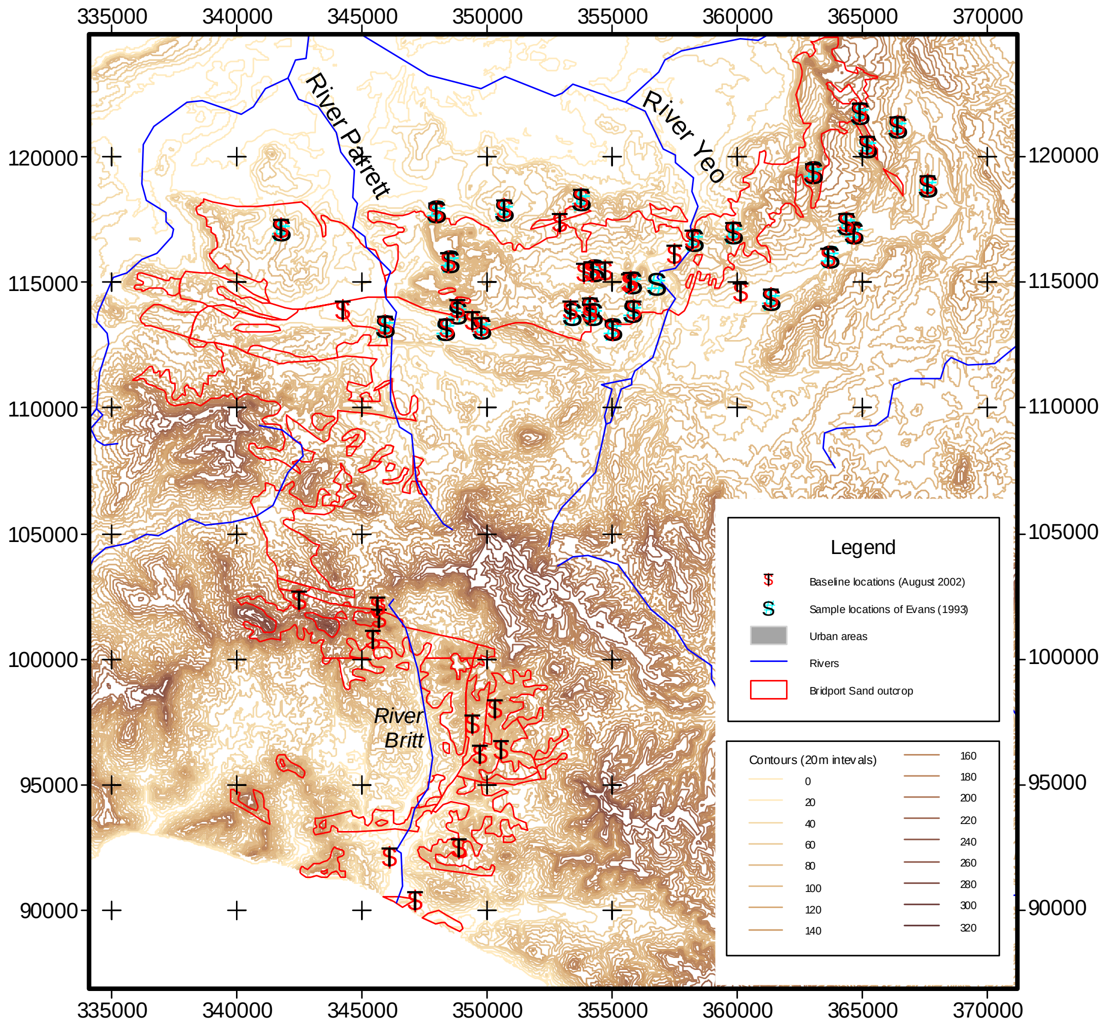


Figure 2.1 **Geographical setting of the study area and Bridport Sands outcrop.**

The study area for this report extends from the coast at Bridport to the area around Yeovil in south Somerset (Figure 2.1). Public water abstraction from the aquifer is limited to boreholes in Compton Durville and South Petherton, Somerset, close to the northern limit of the aquifer in this area. However, many homes in the rural regions of the aquifer outcrop rely on springs and private wells for water supply, both domestic and agricultural. Many of the private wells are very shallow and were dug to capture springs arising from the Bridport Sands. The vulnerability of these shallow abstractions and the groundwater within the aquifer generally, to pollution are important issues from a groundwater protection perspective, especially as many of these private supplies do not have access to mains water. Generally, however, this area is considered to be an area of under-utilised resource potential (O'Shea, 1979). Where overlain by the Inferior Oolite, these strata are considered to form a contiguous aquifer unit, only becoming confined by the Fuller's Earth clays.

For water resources management purposes, the aquifer is currently classified as a Minor Aquifer in the Beaminster – Bridport region and a Major Aquifer in the Crewkerne – Yeovil region. However, it is important to note that within the Water Framework Directive (WFD) terms such as "major" and "minor" are not used. Within these so called major/minor aquifers, "groundwater bodies" will be defined and delineated and the importance that the aquifer represents to the public and the environment at large will be characterised. Notwithstanding the current definition of aquifer type, the nature of the overlying soils are such that the Bridport Sands is considered to be of intermediate vulnerability class 1, although where overlain by the Inferior Oolite, it is generally considered to be of high vulnerability class 1.

Despite the local importance of this aquifer unit, there is a paucity of information available on its physical properties (Allen et al., 1997) though the aquifer thickness is known to vary considerably in thickness. Understanding the natural water quality of the aquifer is however an essential component of the WFD. The Directive requires that groundwater monitoring programmes are established to provide information to establish the status of groundwater bodies. Monitoring is also required to establish the presence of any significant and sustained upward trend in pollutant concentrations resulting from human activity.

Figure 2.2 **Steeply incised valley, with grassy slope at Stoke Abbott, typical scenery of the southern section of the Bridport Sands (NGR 345 101). These areas are dominated by dairy cattle farming with sheep on the poorest pasture on the steepest slopes. Springs typically occur in these valleys, such as in this area.**

Surface drainage in the south is to the English Channel via the River Brit on which the town of Bridport lies (Figure 2.1). The rivers Parrett and Yeo drain the area to the north. This drainage is controlled by an area of high ground where the land rises to *c*.250 m above sea level (Figure 2.2). In the absence of information on groundwater levels and mapped flow contours, it assumed that recharge and discharge are related closely to the surface water catchments, and dominated by topography. The topography of the Bridport Sands outcrop is characterised by steeply sloping grassy hills in the south of the region studied (Figure 2.2).

Whilst little information exists, either on the physical or chemical properties of the aquifer (Allen et al., 1997), or its water resources, the Jurassic sediments which form the aquifer are known to be highly faulted, particularly in the southern part of the study area. It is thought that these faults give rise to an extremely fragmented system, with laterally and vertically discontinuous blocks. There is little information available on whether the faults and fracture networks form permeable pathways or impermeable barriers. The aquifer sediments are comprised of variably (carbonate) cemented feldspathic sandstones, and running sands have been found in boreholes where cementation is poor.

Figure 2.3 Typical pastoral and orchard farming scenery in the Somerset outcrop of the Bridport Sands (NGR 348 115). Good quality pastoral land is dominated by use for dairy cattle raising. Subsidiary land uses include orchards (front area of picture). Springs occur along the slopes of these hills.

The major land use in the area is pastoral and dairy farming although sheep farming and fruit production is also important (Figure 2.3). Arable and dairy farming are important particularly in the Yeovil and South Petherton districts (Figure 2.4). The major settlements, and greatest population density occur around Yeovil (pop. c.38,000 in 1991). The area of Yeovil has historically been a centre of the manufacturing industry, including aircraft development and manufacture, and scrap metal recycling. Several large industrial abstractions of groundwater from the Bridport and Yeovil Sands aquifer are licensed by the Agency.

Figure 2.4 **The topography associated with the Bridport Sands around Yeovil (NGR 352 114) looking towards Yeovil from Camp Hill (NE direction). The region around Yeovil has more arable farming, helped by the more subdued topography than occurs further south.**

The tourist industry provides a significant contribution the economy of the Bridport - Beaminster area, largely driven by the landscape which is designated as part of the Dorset Area of Outstanding Natural Beauty, and the coastal strip up to 5 km inland the Dorset Coast World Heritage Site. There are fewer designations in the Crewkerne – Yeovil area of outcrop, with small areas designated as 'Special Landscape Area'. Water for public supply in the Bridport Area is taken from Litton Cheney (Chalk aquifer boreholes), and Hooke Springs (Chalk aquifer springs). Beaminster itself takes a local supply from Langdon Springs (Chalk aquifer springs). In addition, all this area can be augmented from the Empool Boreholes (semi-confined Chalk) east of Dorchester via a spine main. Charmouth takes water both from the Bridport end and a bulk supply from Devon. Other local industries include brewing, (groundwater provided by their own borehole) golf courses and general agriculture.

Quarrying of a carbonate sequence in the Bridport Sands (Ham Hill Stone) has been carried out since Roman times, particularly for use in the production of carved window and doorframes which are seen throughout the region (Callomon & Cope, 1995). Ham Hill Stone still provides an important building stone both locally and across the country. Waste disposal to landfills or old quarries has also taken place historically. No current domestic waste landfills are operating in the area but large 'dilute and disperse' landfills such as at Odcombe were still receiving wastes until a few years ago. Such landfills have the potential to impact the quality of groundwater locally.

3. BACKGROUND TO UNDERSTANDING BASELINE QUALITY

3.1 Introduction

The geological and hydrogeological characteristics of an aquifer are key variables affecting baseline groundwater chemistry. The rainfall composition, in addition to the mineralogy and geochemistry of the aquifer system, will dominate the recharge composition of the groundwater. Further geochemical transformations of the groundwater will be caused by long residence times within the aquifer. In this region, there is a paucity of existing information upon which to build such an understanding; much of the available literature on the Bridport Sands comes from areas of the same formation further north in its inshore extent, or concealed at great depth in the Wessex Basin.

3.2 Geology

The Jurassic rocks of Britain crop out in a broad band trending south-west to north-east from Dorset in the south to Yorkshire and Cleveland in the north (Allen et al., 1997). They form a sequence of mainly clays, sandstones and limestones up to 1500 m thick (Table 3.1). Although the dominant aquifers of Jurassic age are limestones, sands of Upper Lias age form locally important aquifers. These Upper Lias Sands are now named the Bridport Sands throughout their extent in south and west England (Cox et al., 1999), but were previously referred to as the Yeovil Sands or Midford Sands in the north of the present study area. Bridport Sands was originally reserved for the succession from the Beaminster region south to Bridport. The geology of the study region has been described more fully by Wilson et al. (1958), Barton et al. (2003) and the associated geological maps and is summarised for the study region in Figures 3.1 and 3.2.

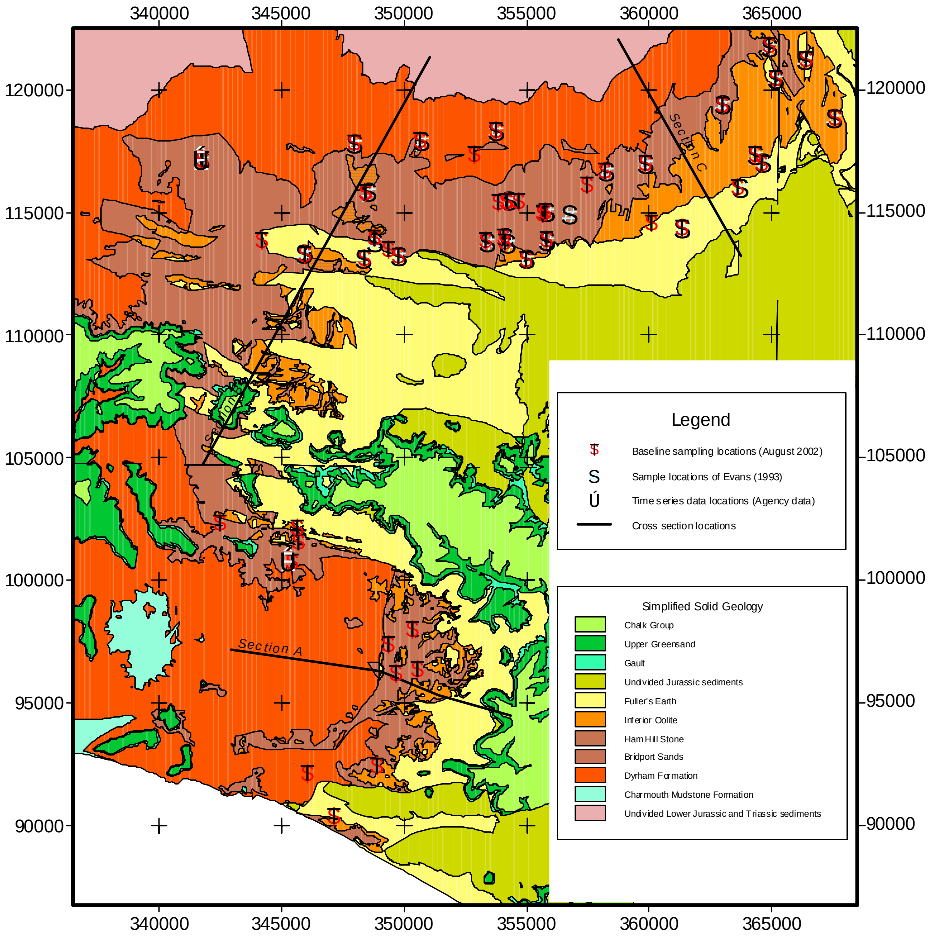


Figure 3.1 Geology of the study region.

Table 3.1 Stratigraphic sequence of the Jurassic rocks of the Wessex Basin.

		Coast	**Inland**
Purbeck Group	Durlston Formation		
	Lulworth Formation		
Portland Group	Portland Stone Formation		
		Portland Sand Formation	Wardour Formation
Ancholme Group	Kimmeridge Clay Formation		
	Corallian Group	Abbotsbury Ironstone Formation	Ringstead Waxy Clay
		Sandsfoot Formation	
		Clavellata Formation	
		Osmington Oolite Formation	Stour Formation
		Nothe Formation	Hazelbury Bryan Formation
	Oxford Clay Formation	Weymouth Member	
		Stewartby Member	
		Peterborough Member	
	Kellaways Formation	Kellaways Sand Member	
		Kellaways Clay Member	
Great Oolite Group	Cornbrash Formation		
	Forest Marble Formation		
	Frome Clay Formation		
	Fuller's Earth Formation	Upper Fuller's Earth Member	
		Fuller's Earth Rock Member	
		Lower Fuller's Earth Member	
Inferior Oolite Group			
Lias Group	Bridport Sands Formation		
		Down Cliff Clay Member	
	Beacon Limestone Formation	Eype Mouth Cephalopod Limestone Member	
		Marlstone Member	
	Dyrham Formation	Down Cliff Sandstone Member	
		Thorncombe Member	
		Eype Argillaceous Member	
	Charmouth Mudstone Formation	Green Ammonite Member	
		Belemnite Marl Member	
		Black Ven Marl Member	
		Shales-with-Beef Member	
	Blue Lias Formation		

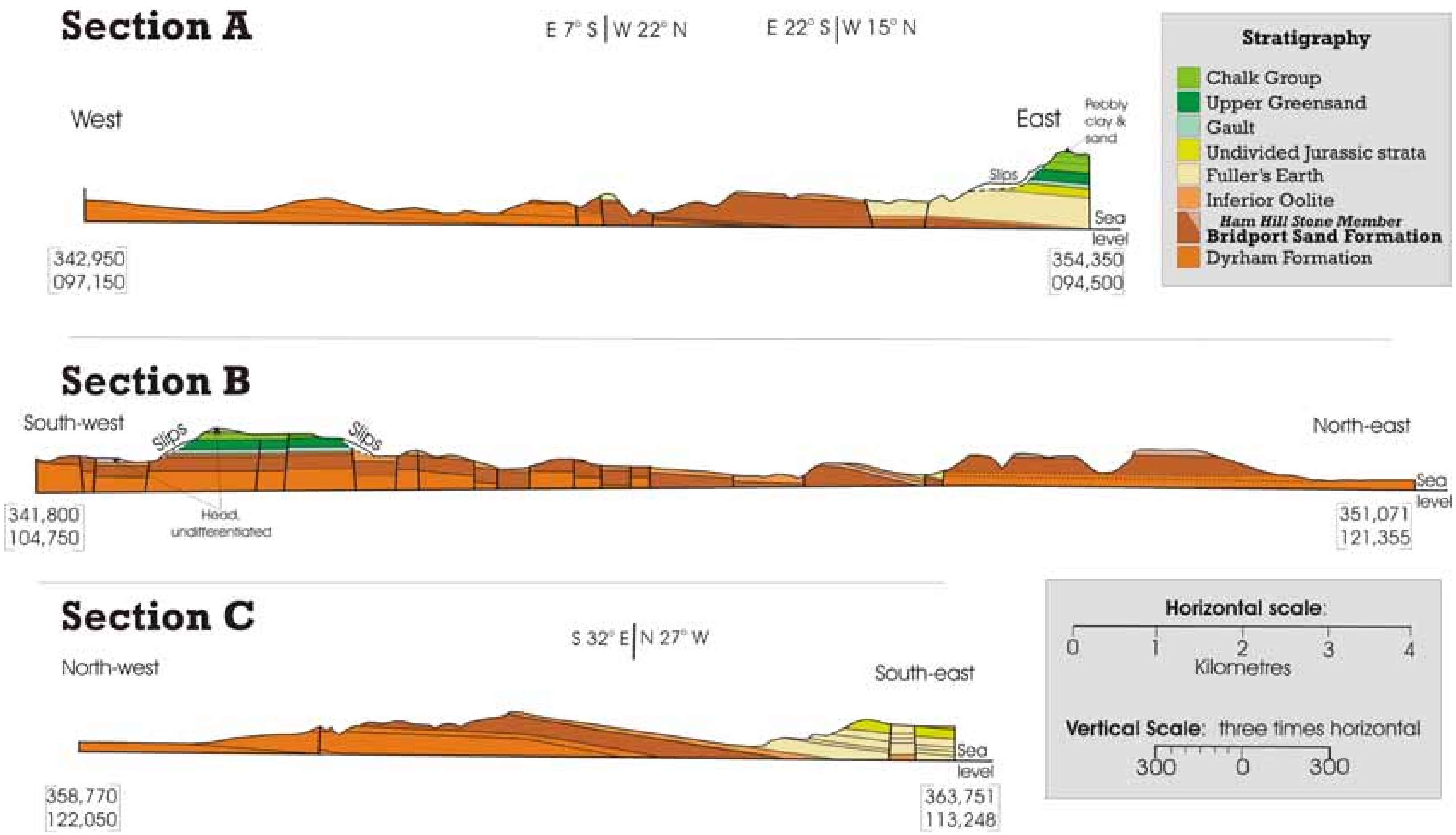


Figure 3.2 **Cross sections of the Bridport Sands aquifer and associated lithologies**

The Bridport Sands are of Lower Jurassic (Upper Lias) age forming part of a cyclic sequence of sediments typical of the Jurassic rocks of Britain. The stratigraphy of the Jurassic sequence in the Wessex Basin of southern England is shown on Table 3.1. The Bridport Sands are up to 120 m thick, comprising alternating rhythmic sequences of fine-grained friable green-grey, weathering to yellow, sub-arkosic sands (up to 2 m thick) and thinner (up to 0.5 m) calcareous sandstones (Davies, 1967; Allen et al., 1997; Barton et al., 2003). These are well exposed along coastal sections near Bridport (Figure 3.4) where the cliffs form alternating friable yellow, silty fine sand and more prominent grey/brown calcite-cemented calcareous sandstone. At Ham Hill, west of Yeovil, the sands pass laterally into a 28 m thick sequence of a well indurated iron-stained sequence of bio-sparite and thin interbedded sandstones called "Ham Hill Stone" (Figure 3.5). These well cemented horizons are laterally continuous over large distances, interrupted only by fractures (Bryant et al., 1988). The lower part of the Bridport Sands (formerly Yeovil Sands) is finer grained and more poorly sorted than the upper. The amount of clay material and the percentage of clay grade material increase northwards from the coast to Yeovil (NT 55 15) to Castle Cary (NT 63 32) and the median grain size of the sand particles and the degree of sorting also increase northwards (Davies, 1967). The subcrop of the Bridport Sands extends eastwards forming one of the reservoir horizons of the Wytch Farm oilfield (Knox et al., 1982).

The Bridport Sands are underlain by the Junction Bed comprising a basal Upper Lias limestone and the underlying Marlstone Rock (Allen et al., 1997) varying in thickness between <1 and 8 m. The Junction Bed is in hydraulic continuity with the underlying Pennard Sands, a sequence of variable thickness comprising fine sandstones and siltstones (Figure 3.3).

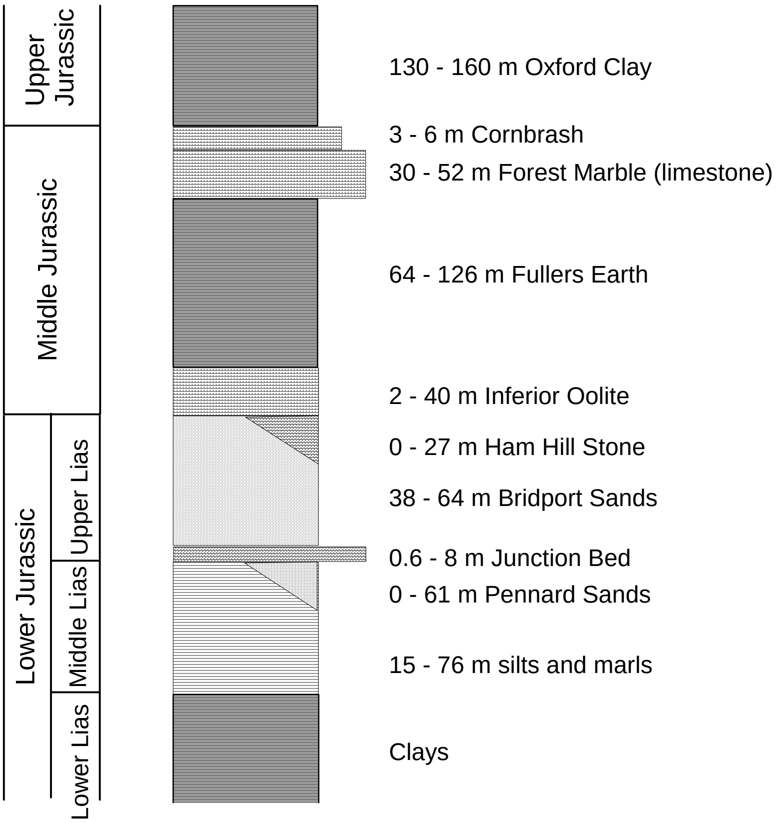


Figure 3.3 **Sedimentary sequence of the Jurassic in Dorset and Somerset.**

Figure 3.4 **Alternating layers of yellow fine silty sand and grey/brown calcite-cemented calcareous sandstones (prominent ledges) near Bridport. The interbedded nature of the sediments is picked out by differential weathering and the yellow colouration is caused by the oxidation of the ferrous iron in the sandstone.**

The Bridport Sands are overlain by limestones of the Inferior Oolite, followed by mudstones of the Fullers Earth formation (Figure 3.2). The Inferior Oolite forms a discontinuous belt up to 3 km wide, a few metres thick to the south-west of Yeovil but thickening to around 18 m in the Sherborne area, and may be laterally equivalent to the uppermost Bridport Sands (Bryant et al., 1988). The region has a structurally complex history, largely affected by its location over a persistent region of weakness (the Bath Axis; Wilson et al., 1958), and has been affected by intra-Jurassic, Cretaceous and Miocene events. The result of these movements was to change the angle of dip of the Lias beds through the area and faulting with sufficient displacement to wholly offset blocks of the aquifer (Figures 3.1 and 3.2). These faults form hydrogeological discontinuities in the study area and are likely to affect groundwater flow. The faults may act as preferential conduits for water flow, or the fractures may form barriers if sealed with cements. There is no information to indicate whether these effects influence water chemistry in the Bridport Sands.

Superficial deposits are largely absent over the aquifer in this region. The only deposits which have been mapped are of alluvium along present day valleys. The lateral extent of these deposits is small, although they can be of some depth, for instance *c.*12 m being recorded at the Palmer’s Brewery borehole, Bridport, in the Britt valley (Wilson et al., 1958).

Figure 3.5 Former Ham Hill Stone quarry at Ham Hill (NGR 347 117). The Ham Hill Stone can be seen to form thinly bedded detrital shelly limestone.

3.3 Hydrogeology

There is little hydrogeological data on the Bridport Sands aquifer system. Groundwater contours for the aquifer are not available, but groundwater flow is thought to follow topography (O'Shea, 1979). The flow of groundwater is considered to be largely intergranular but there is some evidence that fissure/fracture flow is important (Evans, 1993). The interbedded nature of the sediments (Figure 3.4), varying from tightly cemented laterally continuous sands to less well cemented clay rich sands, undoubtedly has a significant effect on both vertical and lateral flow in the aquifer. It is likely that this will produce significant anisotropy in hydraulic conductivity with horizontal permeability much greater than vertical permeability ($K_H >> K_V$), which will promote stratification in water quality. The unconsolidated nature of parts of the aquifer means that boreholes have to be well designed and constructed in order to minimise problems with running sands and to maintain yields (Allen et al., 1997).

The base of the aquifer is represented by the Junction Bed which generally acts as an aquitard to the Bridport Sands. This typically separates the Bridport Sands from the underlying Pennard Sands and restricts the degree of hydraulic continuity between the two (Evans, 1993). The Bridport Sands and overlying Inferior Oolite often act as a single aquifer. The Inferior Oolite varies from 2-40 m in thickness and is dominated by fissure flow (O'Shea, 1979), with fissures being most abundant in the lower half of the formation.

Allen et al. (1997) summarised core analysis data for 135 samples from the Bridport Sands and found that porosity and permeability values of outcrop samples were distinctly higher than those from boreholes as a consequence of weathering. An arithmetic mean for porosity was determined to be 18.9% with an interquartile range of 13.7 to 23.1%. The geometric mean of hydraulic conductivity was 4.9×10^{-4} m d^{-1} with a maximum measured value for an outcrop sample of 0.13 m d^{-1}. There is a poorly defined increase in hydraulic conductivity with increasing porosity (Allen et al., 1997). O’Shea (1976) concluded that the maximum transmissivity in the Bridport Sands of the Upper Parret Basin is 500 to 750 m^2 d^{-1}, but values are often less than this, with yields rarely exceeding 50 l s^{-1}. The higher transmissivities suggest considerable fracture flow. In the Wytch Farm oil field, Colter & Havard (1981) found that strongly cemented horizons of the sands had porosities of less than 10% with negligible permeability compared to intervening horizons, which had porosities around 32% and permeabilities of around 300 mD. The fractured nature of the aquifer is thought to contribute to flow in the aquifer, with both intergranular and fissure flow occurring (O'Shea, 1979). The extensive faulting has lead to the physical fragmentation of the aquifer (Figure 3.2) and may lead to the compartmentalisation of flow within aquifer blocks, particularly if the fractures form barriers or preferential pathways for groundwater flow.

There is no clear distinction between the Lower and Middle Inferior Oolite present in the study area. These limestones are finer grained and more marly than their equivalents in the Cotswolds (Allen et al., 1997). Some horizons are ferruginous with abundant ferruginous ooliths, pellets and concretions.

3.4 Aquifer mineralogy

The composition of both the friable sands and well cemented sandstones is dominated by detrital quartz and feldspar and both have a similar grain size. A comparison of surface and subsurface samples has shown that weathering has removed calcite, dolomite and authigenic clays from the shallow sediments (Bryant et al., 1988). The average feldspar content of the friable sands is approximately 17-20% by volume comprising principally potassium feldspar with some albite (Na-rich plagioclase feldspar). The friable sandstones are more clayey (up to 26% detrital clay) than the cemented sandstones with higher muscovite, biotite and chlorite. The cemented sands are bioclast-rich with bioclasts comprising brachiopod and bivalve shells, gastropods, ammonites, belemnites and bryozoa. These also show widespread evidence of carbonate precipitation and dissolution. The sands around Yeovil contain a higher proportion of silt and are finer grained than those along the coast (Bryant et al., 1988).

The proportion of clays within the sequence is high to moderate, and the sands are feldspathic. The clay content of the sands is generally around 9% comprising chamositic clays (an iron-magnesium rich subgroup of kaolinite) in fresh samples (Evans, 1993) which have altered to illite-smectite in the more weathered samples at outcrop. Iron oxide-rich grains, micrite and bioclastic debris are also present as detrital components. Knox et al. (1982) reports very high proportions of iron rich chlorite ($(Fe_4^{2+}Al_2)(SiAl_2)O_{10}(OH)_8$) as a post depositional alteration product of chamosite in the Upper Lias Bridport sandstones of the Winterbourne Kingstone borehole, Dorset (NGR 38470 09796).

The dominant authigenic mineral, which forms a cement, is a ferroan (Fe-rich) low-magnesium calcite (frequently poikilitic). This cement is often localised in specific horizons where it can form 25-60% of the rock. The concentrations of some elements in these well cemented horizons have been measured by Storey (1991) and are shown in Table 3.2. The $\delta^{13}C$ of the carbonate cement was around –2 ‰, close to a marine signature.

Table 3.2 Ranges in concentrations of selected elements in well cemented sandstones (from Storey, 1991).

Element	**Range (ppm)**	**Average (ppm)**
Magnesium	300-900	300-400
Iron	500-1400	500-600
Manganese	4000-9000	7000-8000
Strontium	1500-3000	1700-2000

Other accessory minerals include muscovite, pyrite, goethite, non-ferroan dolomite, ankerite, siderite, barite and sphalerite which may form 1-5% of the aquifer. Bryant et al. (1988) also reported significant quantities of structureless organic matter in cores from the Marchwood borehole.

The presence of clay minerals has a significant effect on the permeability of the aquifer. Morris & Shepherd (1982) studied clays in the Bridport Sands to determine their effect on recovery of oil from the reservoirs at Wytch Farm. They concluded that the reduction in permeability caused by the clays varied between 30% and 70%.

3.5 Rainfall chemistry

Rainfall chemistry is important in determining the chemistry of recharging groundwaters. Rainfall in this area typically varies from about 750 mm a^{-1} at the coast (Bridport) to about 950 mm a^{-1} over higher ground in the upper Brit catchment, decreasing again to *ca.*800 mm a^{-1} in the Yeovil and South Petherton region (Environment Agency, 1997).

Chemical analyses were available from Yarner Wood, Devon (NGR 278 078), *ca*. 70 km to the west of the study area (NETCEN, 2002). The data are presented in Table 3.3 along with the second data column showing the solute concentrations multiplied by a factor 3. This is intended to be only a rough guide to the composition of initial recharge as modified by evapo-transpiration. However, whilst some elements may behave in an essentially conservative way, e.g. Cl, others are affected by biological or mineralogical interactions. Nitrogen and K are major nutrient elements for plants, and uptake may result in recharge waters having lower concentrations than rainfall. Mineral precipitation and sorption processes in soils and the unsaturated zone may also affect the concentration of some elements, such as Ca, and alter the expected concentration (derived from rainfall).

Table 3.3 Rainfall chemistry at Yarner Wood, Devon (NGR 278 078)

Parameter & units		Value	Value x3
pH		5.00	
SO_4	(mg l^{-1})	1.34	4.03
NO_3	(mg l^{-1})	1.05	3.16
NH_4	(mg l^{-1})	0.31	0.92
Na^+	(mg l^{-1})	2.02	6.07
Mg^{2+}	(mg l^{-1})	0.45	1.35
Ca^{2+}	(mg l^{-1})	0.44	1.32
Cl^-	(mg l^{-1})	3.47	10.42
K^+	(mg l^{-1})	0.08	0.23
Conductivity	(µS cm^{-1})	23.5	70.5
Annual rainfall	(mm)	1106	

Data taken from NETCEN (2002)

3.6 Landuse in the area

The majority of the outcrop in the study area is covered by pastoral farming (Figure 3.6), particularly dairy cattle. Subsidiary agricultural land use includes cider orchards, sheep rearing and arable cultivation. Whilst agricultural use of groundwater (e.g. for irrigation of crops or livestock) is relatively small over the area, many rural homes use private water supplies in this region. Industry is concentrated around the town of Yeovil, which has a historical legacy of a wide range of manufacturing industries including aircraft, dairy products and tanning. Beyond the urban area of Yeovil, towns are small and predominantly centred around agriculture. Industrial uses of groundwater are limited, such as quarrying and brewing. Areas of amenity (parks or semi-natural vegetation) can be found both in the urban area of Yeovil and in the rural areas to the south. Roads traverse much of the outcrop, and although they are not trunk routes, they are heavily used, particularly in the summer months. Tourism is an important source of revenue for the area, particularly from south of Yeovil to the Dorset World Heritage coastline, centred on Bridport.

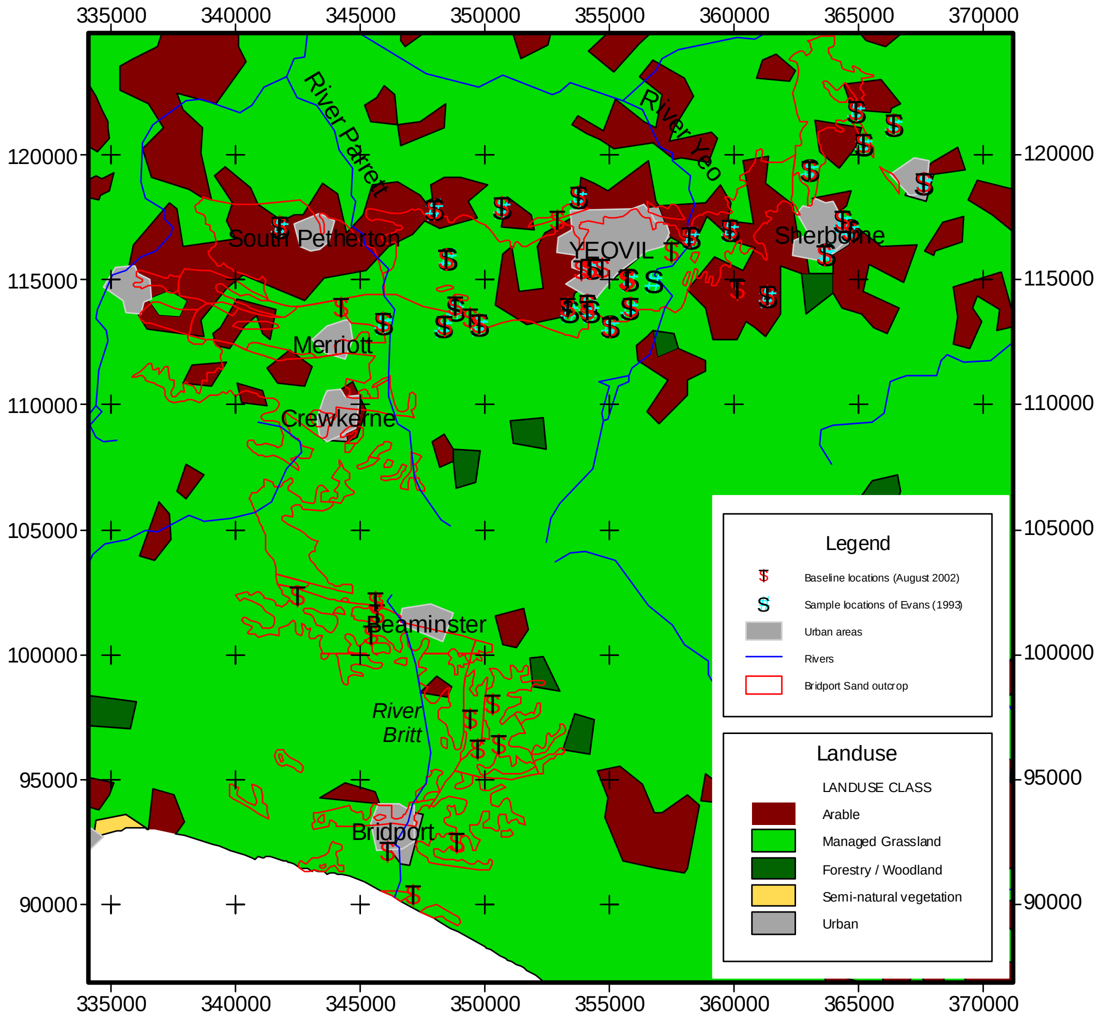


Figure 3.6 **Generalised landuse map of the study area. Data from Land Cover Map 1990, supplied courtesy of the Centre for Ecology and Hydrology © NERC.**

4. DATA AND INTERPRETATION

4.1 Project sampling programme

A total of 21 groundwater samples were collected during July 2002 in both the Yeovil and Bridport areas (Figure 2.1). These were sampled mainly from springs and private domestic supplies. The private domestic supplies were generally relatively shallow wells. Some of these wells were located close to springs and intercepted water that would have discharged at these springs. A total of 7 samples were collected from such captured spring sources, with another 6 sampled from free flowing springs. One sample was collected from a deep private well and 7 samples from pumped boreholes (all but one being in the north of the study area). Where pumped samples have been collected from boreholes, it should be borne in mind that they may represent mixing of several different waters, especially if there is stratification in water chemistry. Several of the boreholes and springs sampled had copious brown precipitates (iron oxyhydroxide) at the point of discharge. Running sands have been reported as a problem in deep boreholes in the Yeovil area which may locally affect the flow dynamics around the borehole. All new samples collected were from the Bridport Sands aquifer.

The physico-chemical parameters pH, redox potential (Eh) and dissolved oxygen (DO) were measured on site using an air-tight flow-through cell where possible. For the springs, measurements were made by inserting the probes as close as possible to spring source. Other on-site measurements made were alkalinity, temperature and specific electrical conductance (SEC). Field measurements were replicated at least three times to obtain a representative value for the sample. Samples were filtered (<0.45 µm) into Nalgene polythene bottles for major and trace element analysis (acidified with 1% v/v HNO_3) and filtered (<0.45 µm), unacidified, samples for anion analysis and nitrogen species (NO_3, NO_2 and NH_4) determinations. Samples were also collected in glass bottles for total organic carbon (TOC), dissolved organic carbon (DOC) (filtered to 0.45 µm through a Ag-membrane filter) and stable isotopes (δ^2H, δ^{18}O and δ^{13}C).

Major cations and sulphate was analysed by inductively coupled plasma atomic emission spectrometry (ICP-AES) and the trace elements were determined using inductively coupled plasma mass spectrometry (ICP-MS). The anions Cl, Br, F, I and N-species were determined by automated colorimetry (SKALAR). Stable isotope analyses were analysed by mass spectrometry, and reported relative to VSMOW for δ^2H and δ^{18}O and to VPDB for δ^{13}C.

4.2 Other Data

The new data (Figure 2.1) were augmented with hydrochemical data from the northern part of the study area (from the same sites as reported by Evans, 1993). The samples were analysed for a wide range of elements by ICP AES, ICP MS and automated colorimetry at the BGS Wallingford laboratories. There was some overlap of sites with the present study and where this occurs, the new data have been selected because of the wider range of parameters analysed.

4.3 Historical data

Only two sample sites in the study region had historical time-series data available for analysis. These were a spring at Stoke Abbott and the Compton Durville public water supply (Wessex Water). The location of these sites is shown in Figure 3.1. Data were only available for a limited suite of analytes.

4.4 Interpretation of pumped groundwater samples

The chemical composition of a groundwater sample will be a function of many factors and the very act of drilling and pumping water from a borehole will cause variations in the chemistry. Variations in water chemistry may arise as a result of:

- differences in borehole design and construction (depth, depth of casing)
- intercepting different stratigraphic horizons occurring in the borehole (including fractures intersected)
- different pumping histories
- changes in redox conditions during pumping/sampling

4.4.1 Differences in borehole design

Water quality stratification may exist in the aquifer and is likely to be accentuated as a result of the general layering within the aquifer. As a consequence, differences in borehole design, in particular depth of casing and depth of borehole, may produce differences in water quality unrelated to geochemical reactions along a flow path.

4.4.2 Differences in stratigraphy

Changes in sedimentary facies or lithology invariable leads to changes in water chemistry. This may also occur in parts of the aquifer which have lost mineral phases due to previous dissolution e.g. carbonate minerals are often weathered from the shallow parts of some aquifers.

4.4.3 Differences in pumping history

Where large volumes of water have been pumped historically from abstraction boreholes, significant recharge or alteration of flow patterns are likely to have been induced. This is likely to increase the proportion of modern (with potentially higher NO_3 concentrations) groundwater that is pumped.

It is not possible in this report to thoroughly assess which factors may be influencing water quality for each of the water sampling boreholes. This report presents a broad assessment of the water quality variations observed across the aquifer and the controlling geochemical processes. Chemical reactions are both time and space dependant and the data presented simply represents a snapshot of the water quality which is in a constant state of change.

4.5 Data handling

Sample site selection was dictated by the occurrence of suitable sampling locations within the selected study areas.

The general hydrochemical characteristics of the data are described in Chapter 5. Where data is less than the detection limit for the method used, a value of half the detection limit has been applied for statistical purposes. Changing detection limits between different laboratories and over time are problematical when calculating average values, and here all data have been adjusted to half the detection limit value of data from the present study. Pre-existing data was rejected where charge balance errors were greater than 10%.

5. HYDROCHEMICAL CHARACTERISTICS

5.1 Introduction

This section deals with the fundamental hydrochemical characteristics of the groundwater in the Bridport Sands Formation of Dorset and Somerset. A summary of the data are presented in Tables 5.1 and 5.2 and includes analyses from all sites studied within the study area. The tables show the ranges and averages of data as well as an upper concentration (defined as mean + 2σ or 97.7th percentile). The median is preferred to the mean as an average as it is more robust and less affected by extreme values. The 97.7 percentile is used as a practical cut off to define outlying data, and where the chemistry has not been modified by anthropogenic inputs, can be defined as the upper baseline.

Table 5.1 Summary of major and minor element data for groundwaters.

Parameter	units	minimum	maximum	mean	median	97.7percentile	number
T	^{o}C	10.3	15.3	12.1	11.8	14.8	52
PH		6.35	8.03	7.15	7.08	7.87	52
Eh	mV	132	485	323	333	437	52
DO	mg l^{-1}	<0.1	7.7	4.2	4.9	7.5	51
SEC	µS cm^{-1}	367	926	656	669	892	52
$\delta^{2}H$	‰	-44.0	-35.9	-39.7	-39.6	-36.1	11
$\delta^{18}O$	‰	-7.0	-6.1	-6.6	-6.7	-6.1	11
$\delta^{13}C$	‰	-18.2	-14.6	-16.2	-16.4	-14.6	20
Ca	mg l^{-1}	42	165	115	116	156	52
Mg	mg l^{-1}	2.2	15	5.9	5.0	13	52
Na	mg l^{-1}	7.3	101	22	16	75	52
K	mg l^{-1}	0.4	11	2.4	2.0	5.0	52
Cl	mg l^{-1}	12	55	28	26	49	52
SO_4	mg l^{-1}	14	113	50	44	110	52
HCO_3	mg l^{-1}	115	447	297	300	413	52
NO_3-N	mg l^{-1}	0.009	42.7	5.0	4.9	16.7	52
NO_2-N	mg l^{-1}	<0.001	0.080	0.007	0.002	0.048	52
NH_4-N	mg l^{-1}	<0.003	0.140	0.014	0.010	0.068	52
P	mg l^{-1}	<0.01	0.30	0.08	0.10	0.19	52
TOC	mg l^{-1}	0.38	13.30	2.50	1.56	9.22	20
DOC	mg l^{-1}	0.95	7.94	3.09	2.32	7.21	20
F	mg l^{-1}	0.12	0.74	0.29	0.27	0.69	52
Br	mg l^{-1}	0.04	0.17	0.08	0.08	0.15	52
I	mg l^{-1}	0.002	0.009	0.004	0.003	0.009	21
Si	mg l^{-1}	2.8	9.8	5.4	5.1	9.2	52

Table 5.2 Summary of trace element data for groundwaters

Parameter	units	minimum	maximum	mean	median	97.7percentile	number
Ag	µg l^{-1}	<0.03	0.07	0.05	0.07	0.07	52
Al	µg l^{-1}	0.36	1103	29	3.0	66	52
As	µg l^{-1}	0.15	12.00	0.94	0.52	3.74	52
Au	µg l^{-1}	<0.05	0.07	<0.05	<0.05	0.05	21
B	µg l^{-1}	<20	573	58	22	372	52
Ba	µg l^{-1}	1.3	17.6	6.8	5.7	16.2	52
Be	µg l^{-1}	<0.05	<0.05	<0.05	<0.05	<0.05	52
Bi	µg l^{-1}	<0.05	0.40	<0.05	<0.05	<0.05	52
Cd	µg l^{-1}	<0.05	0.67	0.093	0.08	0.45	52
Ce	µg l^{-1}	<0.01	1.81	0.058	0.01	0.22	52
Co	µg l^{-1}	<0.02	16.48	0.63	0.22	3.45	52
Cr	µg l^{-1}	<0.5	6.70	0.52	<0.5	1.76	52
Cs	µg l^{-1}	<0.01	0.045	0.029	0.045	0.045	52
Cu	µg l^{-1}	<0.04	68.97	2.56	0.50	10.8	52
Dy	µg l^{-1}	<0.01	0.102	<0.01	<0.01	0.019	52
Er	µg l^{-1}	<0.01	0.037	<0.01	<0.01	0.010	52
Eu	µg l^{-1}	<0.01	0.036	<0.01	<0.01	<0.01	52
Fe	µg l^{-1}	<5	887	133	6.5	844	52
Ga	µg l^{-1}	<0.05	0.273	<0.05	0.050	0.050	52
Gd	µg l^{-1}	<0.01	0.187	<0.01	<0.01	0.027	52
Ge	µg l^{-1}	<0.05	0.220	0.053	0.050	0.200	52
Hf	µg l^{-1}	<0.02	<0.02	<0.02	<0.02	<0.02	21
Hg	µg l^{-1}	<0.1	0.100	<0.1	<0.1	<0.1	21
Ho	µg l^{-1}	<0.01	0.016	<0.01	<0.01	<0.01	52
In	µg l^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	21
Ir	µg l^{-1}	<0.05	0.025	<0.05	<0.05	<0.05	21
La	µg l^{-1}	<0.01	0.769	0.030	<0.01	0.098	52
Li	µg l^{-1}	3.4	57	16	13	50	52
Lu	µg l^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	52
Mn	µg l^{-1}	<2	348	29	1.00	282	52
Mo	µg l^{-1}	<2	<2	<2	<2	<2	21
Nb	µg l^{-1}	<0.01	0.02	0.01	0.01	0.01	21
Nd	µg l^{-1}	<0.01	0.75	0.03	0.01	0.12	52
Ni	µg l^{-1}	<0.2	72	6.2	6.0	17	52
Os	µg l^{-1}	<0.05	<0.05	<0.05	<0.05	<0.05	21
Pb	µg l^{-1}	<0.1	3.6	0.40	0.27	1.58	52
Pd	µg l^{-1}	<0.2	<0.2	<0.2	<0.2	<0.2	21
Pr	µg l^{-1}	<0.01	0.190	<0.01	<0.01	0.026	52
Pt	µg l^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	21
Rb	µg l^{-1}	0.052	1.975	0.639	0.488	1.594	52
Re	µg l^{-1}	<0.01	0.010	<0.01	<0.01	0.010	21
Rh	µg l^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	21
Ru	µg l^{-1}	<0.05	0.025	0.025	0.025	0.025	21
Sb	µg l^{-1}	<0.05	0.220	0.033	0.030	0.077	52
Sc	µg l^{-1}	<0.8	3.03	1.26	1.20	2.69	52
Se	µg l^{-1}	<0.5	1.50	0.62	0.60	1.44	52
Sm	µg l^{-1}	<0.05	0.17	0.02	0.01	0.03	52
Sn	µg l^{-1}	0.11	0.50	0.21	0.20	0.38	21
Sr	µg l^{-1}	133	881	348	303	683	52
Ta	µg l^{-1}	<0.05	<0.05	<0.05	<0.05	<0.05	21
Tb	µg l^{-1}	<0.01	0.02	<0.01	<0.01	<0.01	52
Te	µg l^{-1}	<0.05	0.11	<0.05	<0.05	0.07	21
Th	µg l^{-1}	<0.05	0.08	<0.05	<0.05	<0.05	52
Ti	µg l^{-1}	<10	<10	<10	<10	<10	21
Tl	µg l^{-1}	<0.01	0.04	0.01	0.01	0.04	52
Tm	µg l^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	52
U	µg l^{-1}	<0.05	5.47	0.60	0.54	1.18	52
V	µg l^{-1}	<1	3.00	2.00	3.00	3.00	52
W	µg l^{-1}	<0.1	0.10	<0.1	<0.1	<0.1	21
Y	µg l^{-1}	<0.01	0.35	0.03	0.01	0.09	52
Yb	µg l^{-1}	<0.01	0.04	<0.01	<0.01	<0.01	52
Zn	µg l^{-1}	<0.5	227	14	2.7	70	52
Zr	µg l^{-1}	<0.5	<0.5	<0.5	<0.5	<0.5	21

The summary data are shown graphically on a Piper Plot (Figure 5.1), boxplots (Figures 5.2 and 5.4) and cumulative frequency plots (Figures 5.3 and 5.5). The boxplots (or box and whisker plots) display the ranges of data and are designed to highlight the distribution of data of a percentile basis (the boxes show the range between the 25th and 75th percentiles, the whiskers represent the 10th and 90th percentiles and the dots the 5th and 95th percentiles). In addition the median is shown as a horizontal black line and the mean as a blue line within the box. The solid black line on the graph represents a diluted seawater curve which has been normalised to the median Cl of the samples. This provides a general indication, in most aquifers, of inputs from water-rock interaction above the marine-derived (rainfall or connate) inputs. The solid grey line on Figure 5.3 shows typical detection limits for each element. Cumulative probability plots are useful in visualising the distribution of data and may be of use in determining outlying data or discerning pollution. Geochemical processes may alter the distribution of populations in several different ways (Box 5.1).

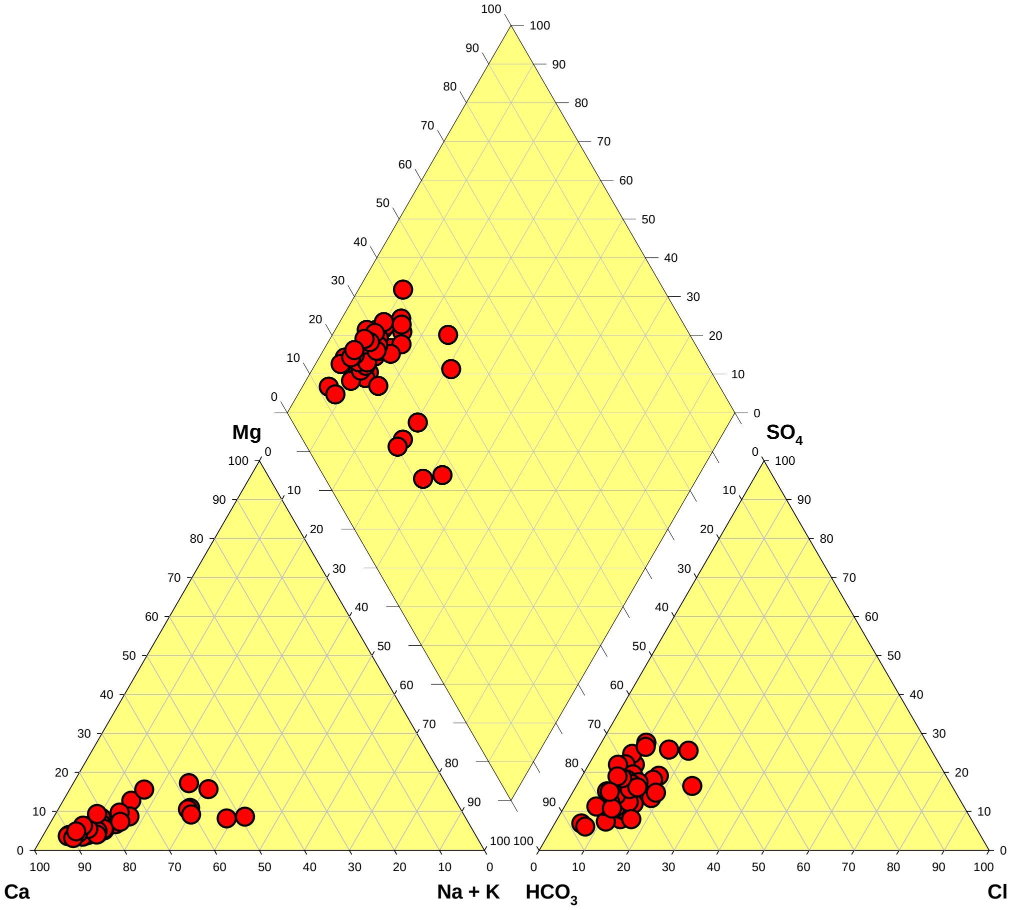


Figure 5.1 **Piper plot showing the variations in relative major cations and anions in the Bridport Sands aquifer.**

5.2 Water types and physicochemical characteristics

The groundwaters have a range in temperatures (10.3 - 15.3 °C) but are typically between 10 and 13 with a median of 11.8 °C. Specific electrical conductance (SEC) shows that they are weakly to moderately mineralised (367 – 926 $\mu S\ cm^{-1}$), and pH varies from slightly acidic (pH 6.35) to slightly alkaline (pH 8.03). The redox conditions in the groundwaters are also variable from moderately reducing (Eh 132 mV, DO less than detection) to oxidising (Eh 485, DO 7.7 $mg\ l^{-1}$).

The data are shown on a Piper plot on Figure 5.1. The majority of groundwaters are of Ca-HCO_3 type and show little variation in terms of the relative proportions of major cations and anions. For this main group, there is a slightly greater scatter on the anion plot towards SO_4 compared to that seen in the cations (Figure 5.1). Several samples plot outside this main grouping through relatively higher Na or Cl and SO_4. The trend towards higher Na is not reflected to the same degree in Cl and the waters trend towards a Na-HCO_3 composition on the central plot (Figure 5.1). The most extreme enrichment in Na was found in the Westland boreholes. Some other boreholes show an enrichment in Na, Cl and SO_4 and there is a slight trend towards a seawater composition (although SO_4 is enriched more than Cl). These samples had low SEC and are from outcrop areas of the Pennard Sands (e.g. Target Farm (NGR 353720 118280) SEC 367 µS cm^{-1}). The samples from springs and boreholes also have higher Mg/Ca ratios than samples from the Yeovil Sands.

5.3 Major elements

The range of major element concentrations is shown on a box plot in Figure 5.2 with a diluted seawater curve shown for comparison. The highest major cation and anion concentrations present in the groundwaters are Ca and HCO_3. Median Na plots close to the dilute seawater line, but the range extends to higher concentrations than for Cl. Significant enrichments in Mg, K and SO_4 are also clear with median concentrations approaching an order of magnitude higher than the dilute seawater line. There is a large range in nitrate-N concentrations from below detection limit to concentrations greater than current drinking water limits.

A cumulative probability plot (Figure 5.3) for the major elements also highlights the ranges in data. Many of the elements show near linear (log-normal) distributions. The trends for Ca and HCO_3 reflect rapid dissolution with a long tail at low concentrations for the more acidic samples. There is a distinct population shift in Na at high concentrations reflecting the higher Na in the samples which trend towards Na-HCO_3 composition. The NO_3 profile is complex and reflects both natural denitrification and anthropogenic influences that are discussed later.

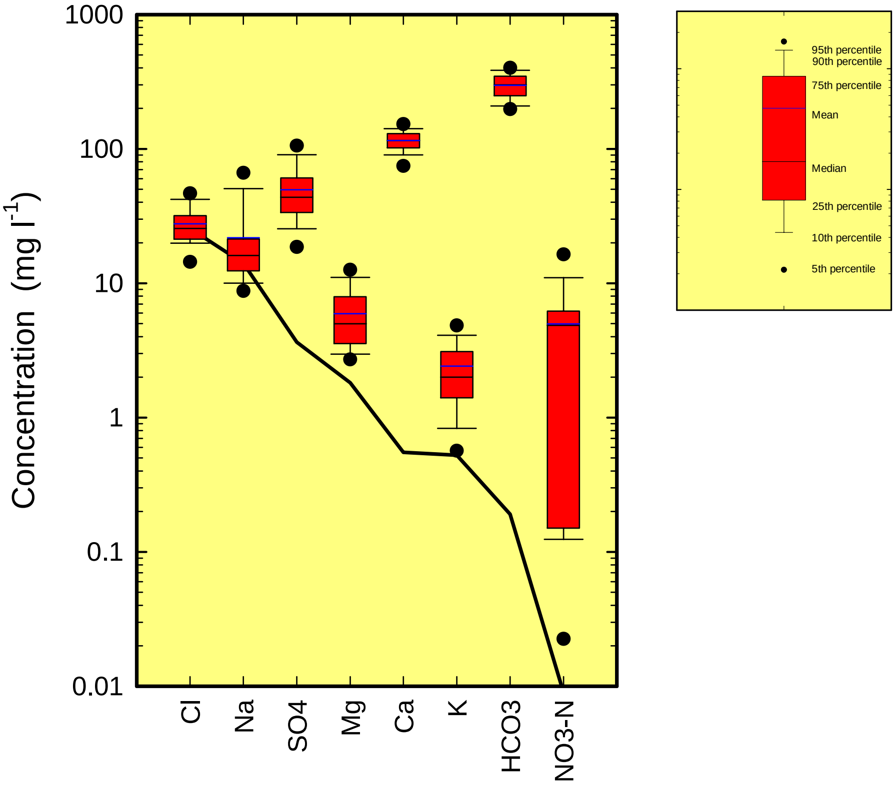


Figure 5.2 **Boxplot of major elements in the Bridport Sands aquifer. Dark line represents diluted seawater line.**

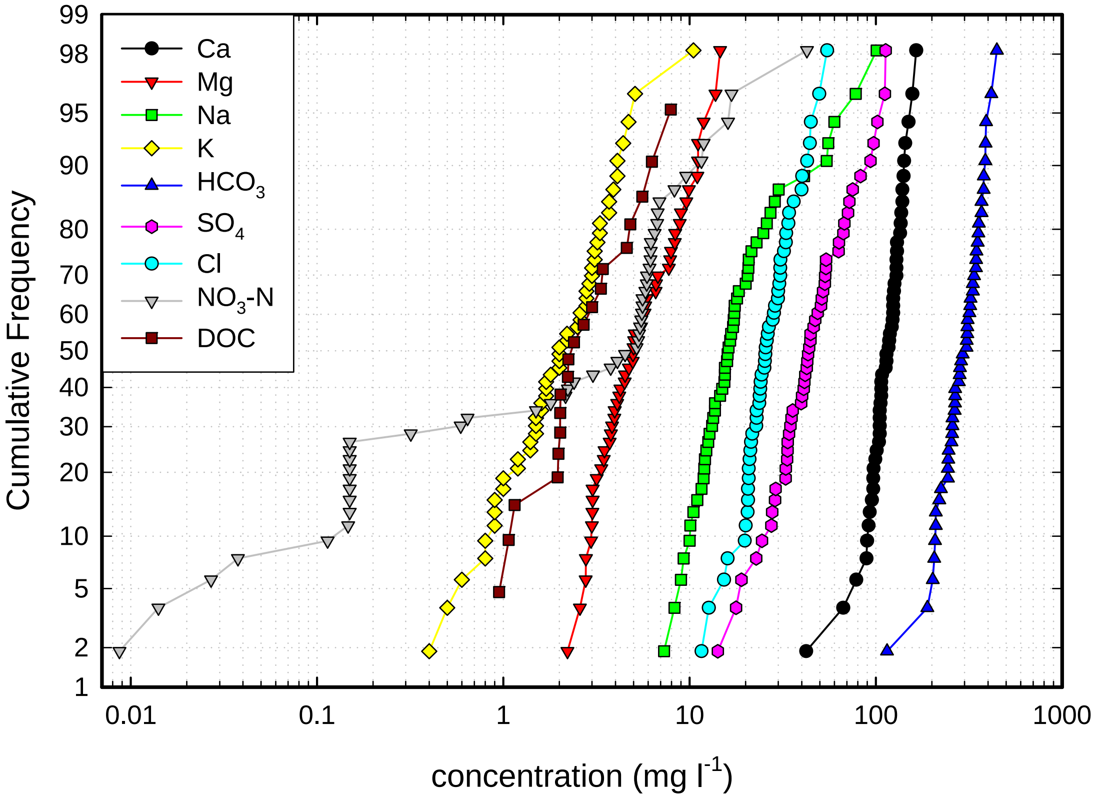


Figure 5.3 Cumulative probability plot of major elements in the Bridport Sands aquifer.

5.4 Minor and trace elements

The ranges and average concentrations of minor and trace elements are displayed on a box plot in Figure 5.4. Bromide shows a relatively small range which plots close to the dilute sea water line whereas the other halogen elements, I and F lie above this line. The I/Cl ratio is commonly enriched in rainfall compared to seawater and I is most likely to be derived from rainfall. Fluoride concentrations are variable but reach moderately high concentrations (up to 0.74 mg l^{-1}) but are still well below current drinking water standards. Silicon concentrations display a narrow range limited by saturation with a silica phase, probably chalcedony.

The highest median concentration for the trace elements is Sr (median 303 µg l^{-1}). Barium occurs at relatively low concentrations compared with Permo-Triassic sandstones (Shand et al., 2002; Griffiths et al., 2002) and the Lower Greensand (Shand et al., 2003). Iron and Mn display the widest range in concentrations varying over approximately three orders of magnitude. Most other trace elements are present at low concentrations with median values often being below detection limit. However, significant concentrations of Al, Cu and Zn are present locally.

The population distributions of most trace elements are more complex than for the major elements (Figure 5.5). There is a distinct shift in populations for Sr above the 80th percentile. Iron and Mn show a very wide range in concentrations (the vertical lines at low concentrations represent data below the detection limit). Arsenic is typically present at low concentrations less than 1 µg l^{-1} with only four samples above this, up to 12 µg l^{-1}.

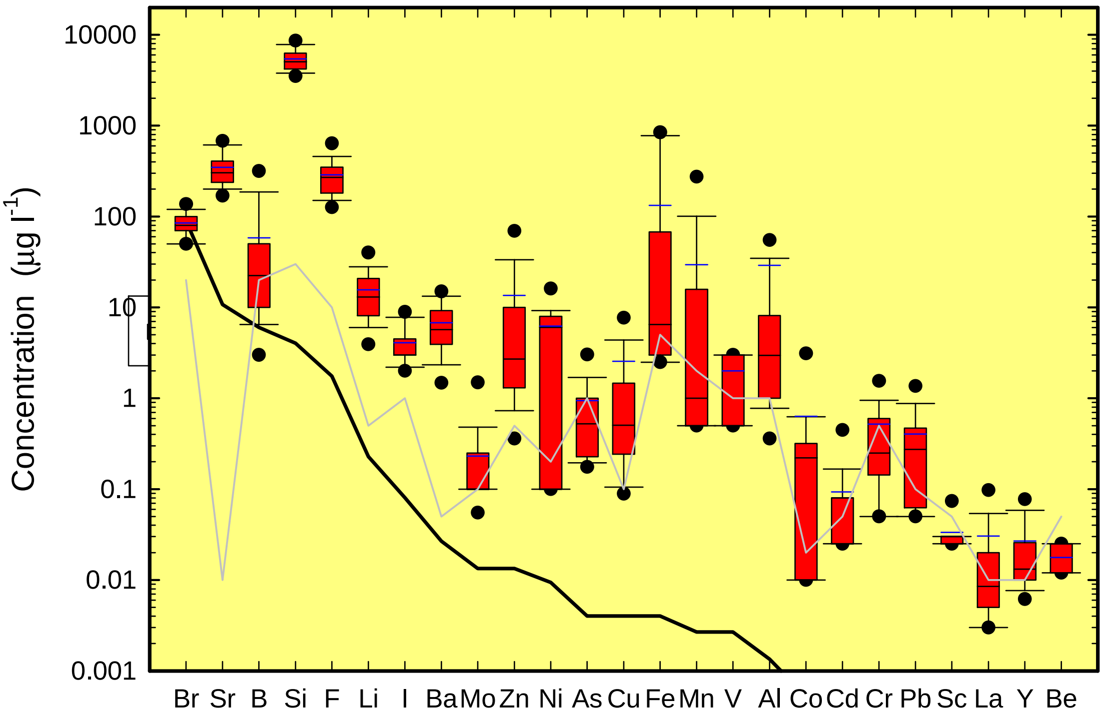


Figure 5.4 Box plot of minor and trace elements in the Bridport Sands aquifer. Dark line represents diluted seawater line and grey line represents typical detection limits.

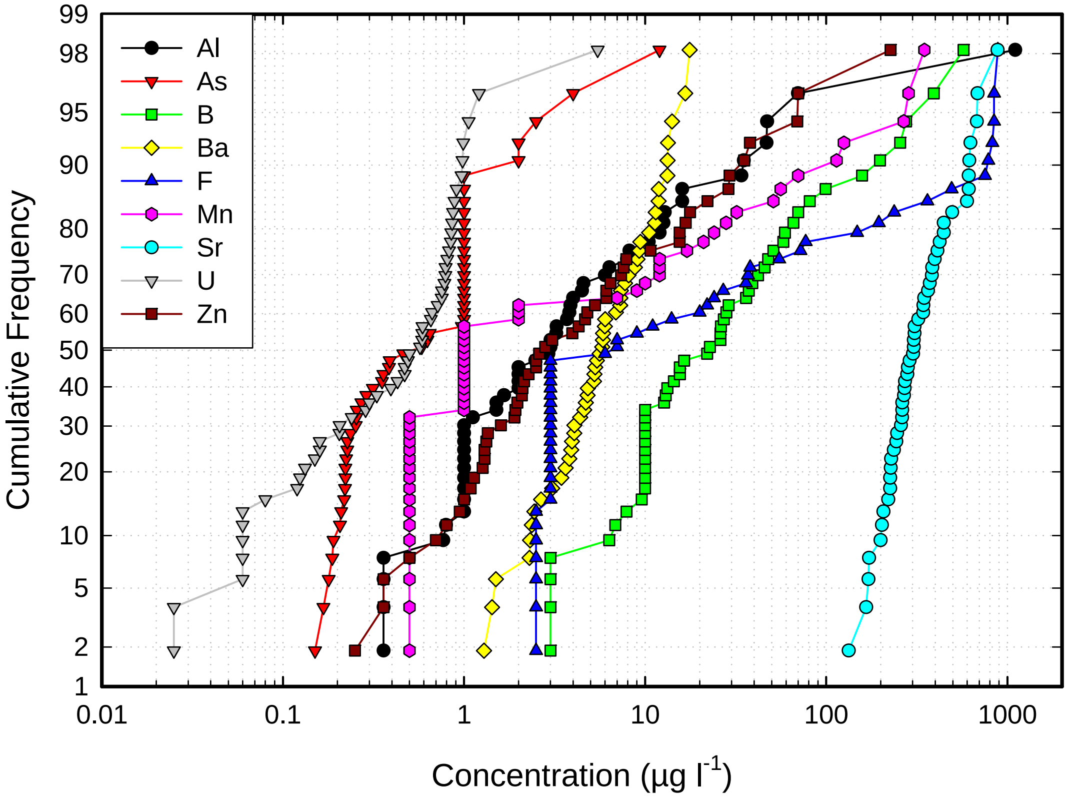
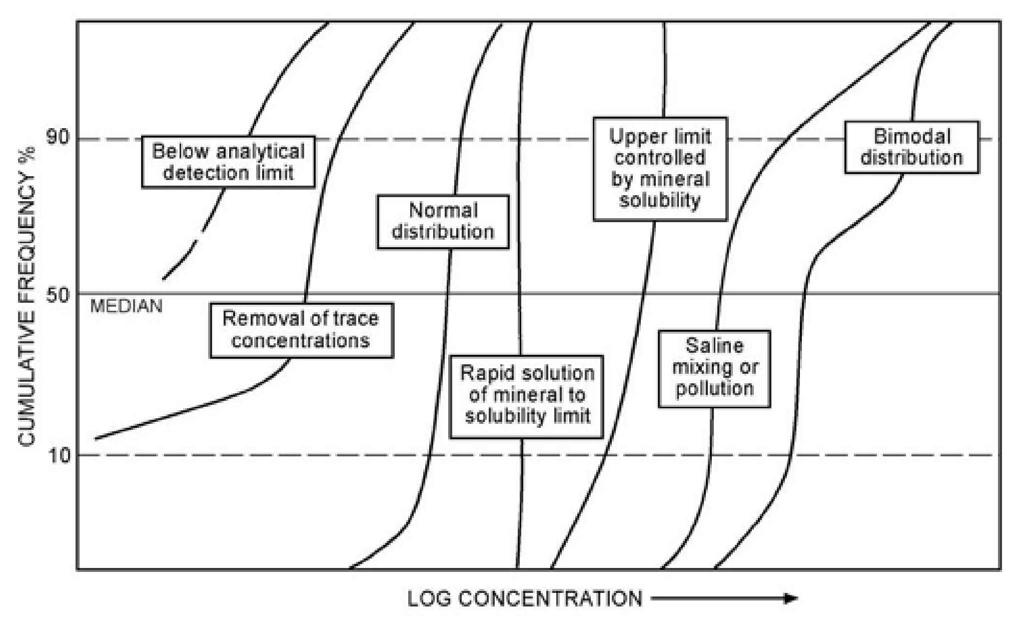


Figure 5.5 Cumulative probability plot of minor and trace elements in the Bridport Sands aquifer.

Box 5.1 **Use of cumulative frequency diagrams to indicate baseline characteristics in groundwaters**



i) The median and upper and lower percentile concentrations are used as a reference for the element baseline which can be compared regionally or in relation to other elements.
ii) Normal to multi-modal distributions are to be expected for many elements reflecting the range in recharge conditions, water-rock interaction and residence times under natural aquifer conditions.
iii) Narrow ranges of concentration may indicate rapid attainment of saturation with minerals (e.g. Si with silica, Ca with calcite).
iv) A strong negative skew may indicate selective removal of an element by some geochemical process (e.g. NO_3 by *in situ* denitrification).
v) A narrow range in concentration at the upper limit may indicate a mineral solubility control (e.g. F by fluorite)
vi) A positive skew most probably indicates a contaminant source for a small number of the groundwaters and this gives one simple way of separating those waters above the baseline. Alternatively the highest concentrations may indicate waters of natural higher salinity.

5.5 Pollution indicators

The focus in the Baseline project has been on areas where contamination is minimal. Areas known to have suffered from point source pollution are therefore avoided. However, the effects of diffuse pollution are more difficult to avoid since it typically occurs on a regional scale. No data were available on pesticides which may indicate the presence of modern recharge, but the presence of high nitrate concentrations implies that at least some of the groundwaters are affected by diffuse pollution from agricultural or urban pollution. Elevated concentrations of Cl, Na and K are also likely to occur in such areas, but these are difficult to assess because concentrations may be within the range of the regional baseline as a consequence of mixing with formation waters. A determination of the baseline for specific sites requires further information such as good historical records which are limited in this area. Comparisons with known pristine sites, knowledge of the residence time or the application of geochemical knowledge may help highlight these and will be discussed in the following chapter.

6. GEOCHEMICAL CONTROLS AND REGIONAL CHARACTERISTICS

6.1 Introduction

This section deals with the dominant geochemical processes that influence groundwater chemistry including:

- mineral dissolution/precipitation,
- redox reactions,
- ion exchange and,
- mixing of recent waters with older formation water.

Spatial and temporal variations in hydrochemistry and indicators of age will also be assessed.

6.2 Mineral dissolution reactions

Mineral dissolution reactions exert an important control on water chemistry in most groundwater systems. The effects of such reactions are largely controlled by the speed at which reactions occur (reaction kinetics), the solubility of the mineral phase and residence time. The dissolution of minerals such as evaporite minerals (e.g. halite, gypsum) and carbonates (e.g. calcite, dolomite) are rapid, whereas silicate minerals generally have much slower dissolution kinetics.

The groundwaters in the Bridport Sands are mainly of Ca-HCO_3 type and their chemistry is dominated by the dissolution of calcite present in the cement through the reaction:

$$\underset{\text{calcite}}{CaCO_3} + \underset{\text{carbonic acid}}{H_2CO_3} \Leftrightarrow Ca^{2+} + 2HCO_3^-$$

The calcite reacts with carbonic acid introduced to the water initially through dissolution of CO_2 in the atmosphere and particularly through dissolution of CO_2 in the soil zone. The equation above indicates that for each mole of Ca produced, two moles of HCO_3 are produced. The dominance of this reaction in the groundwaters is seen on a plot of HCO_3 vs. Ca (Figure 6.1) where most waters lie on a line with gradient of 2. Dolomite is not known to be present in the aquifer and this is reflected in the relatively low Mg concentrations and Mg/Ca ratio (Figure 5.1). The Mg present in the groundwaters is likely to be derived partly from rainfall inputs and partly from Mg present in the calcite of the aquifer. The waters which sit to the right of the calcite dissolution line on Figure 6.1 are the Na-HCO_3 type waters where ion exchange has occurred and will be discussed later (section 6.4).

The presence of abundant calcite means that most of the groundwaters are neutral to slightly alkaline in terms of pH due to the consumption of rainfall- and soil-derived acidity. There is general correlation between $\delta^{13}C$ and Ca and Sr concentrations, although with some scatter (Figure 6.2). A heavier isotopic signature would be expected with greater reaction and the range may indicate the extent of reaction and a guide to residence time (section 6.9). The scatter may reflect either differences in end-members (soil CO_2, calcite in aquifer) or differences in recharge history (open or closed system dissolution with respect to CO_2). Most of the groundwaters are at or close to saturation with respect to calcite (Figure 6.3). The low SEC, more acidic groundwaters, are undersaturated with respect to calcite and indicate either a short residence time or that they occur in shallow parts of the aquifer which have previously been decalcified.

Evaporite minerals are not known from the lithologies present in the Bridport Sands aquifer and this is consistent with the low mineralisation in the groundwaters: evaporite minerals are very soluble with very rapid reaction kinetics.

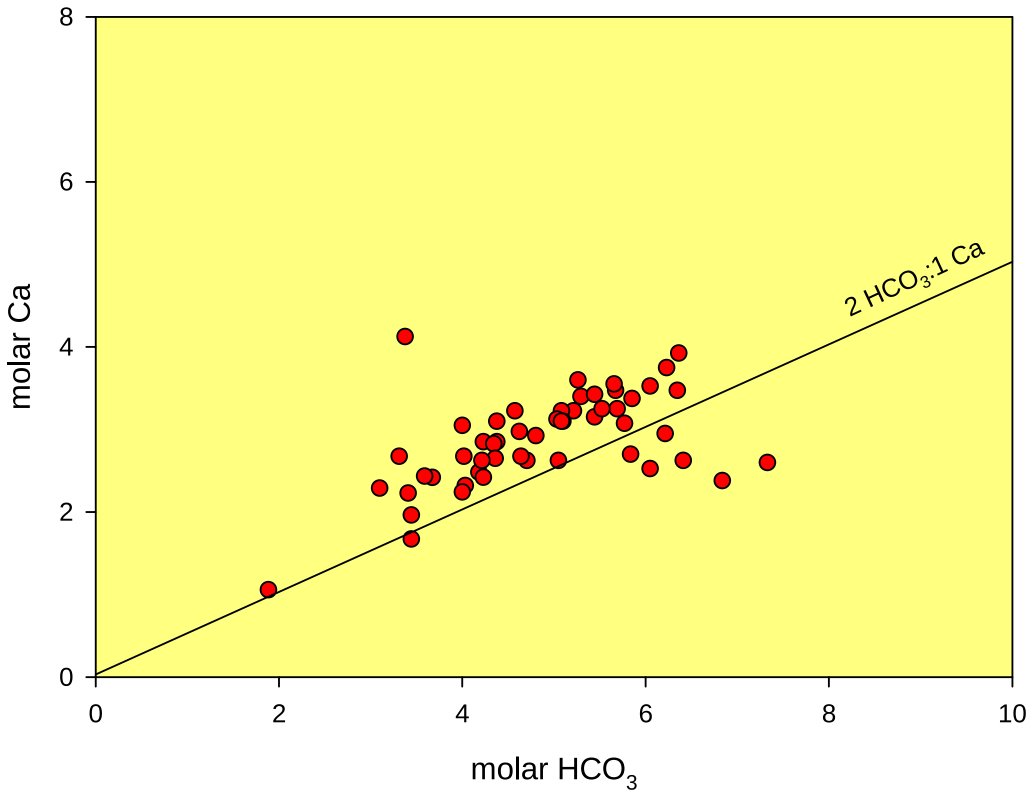


Figure 6.1 **Plot of molar concentrations of Ca vs. HCO$_3$. Samples lie parallel to a line representing 2 HCO3: 1 Ca as expected from dissolution of calcite.**

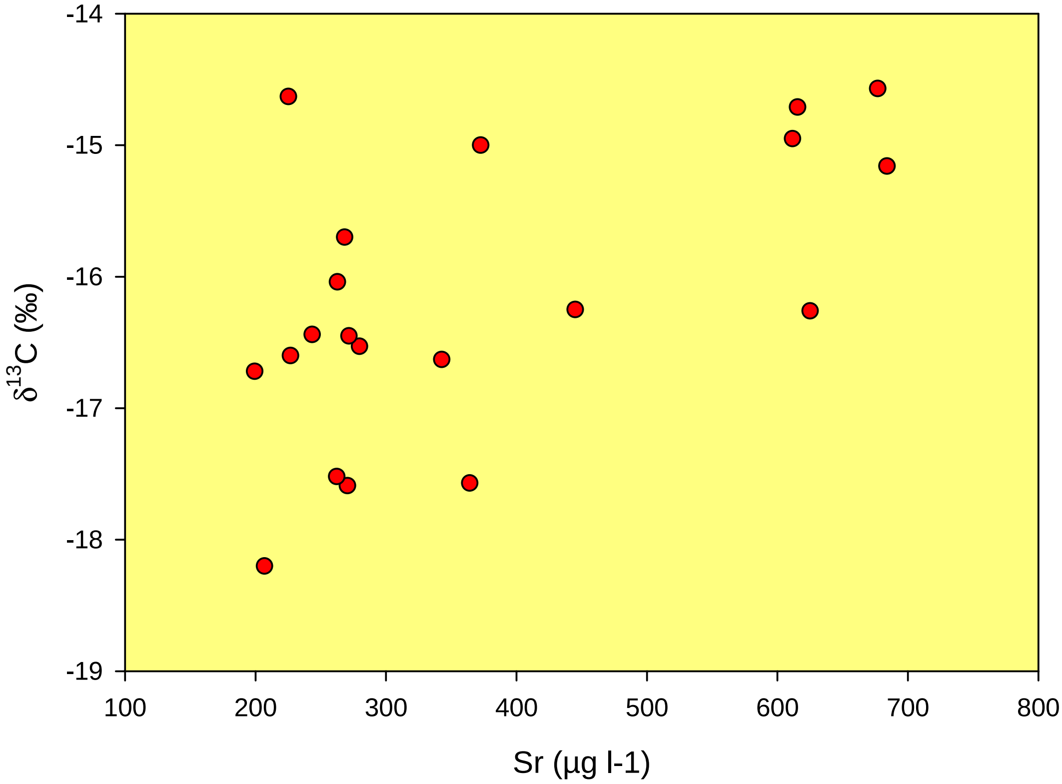


Figure 6.2 **Plot of Sr concentration vs. δ^{13}C. The scatter may reflect variations in host carbonate signature or differences in recharge history (open or closed system calcite dissolution).**

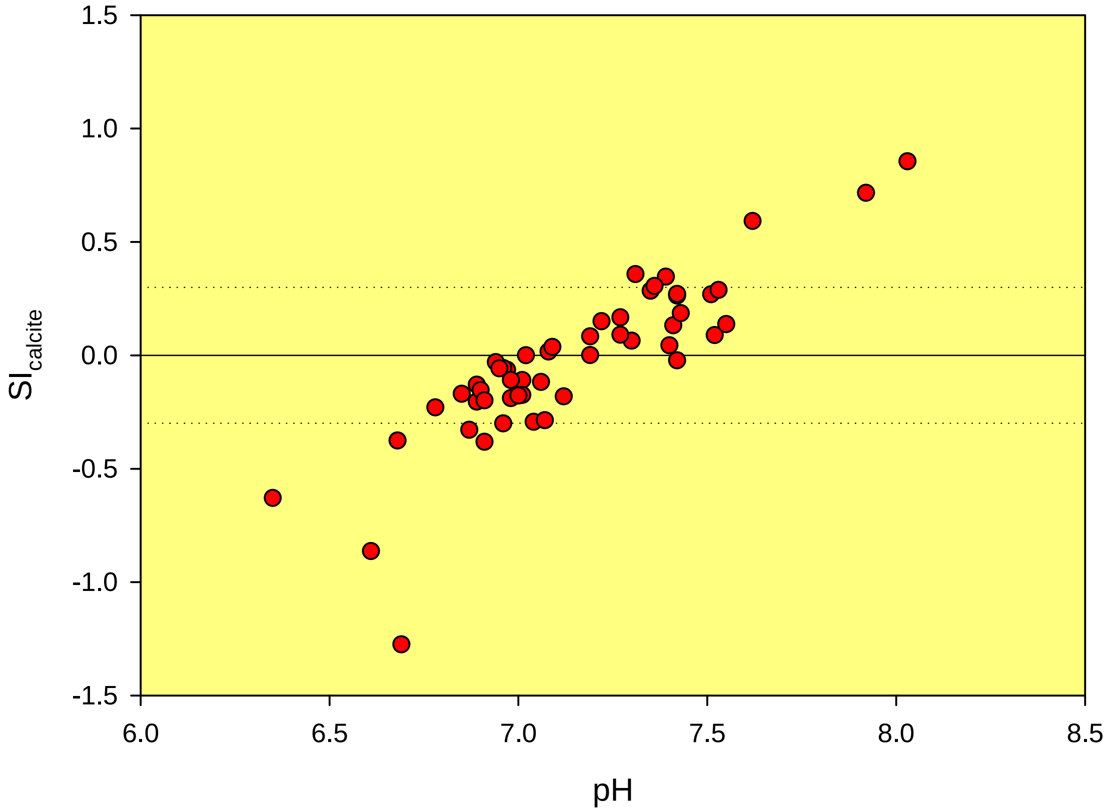


Figure 6.3 **Plot of pH vs. the saturation index of calcite (see text for discussion).**

Although silicate dissolution reactions are relatively slow, the presence of Si in the groundwaters up to 9.8 mg l^{-1} indicates that they are important in the aquifer. Concentrations are limited by the solubility of a SiO_2 phase, probably chalcedony, with most waters approaching saturation with respect to this phase. The source is unlikely to be quartz because the dissolution kinetics is extremely slow and quartz very stable. Dissolution of feldspars is the most likely source which also provides major cations such as Ca, Na and K as well as several trace elements e.g. the dissolution of K-feldspar:

$$KAlSi_3O_8 + 2CO_2 + 11H_2O \Leftrightarrow 2K^+ + 2HCO_3^- + Al_2Si_2O_5(OH)_4 + 4H_4SiO_4$$

The dissolution of feldspars is an incongruent irreversible reaction and typically produces a cation, bicarbonate, silica and a solid clay mineral product. Concentrations of K show a general increase with an increase in Si (Figure 6.4) probably controlled by the dissolution of K-feldspars. The sample with a very high K/Si ratio also contains very high NO_3-N and the elevated K is probably anthropogenic derived from agricultural or septic tank pollution.

Fluoride concentrations are generally low, typically less than 0.5 mg l^{-1}, but a few are higher, up to 0.79 mg l^{-1}. All groundwaters are undersaturated with respect to fluorite. The highest concentrations are found in the Na-HCO_3 type groundwaters and this is likely to reflect a longer residence time of these waters rather than a solubility control since the they are undersaturated with respect to fluorite.

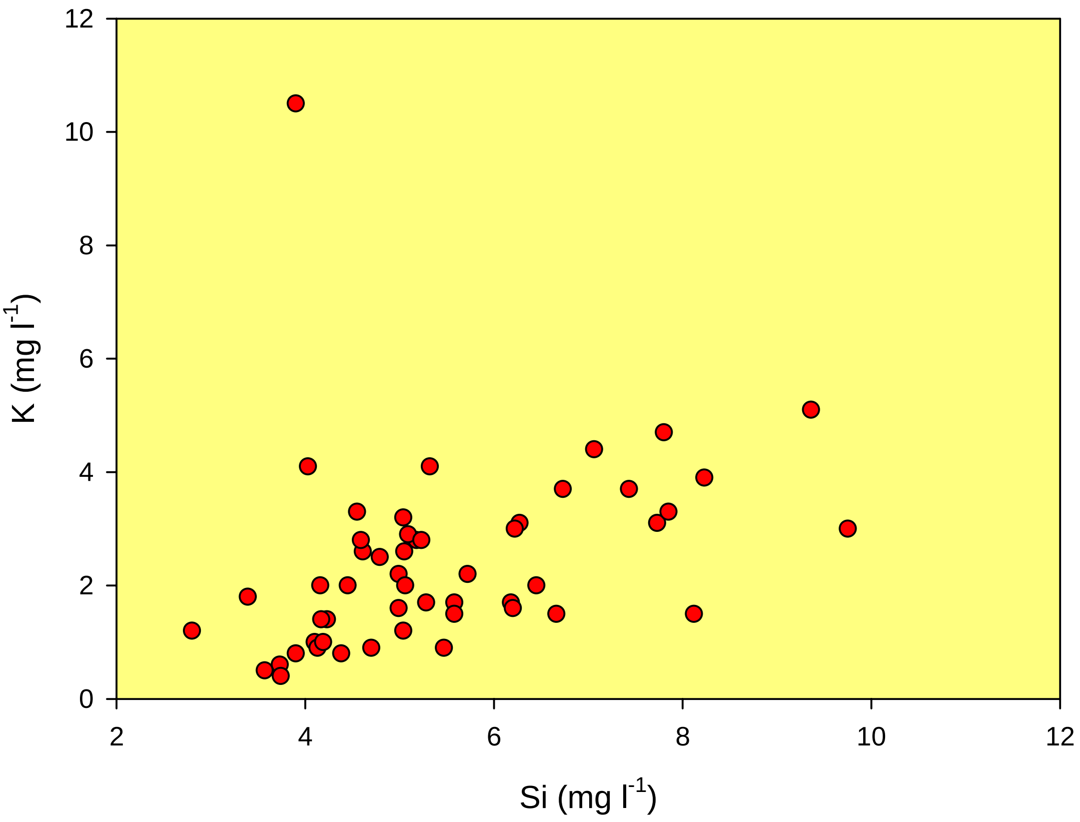


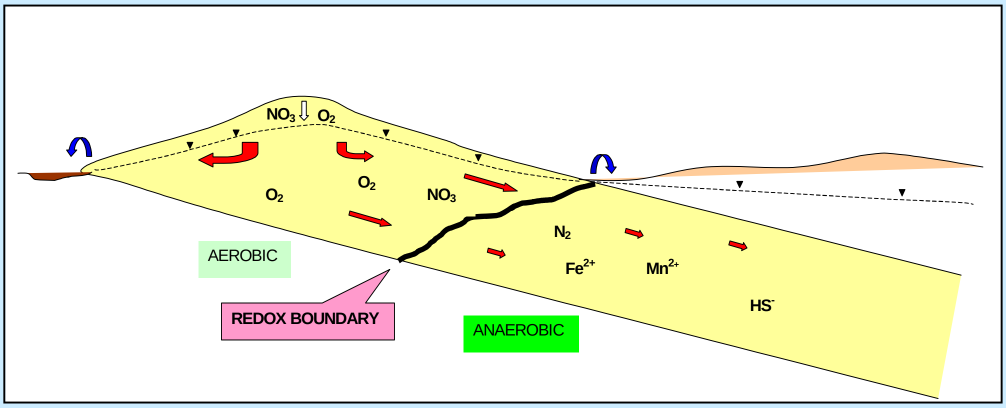
Figure 6.4 **Plot of Si vs. K. The sample with very high K was from a small spring where deforestation had taken place and contained very high nitrate. See text for details.**

6.3 Redox reactions

Redox boundaries (Box 6.1) are relatively common in aquifers, particularly where they become confined, or at the boundaries of young and old flow systems. The redox potential (Eh) and dissolved oxygen (DO) concentration provide the primary indicators of the redox status of natural groundwaters. These parameters are unstable and extremely sensitive to changes caused by contact with the atmosphere and, therefore, should be monitored in a flow-through cell where the water is pumped directly from the borehole. This was only possible at a few sites and therefore it is difficult to assess the redox status of the waters with any degree of confidence.

Concentrations of Fe and Mn are plotted against Eh on Figure 6.5 and show that most samples with high Eh contain very low concentrations of Fe and Mn (a similar plot is seen if DO is used instead of Eh). These trace elements provide a good indicator of the redox conditions in these circumneutral pH groundwaters where DO and Eh are poorly constrained. Nitrate concentrations are variable with the highest concentrations occurring in the more oxidising groundwaters. Figure 6.6 shows NO_3-N plotted against Fe and it is clear that the reducing waters (containing Fe) contain very low NO_3-N. This is consistent with the removal of NO_3 by denitrification under reducing conditions.

BOX 6.1 REDOX BOUNDARY



Water at recharge is generally saturated with dissolved oxygen at the partial pressure of the atmosphere (10-12 mg l^{-1} depending upon barometric conditions). Passing through the soil and the unsaturated zone some of this O_2 will react as a result of microbiological processes and oxidation-reduction reactions. However, almost all water reaching the water table still contains several mg l^{-1} O_2. Geochemical reactions (oxidation of traces of pyrite, organic matter and Fe^{2+} present in minerals) progressively remove the O_2 along flow lines. Once all the oxygen has reacted an abrupt change of water chemistry takes place (redox boundary). Other changes may occur at and down-gradient of the redox boundary, especially denitrification and the probability that total dissolved iron (Fe^{2+}) concentrations will increase. Sulphate reduction and the production of sulphide (H_2S as HS^- in solution) may also occur at greater depths.

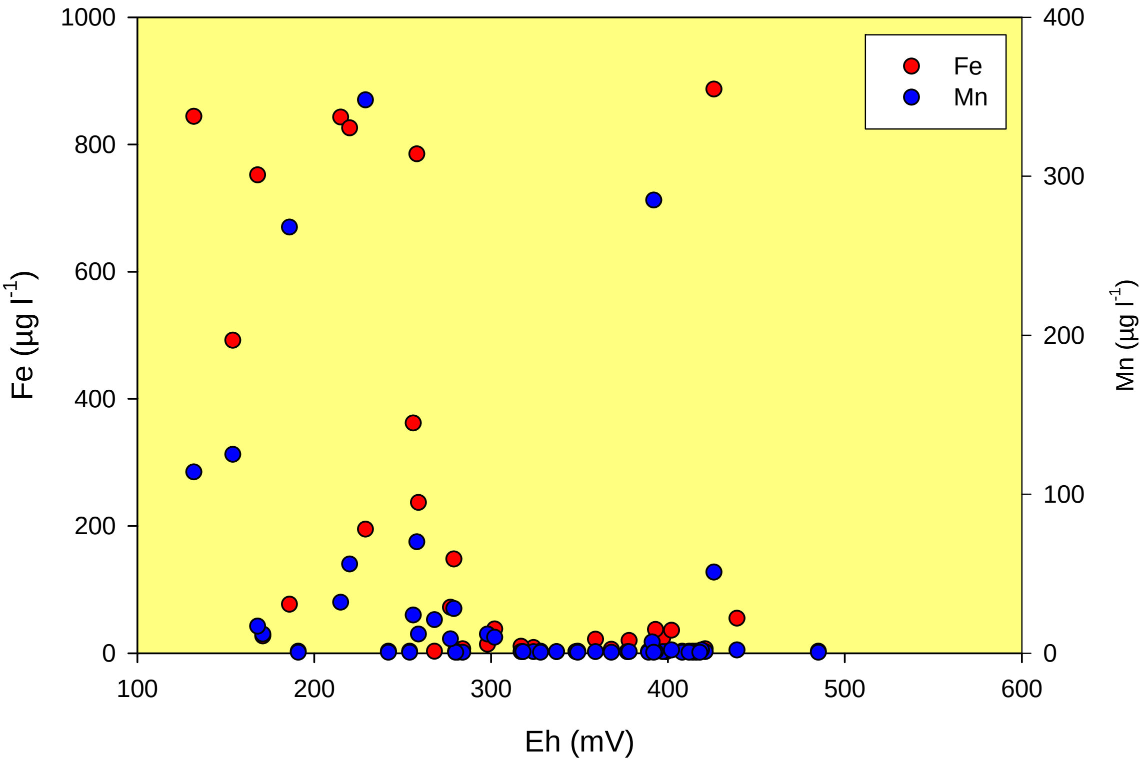


Figure 6.5 **Plot of Eh vs. Fe and Mn in the Bridport Sands aquifer.**

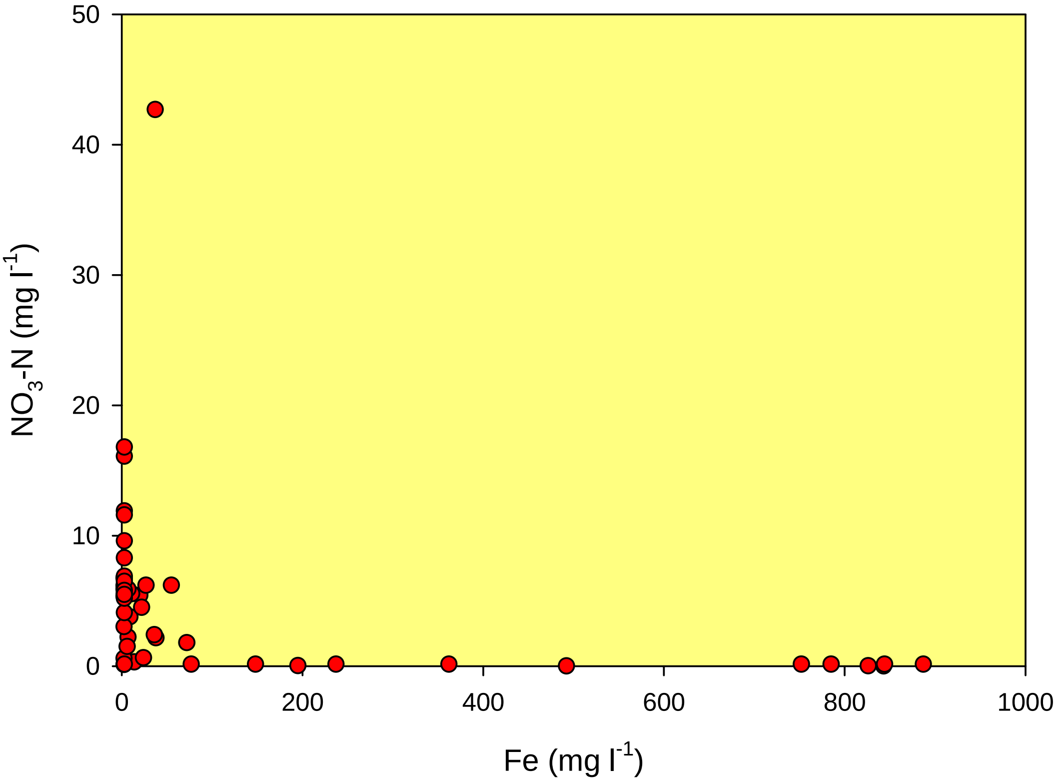


Figure 6.6 Plot of Fe vs. NO3-N in the Bridport Sands aquifer.

6.4 Ion exchange reactions

The freshening of aquifers which originally contained seawater can lead to significant chemical changes in groundwater as it flows through and displaces connate or formation water. Any clays present will initially have Na as the dominant sorbed cation and freshening by a typical Ca-HCO_3 type recharge groundwater will change the composition of this groundwater to attain equilibrium with the clays. In this case Ca in the groundwater will exchange with Na on the clays leading to groundwaters of Na-HCO_3 type:

$$\frac{1}{2}\mathrm{Ca}^{2+} + \mathrm{Na} - X \rightarrow \frac{1}{2}\mathrm{Ca}\text{ - }X + \mathrm{Na}^{+}$$

Some of the groundwaters show a trend towards higher Na but no concomitant increase in Cl. These waters also have relatively low Ca/HCO_3 ratios, consistent with ion exchange of Ca for Na and very high Na/Cl ratios (Figure 6.7). These include the boreholes at Westland and two boreholes in Yeovil. These boreholes are thought to abstract at least some of their water from the Pennard Sands. Evans (1993) noted that groundwaters from the Pennard Sands have higher Mg/Ca ratios than the Bridport Sands and this has been confirmed in the present study. Samples from springs and boreholes on the Pennard Sands do not however have generally high Na/Cl ratios and this characteristic is only found around Yeovil where the Pennard Sands is relatively deep and confined beneath the Junction Bed (Figure 6.8). Some of the deeper boreholes from the Westland site intercept both Pennard Sands and Bridport Sands and it is possible that mixing between these units has occurred due to the installation of boreholes. Further work would be useful to clarify the anomalous chemistry of this area.

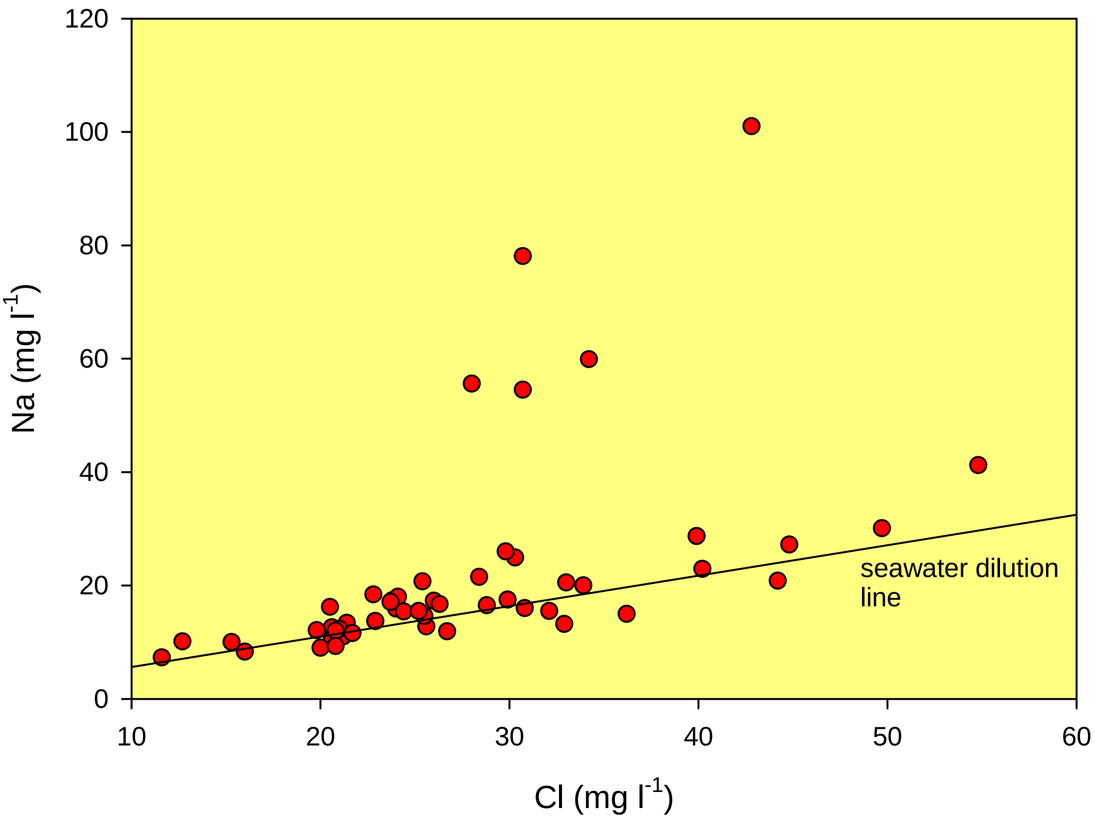


Figure 6.7 Plot of Na vs. Cl for groundwater samples. The seawater dilution line represents mixing between a seawater and rainfall. Most groundwaters plot close to this line except the Na-HCO3 type waters.

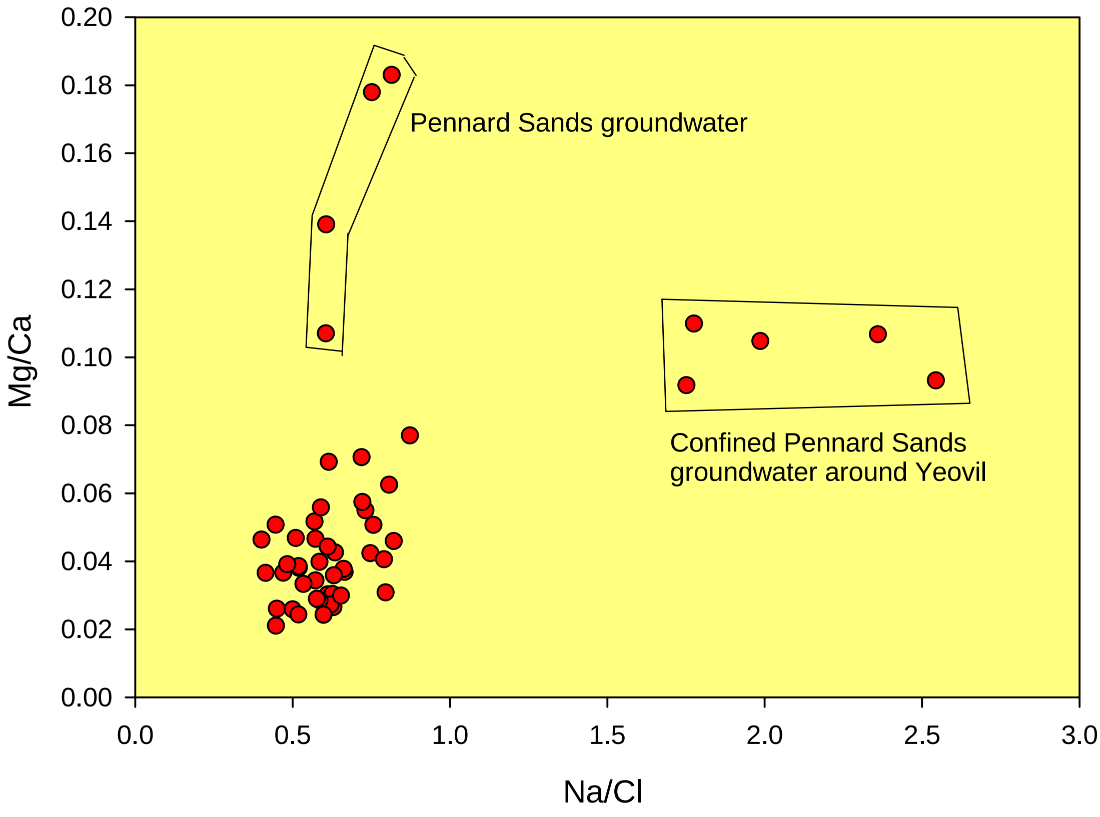


Figure 6.8 Plot of Na/Cl vs. Mg/Ca highlighting the differences between Pennard Sands and Bridport Sands aquifers.

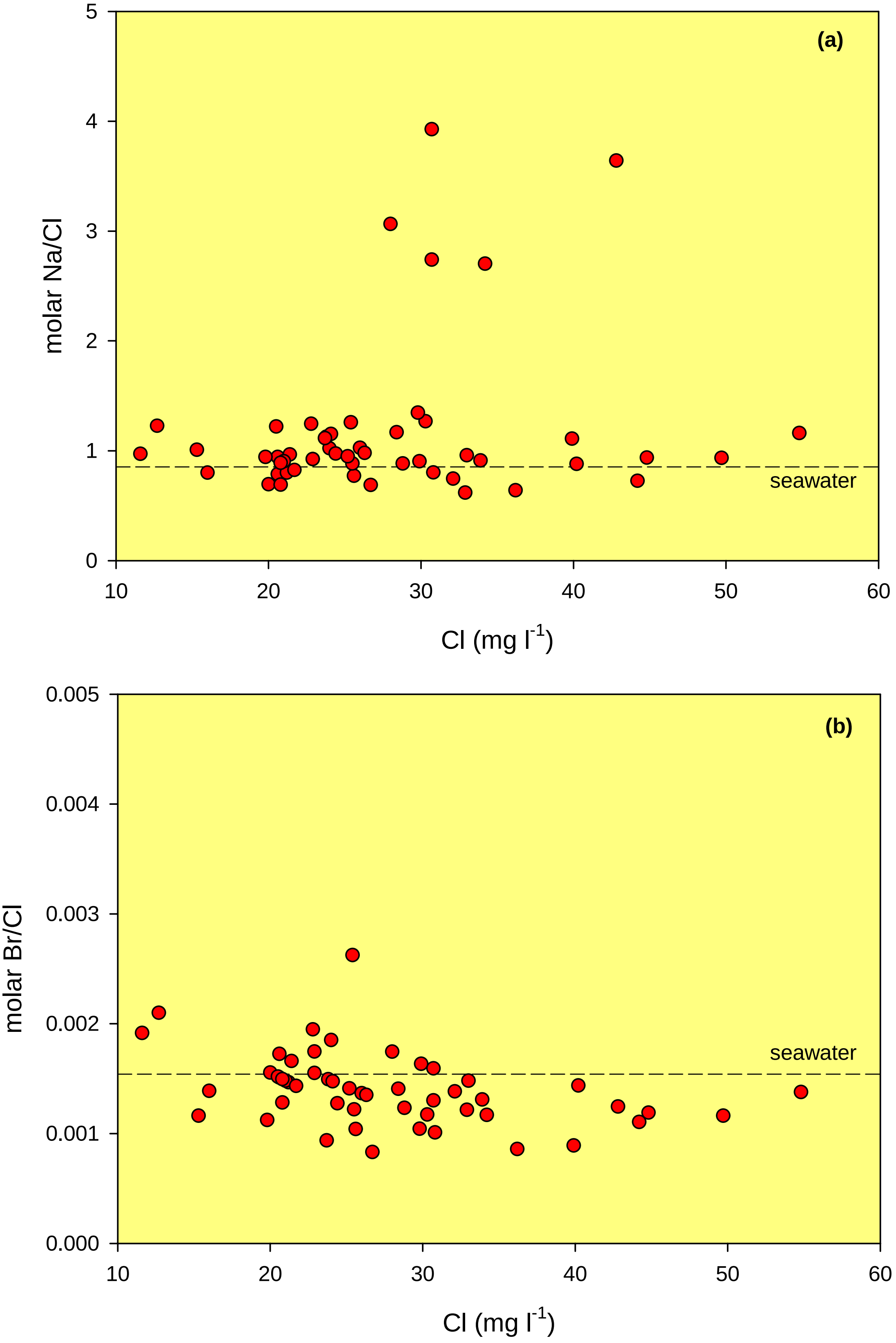


Figure 6.9 Plots of (a) molar Na/Cl and (b) Br/Cl ratio against Cl.

6.5 Mixing with older formation water

Many groundwaters in UK aquifers show a wide range in Cl concentrations controlled by mixing with remnants of formation water, dissolution of Cl-bearing mineral phases or anthropogenic inputs. The relative importance of these processes can often be indicated by a comparison of Cl concentrations with other solutes.

Chloride concentrations in the groundwaters are relatively low but show some variation (11.6 – 54.8 mg l^{-1} Cl). The lower concentrations are typical of rainfall modified by evapotranspiration (Table 3.1). The higher concentrations, however, require an additional component to rainfall. There are no known evaporite sequences in the aquifer and, combined with the low Cl concentrations make it extremely unlikely that evaporite dissolution has been important. Chloride correlates with other cations derived from a marine source including Na, K and Li although there is considerable scatter. The ratios Na/Cl and Br/Cl are often used as an indicator of salinity. The Na/Cl ratio does not vary with Cl concentration (Figure 6.9a) with the exception of the Na-HCO_3 waters (which have a very high Na/Cl). Griffiths et al., 2003 in a study of groundwaters in the Permo-Triassic aquifer around Manchester showed that a decrease in Br/Cl was due to dissolution of halite. Most samples lie close to seawater (no rainfall Br data were available) and it is likely that mixing with an older formation water is the dominant control on Cl in these groundwaters. However, some of the samples have a slightly lower Br/Cl ratio (Figure 6.9b) than seawater and although this is unlikely to be due to dissolution of geogenic evaporite minerals as discussed above, the small decrease may be related to road salt application.

The groundwaters from the Yeovil area are also unusual in having very high B concentrations and B/Cl ratios. Sodium correlates well with B and it is not clear from the available information whether this is a natural feature of these groundwaters or related to anthropogenic (e.g. detergents contain high concentrations of B) inputs.

6.6 Trace elements

The highest trace elements concentrations in these groundwaters is commonly Sr which can reach concentrations up to 881 µg l^{-1} (Figure 5.4 - 5.5). The most common source of Sr in aquifers is often calcite which contains relatively high concentrations of Sr. There is a poor correlation with Ca although this may be due to solubility controls and ion-exchange which may modify or limit Ca in solution. There is a stronger correlation with Mg and Si, so it is likely that Sr is derived both from carbonate and silicate minerals (feldspars generally contain higher concentrations of Sr than carbonates but dissolution kinetics is slower).

Barium concentrations are typically low (median of 5.7 µg l^{-1}) even though barite is known to be present in the aquifer. The low SO_4 and undersaturation with respect to barite indicate that saturation with this mineral is not a control on the upper limits of concentration. It is thus likely that either barite is limited in extent or that the groundwaters have not had time to equilibrate with this mineral.

Iron and Mn may reach moderate concentrations and are controlled by the redox status of the groundwaters as described in section 6.3. High boron concentrations and B/Cl ratios were found in several sites, particularly those around in the Pennard Sands from around Yeovil. It is not clear whether these represent baseline concentrations or anthropogenic modification. Most other metals are present at low concentrations mainly due to the low mobility at circumneutral pH. Aluminium is generally low (typically less than 50 µg l^{-1}), although one sample had a concentration of 1100 µg l^{-1}. It is probable that this sample (from a low flow spring) contained colloidal particles as other relatively immobile elements (e.g. rare earth elements) were also enhanced in this sample. Locally, slightly elevated concentrations of As, Cu, U and Zn were found, however concentrations were generally not very high.

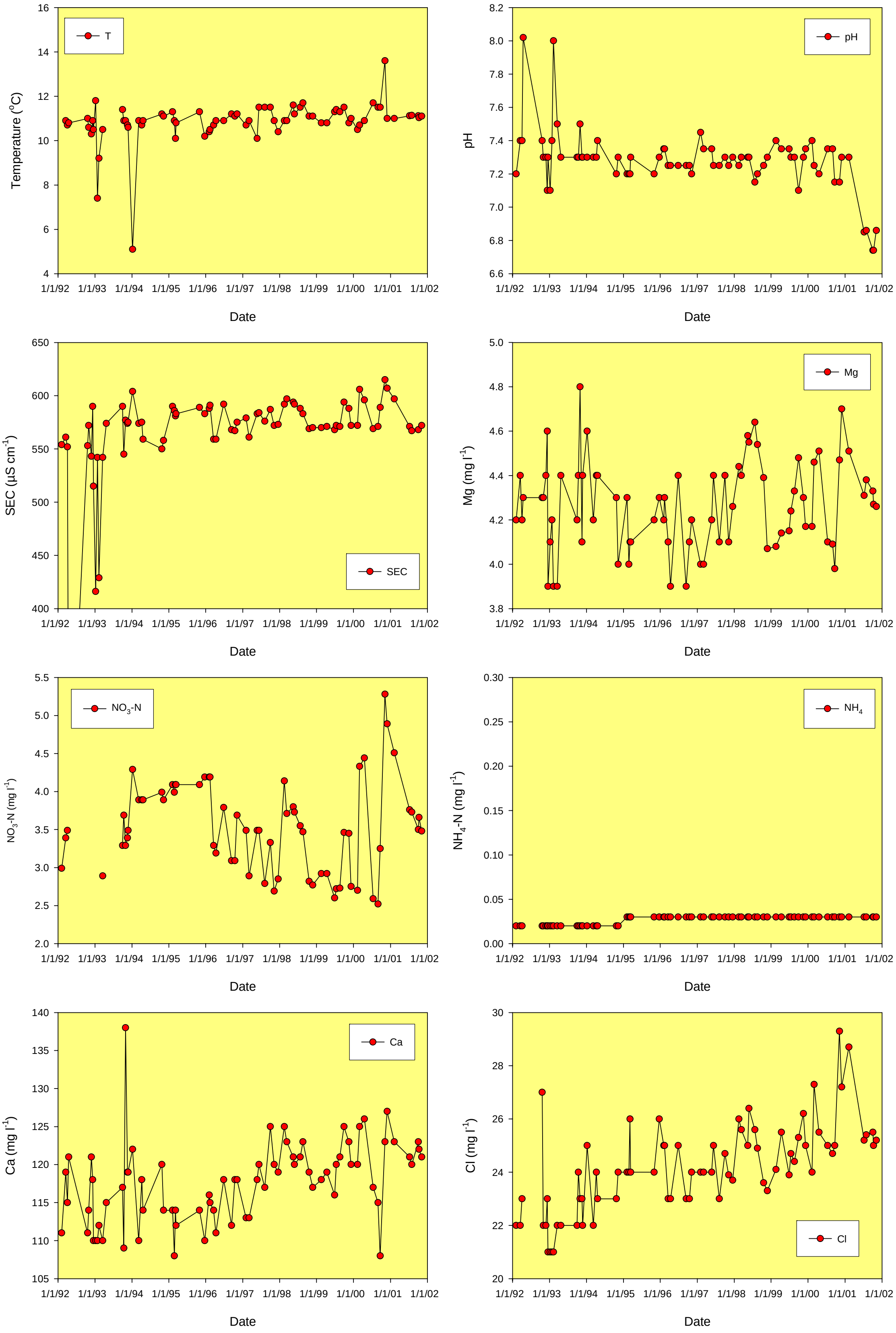


Figure 6.10. Time series data for the Stoke Abbot Spring.

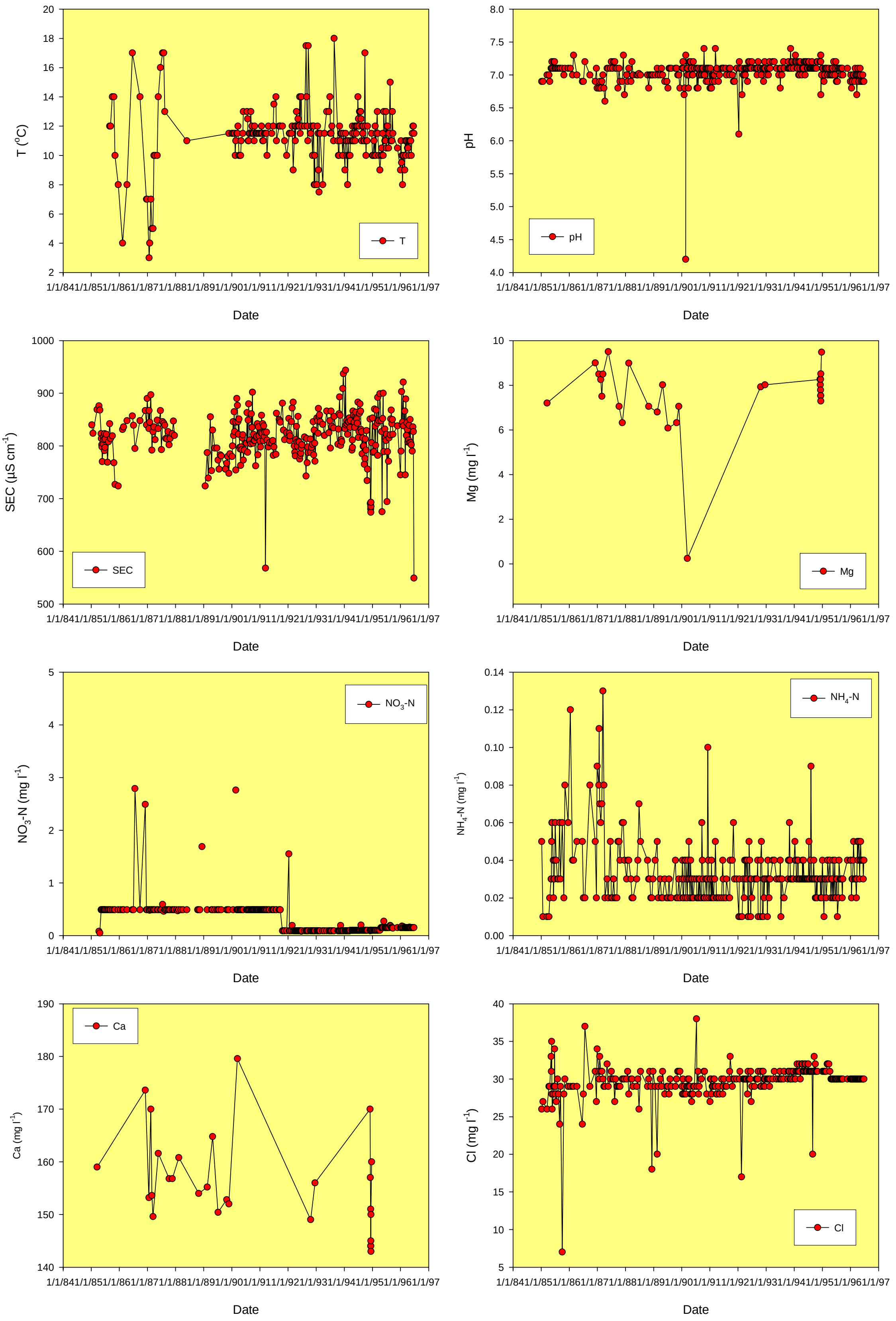


Figure 6.11. Time series data for the Compton Durville borehole.

6.7 Temporal variations

Only two sites in the study area have been monitored over time (Figures 6.10 and 6.11): Stoke Abbot Spring (NGR 34550 10150) and Compton Durville borehole (NGR 34172 11707), but the time periods are relatively short. Sampling was also variable and for many years data exist only for part of the year.

The Stoke Abbott spring showed little variation in pH, T and SEC over the time period. It is likely that the spikes seen are due to instrumentation problems. During years where samples were available monthly (e.g. 1998) several elements show seasonal fluctuations. Apart from these seasonal fluctuations, there are no clear trends except for Ca and Cl which show a slight increase in concentration with time.

The temperature and SEC of the Compton Durville source (Figure 6.11) also appears to fluctuate on a seasonal basis, and there is possibly a similar variation in the conductivity SO_4 and NH_4 concentrations of the source.

6.8 Depth variations

There are no data available on depth samples within individual boreholes or from piezometers. In addition the depths of many of the boreholes in the study area are not known. However, selected data have been plotted against depth of borehole in an attempt to see if deeper boreholes have a different chemistry from shallow boreholes (Figure 6.12). Spring samples have also been plotted and these show a wide range in compositions probably reflecting the wide range in residence times and complex flow pathways typically associated with spring discharges. There are no clear trends with depth of borehole but, in general, the deeper boreholes often contain the highest SEC and major element concentrations. From the limited data available it would also appear that the deeper groundwaters are more reducing as indicated by the lower NO_3 and higher Fe concentrations (Figure 6.12). Barium shows a relatively consistent increasing trend with depth but this is less clear for Sr. The complexity and probable compartmentalisation of flow systems in the Bridport Sands aquifer makes it likely that no simple relationship between age and depth exists. However, more comprehensive, and better quality data would be required to prove this.

6.9 Age of the groundwater

There are no previous direct age measurements on the groundwaters in the Bridport Sands aquifer and groundwater dating was beyond the scope of the present investigation.

Stable isotopes (δ^2H and δ^{18}O) have been used to distinguish older Pleistocene (pre 10,000 year old) water from Holocene (post 10 000 year old) groundwaters in sandstone aquifers of the UK (Edmunds et al., 1982). The basis of this interpretation is that the climate during the Pleistocene period was colder resulting in lighter (more negative) signatures of the stable isotopes δ^2H and δ^{18}O. The samples analysed for these stable isotopes all lie close to the meteoric water line (Figure 6.13a). There is a slight trend towards lighter values of δ^2H and δ^{18}O (δ^{18}O of -6.0 to -6.5; δ^2H of -40 to -45) than expected for modern groundwaters (Darling et al., 2003). The lighter values also correspond with heavier δ^{13}C (Figure 6.13b) and higher major element concentrations and may indicate that these have a slightly older mean residence time, however this would need to be confirmed by direct age determinations.

Evans (1993) discussed tritium data obtained from Wessex Water plc. Many of the boreholes contained moderately high tritium (up to 78 T.U.) and indicate that these have a significant component of post 1950's water. Tritium in some boreholes, including Westland, were low (ca. 4 T.U) showing that these have a much smaller component of post 1950's recharge. Further work is recommended on obtaining more precise age information.

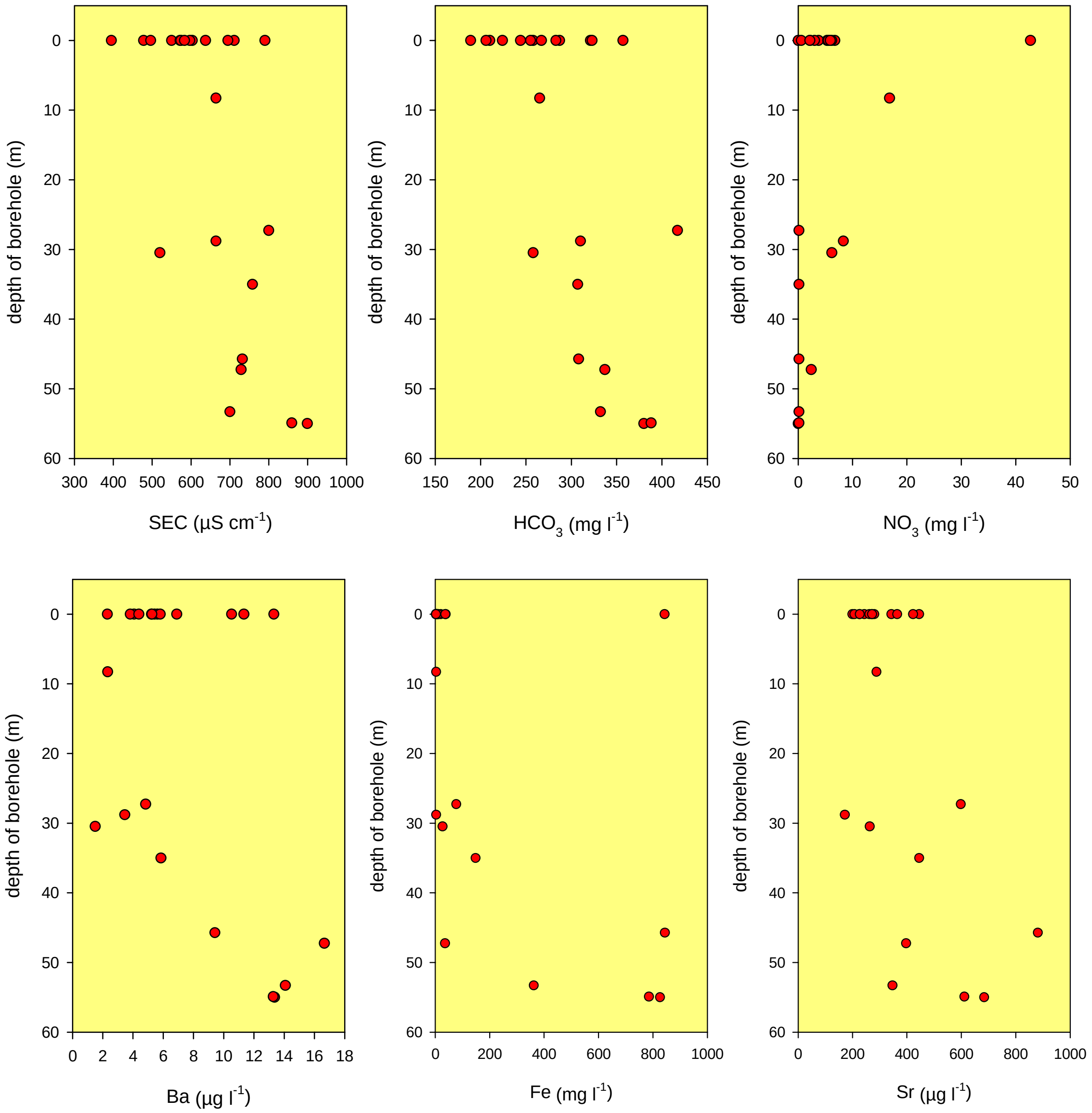


Figure 6.12 Variations in SEC and selected solutes with depth of borehole. Spring samples are plotted at zero depth.

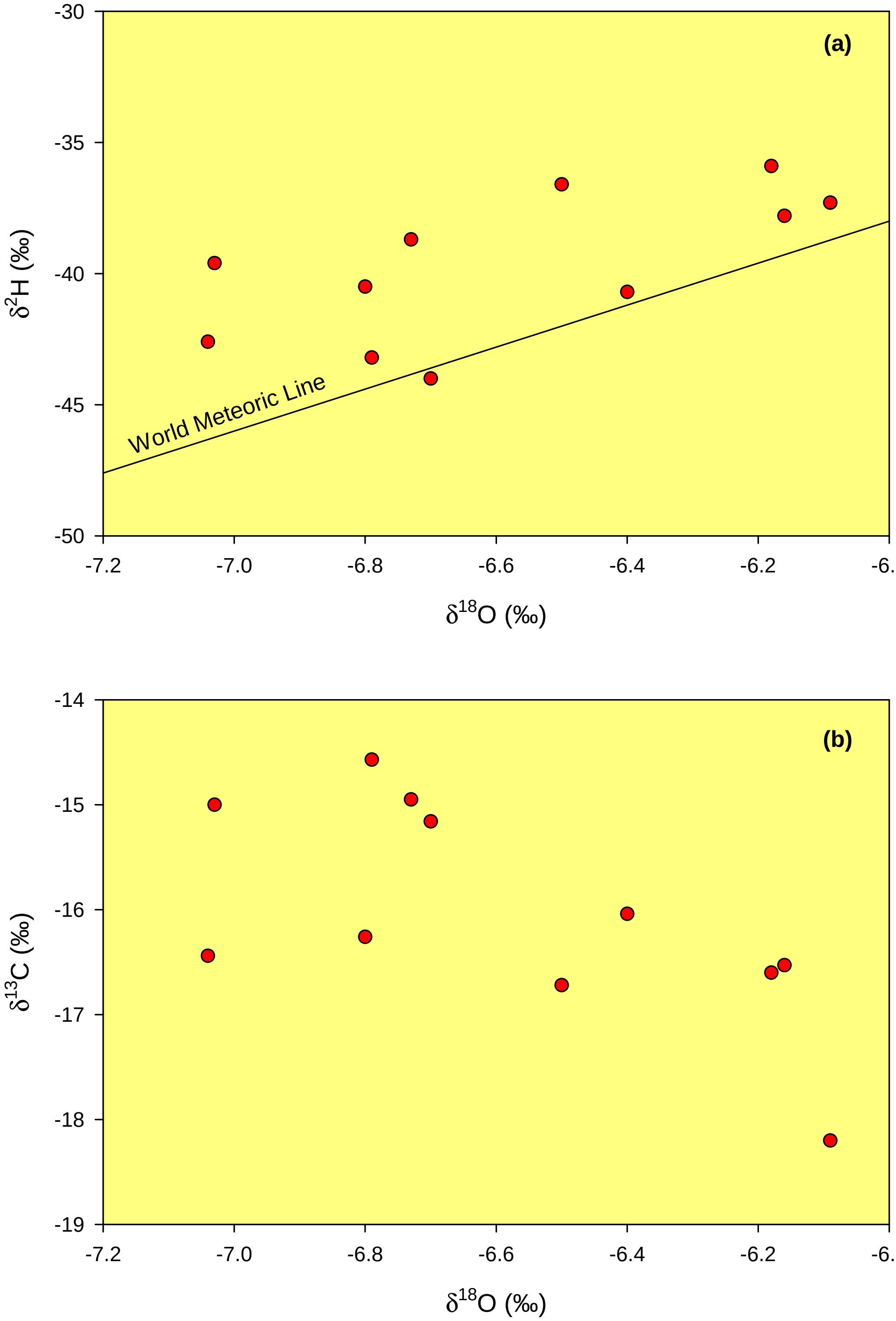


Figure 6.13 Variations between (a) δ^2H and δ^{18}O and (b) δ^{13}C and δ^{18}O in groundwaters.

Table 6.1 Comparison of summary data from Yeovil and Bridport sectors of the aquifer. See text for details

		North				South			
		minimum	maximum	median	number	minimum	maximum	median	number
T	^{o}C	10.3	15.3	**11.8**	41	10.9	14.8	**12.3**	11
pH	field	6.35	8.03	**7.19**	41	6.61	7.92	**6.98**	11
Eh	mV	132	485	**328**	41	259	421	**337**	11
DO	mg l^{-1}	0.05	7.7	**4.85**	40	0.05	7.24	**5.3**	11
SEC	µS cm^{-1}	367	926	**698**	41	395	766	**583**	11
δ^{2}H	‰	-44	-39	**-42**	6	-41	-36	**-37**	5
δ^{18}O	‰	-7.0	-6.7	**-6.8**	6	-6.5	-6.1	**-6.2**	5
δ^{13}C	‰	-16.6	-14.6	**-15.2**	9	-18.2	-14.6	**-16.6**	11
Ca	mg l^{-1}	42.3	165	**122**	41	66.9	136	**105**	11
Mg	mg l^{-1}	2.21	14.6	**5.0**	41	2.78	13.8	**4.2**	11
Na	mg l^{-1}	8.3	101	**16.2**	41	7.3	41.2	**16**	11
K	mg l^{-1}	0.4	10.5	**2**	41	1	5.1	**1.7**	11
Cl	mg l^{-1}	12.7	44.8	**25.5**	41	11.6	54.8	**26.3**	11
SO_4	mg l^{-1}	14.2	113	**46.4**	41	17.8	75.1	**32.9**	11
HCO_3	mg l^{-1}	115	447	**310**	41	210	323	**258**	11
NO_3 as N	mg l^{-1}	0.009	42.7	**5.30**	41	0.147	5.91	**3.03**	11
NO_2 as N	mg l^{-1}	<0.001	0.052	**0.002**	41	<0.001	0.0804	**0.016**	11
NH_4 as N	mg l^{-1}	<0.003	0.140	**0.010**	41	<0.003	0.009	**0.004**	11
P	mg l^{-1}	<0.01	0.300	**0.100**	41	<0.01	0.124	**0.035**	11
TOC	mg l^{-1}	0.71	3.96	**1.6**	9	0.38	13.3	**1.52**	11
DOC	mg l^{-1}	1.15	5.58	**2.02**	9	0.95	7.94	**3**	11
F	µg l^{-1}	0.12	0.74	**0.25**	41	0.18	0.465	**0.345**	11
Br	µg l^{-1}	0.04	0.15	**0.08**	41	0.05	0.17	**0.08**	11
I	µg l^{-1}	0.003	0.009	**0.004**	10	0.002	0.007	**0.003**	11
Si	mg l^{-1}	2.8	9.75	**4.99**	41	4.1	9.36	**5.58**	11
Al	µg l^{-1}	0.36	1103	**3**	41	1	34	**2**	11
As	µg l^{-1}	<1	12	**0.3**	41	1	2	**1**	11
B	µg l^{-1}	<20	573	**26.2**	41	<20	58	**10**	11
Ba	µg l^{-1}	1.29	17.6	**5.86**	41	3.81	8.79	**5.42**	11
Be	µg l^{-1}	<0.05	0.03	**0.01**	41	<0.05	0.03	**0.03**	11
Cd	µg l^{-1}	<0.05	0.67	**0.08**	41	<0.05	0.03	**0.03**	11
Ce	µg l^{-1}	<0.01	1.81	**0.01**	41	<0.01	0.16	**0.02**	11
Co	µg l^{-1}	<0.02	16.5	**0.3**	41	<0.02	0.01	**0.01**	11
Cr	µg l^{-1}	<0.5	6.7	**0.21**	41	0.5	1.4	**0.6**	11
Cs	µg l^{-1}	<0.01	0.045	**0.045**	41	<0.01	<0.01	**<0.01**	11
Cu	µg l^{-1}	<0.04	69.0	**0.9**	41	0.1	1.2	**0.3**	11
Fe	µg l^{-1}	2.5	887	**3**	41	2.5	237	**9**	11
Ga	µg l^{-1}	<0.05	0.2726	**0.05**	41	<0.05	<0.05	**<0.05**	11
Gd	µg l^{-1}	<0.01	0.19	**0.00**	41	<0.01	0.01	**0.01**	11
Ge	µg l^{-1}	<0.05	0.22	**0.05**	41	<0.05	<0.05	**<0.05**	11
La	µg l^{-1}	<0.01	0.77	**<0.01**	41	<0.01	0.07	**0.01**	11
Li	µg l^{-1}	3.4	56.8	**12.3**	41	7	53.0	**15.0**	11
Mn	µg l^{-1}	0.5	348	**1**	41	1	12	**1**	11
Mo	µg l^{-1}	<2	<2	**<2**	10	<2	<2	**<2**	11
Ni	µg l^{-1}	<0.2	71.7	**6.51**	41	<0.2	1.70	**0.10**	11
Pb	µg l^{-1}	<0.2	1.7	**0.32**	41	<0.2	3.6	**0.05**	11
Rb	µg l^{-1}	0.05	2.0	**0.53**	41	0.15	1.34	**0.36**	11
Sb	µg l^{-1}	<0.05	0.22	**0.03**	41	<0.05	0.03	**0.03**	11
Sc	µg l^{-1}	<0.8	3.03	**1**	41	1.21	2.52	**1.79**	11
Se	µg l^{-1}	<0.5	1.5	**0.57**	41	0.5	1.2	**0.7**	11
Sr	µg l^{-1}	133	881	**322**	41	199	364	**263**	11
Tl	µg l^{-1}	<0.01	0.04	**0.01**	41	<0.01	<0.01	**<0.01**	11
U	µg l^{-1}	<0.05	5.5	**0.59**	41	0.16	0.99	**0.49**	11
V	µg l^{-1}	<1	3	**3**	41	<1	1	**0.5**	11
W	µg l^{-1}	<0.1	0.1	**<0.1**	10	<0.1	<0.1	**<0.1**	11
Y	µg l^{-1}	<0.01	0.35	**0.01**	41	0.01	0.07	**0.02**	11
Yb	µg l^{-1}	<0.01	<0.01	**<0.01**	41	<0.01	<0.01	**<0.01**	11
Zn	µg l^{-1}	<0.5	227	**4.0**	41	<0.5	6.1	**1.9**	11

6.10 Regional variations

The spatial variations in chemistry across the area reflect much of what was discussed in previous sections, particularly with regard to the heterogeneity of the aquifer. An initial comparison has been made between the northern (Yeovil) and southern (Bridport) sectors, since these form separate geographical areas of outcrop (Figure 3.1). Table 6.1 summarises the hydrochemical data and it is shown that there are no real significant differences in the summary statistics from each area. Average concentrations for most parameters and elemental concentrations are almost identical, the only real differences being slightly higher SEC, SO_4, B, Ni and Zn in the northern study area. There are also higher maxima in the northern area for some elements including Na, Ca, SO_4, HCO_3, Ba, Cu, Fe, Mn, Sr, U and Zn, but median values are generally very similar.

The data have been plotted on maps to highlight the degree of heterogeneity across the aquifer (Figures 6.14 – 6.16). These plots indicate that there is considerable spatial variation in the groundwaters. The Yeovil sector tends to have slightly higher pH and SEC (Figure 6.14) although these have a large range in values. Selected major elements are shown on Figure 6.15. Calcium and HCO_3 are likewise higher in the Yeovil sector, but the larger range has meant that median concentrations are relatively similar. The boreholes nearest the coast show elevated concentrations of Na and Cl (as well as Br and K) which may be related to sea-salt deposition. These plots also highlight the high Na and HCO_3 in the boreholes sampled from the vicinity of Yeovil.

Spatial variations in selected trace elements are shown on Figure 6.16. These also show the large spatial variations across the aquifer and no clear spatial trends are obvious. The high B concentrations around Yeovil are highlighted and concentrations show a relatively similar distribution to that of Na (Figure 6.15). Nickel and Rb both show generally higher concentrations in the northern sector and the source may be from the higher proportion of clay material present in the aquifers sediments further north (section 3.2). Strontium likewise is higher in the northern sector, a trend that is similar to Ca.

The large spatial variations described above, and lack of spatial trends are consistent with the likely groundwater flow patterns in the aquifer i.e. compartmentalised and probably dominated by relatively local flow systems. Spatial variations in the northern Yeovil sector are generally greater than further south but median concentrations are typically similar. This may be related, in part, to sampling as some of the boreholes further north may contain groundwaters from the Pennard Sands or from boreholes which abstract from a mixture of Yeovil Sands and Inferior Oolite (these are often treated as the same aquifer unit where in hydraulic continuity).

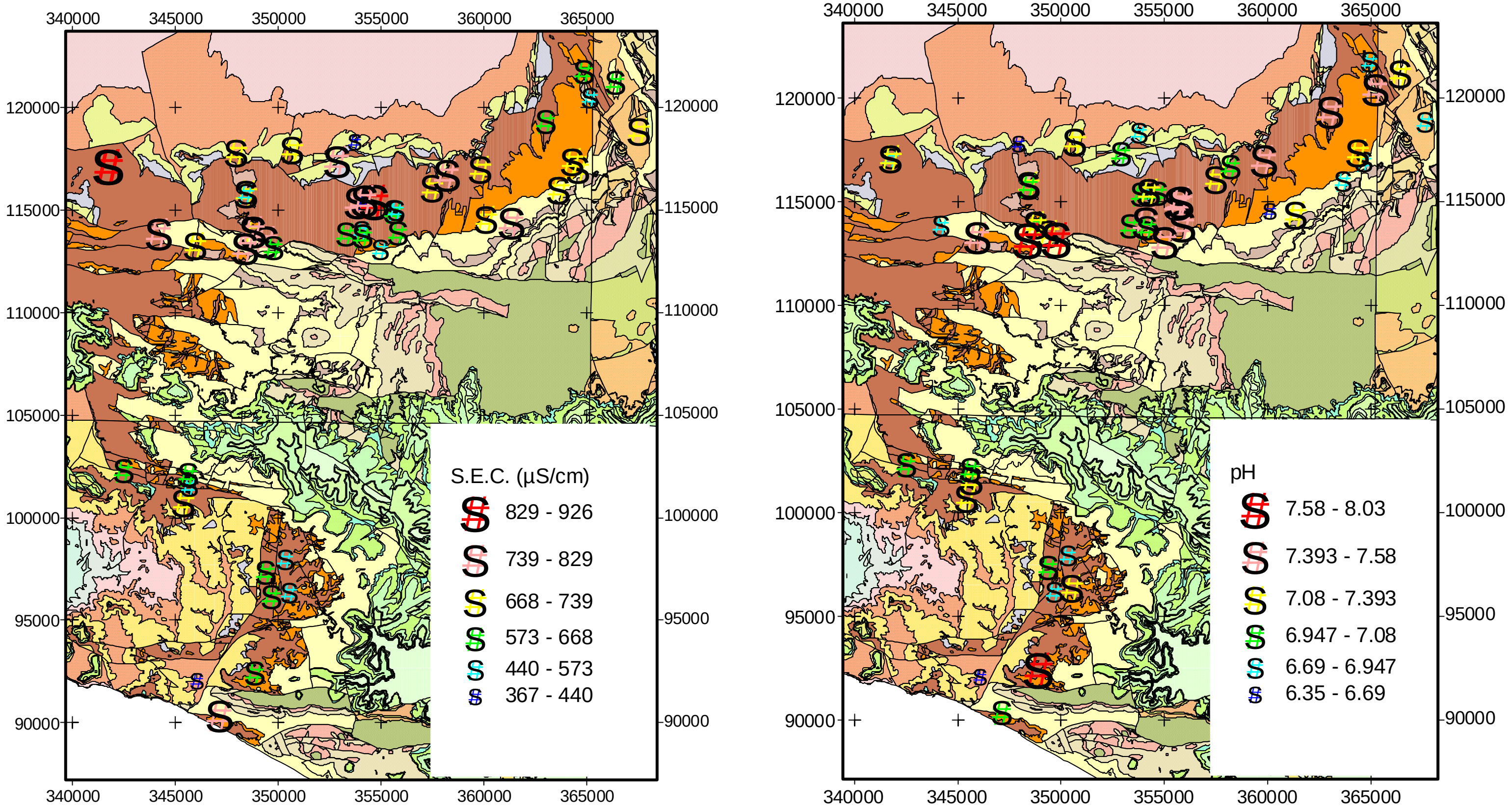


Figure 6.14 **Regional plots for pH and SEC in the Bridport Sands aquifer.**

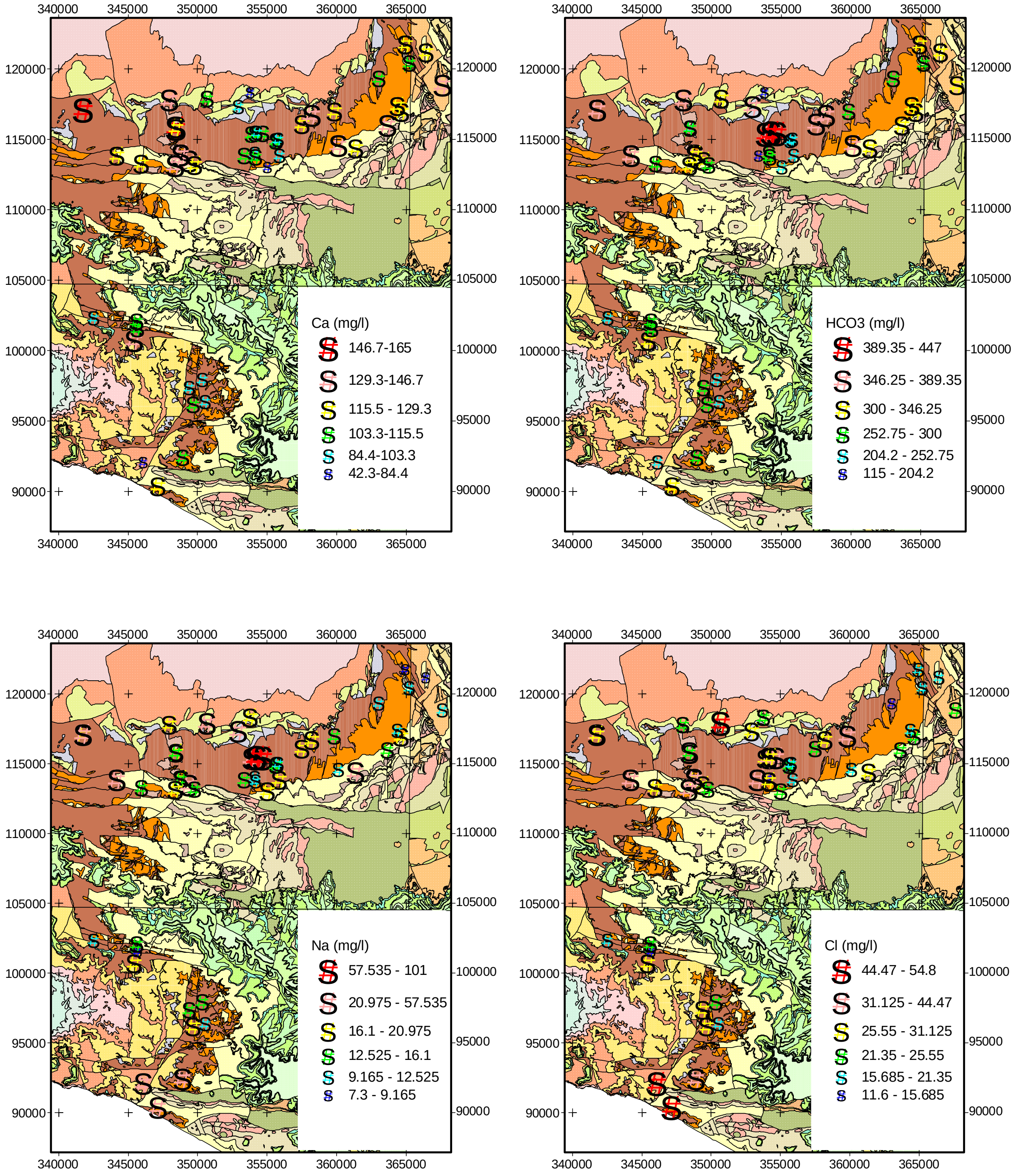


Figure 6.15 Regional plots for Ca, HCO_3, Na and Cl in the Bridport Sands aquifer.

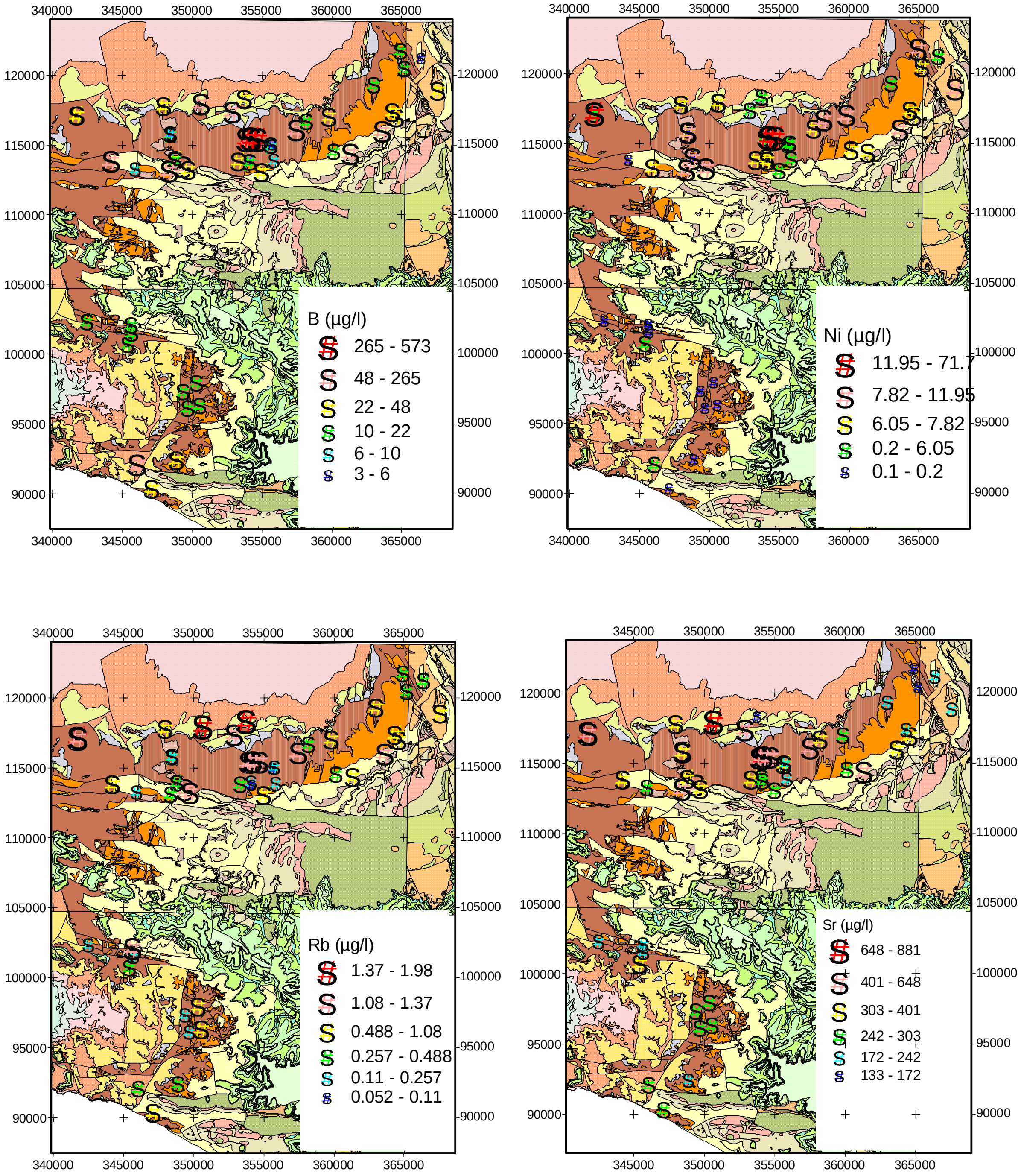


Figure 6.16 **Regional plots for B, Ni, Rb and Sr in the Bridport Sands aquifer.**

7. BASELINE CHEMISTRY OF THE AQUIFER

The baseline chemistry of groundwater in an aquifer is determined by a range of physical as well as chemical processes. The primary input to most major aquifers is rainfall, although connate or formation water may be present in parts of the aquifer where flushing has not been complete. In addition, leakage from underlying or overlying aquifers may modify the groundwater chemistry either locally or regionally. A series of chemical reactions take place during recharge and groundwater flow, the most important being mineral dissolution and precipitation, mixing, redox reactions, ion exchange and sorption/desorption reactions. Water-rock interaction is complicated by the fact that most aquifers are heterogeneous in terms of mineralogy and geochemical environment (e.g. redox status). This is certainly the case with the Bridport Sands aquifer where the complex faulting and geology has most likely led to compartmentalisation of the aquifer in terms of groundwater flow. Many chemical reactions are also time-dependent and this gives rise to a range in baseline chemistry as the groundwaters move from areas of recharge to discharge.

Superimposed on this “natural” baseline are anthropogenic influences. These include point-source and diffuse pollution which directly modify the baseline chemistry. However, the baseline can also be modified indirectly, for example, by abstraction: this can induce leakage from overlying units or upconing of deeper water of a different chemical composition. Although such changes can occur where the introduced solutes are derived “naturally”, and therefore represent baseline, the aquifer or unit being characterised has been modified, hence the need to define the baseline of a specified system.

In the present study, boreholes which were known to be affected by point-source pollution have not been sampled. However, many groundwaters especially where the aquifer is unconfined, show signs of diffuse pollution, dominantly from urban or agricultural activities and these have been included. The determination of baseline in such cases can be determined from historical records, where these exist, by comparing with pristine areas, applying statistical techniques or modelling. Most of these have limitations and should be used together to provide a reasonable estimate of the baseline composition (Shand & Frengstad, 2001).

The chemistry of groundwaters in the study area is overwhelmingly controlled by natural processes. The majority are of Ca-HCO_3 type and the dominant control is through reaction of recharge water with calcite in the aquifer. Silicate reactions, mainly slower dissolution of feldspar, have led to an increase in Si and cations, particularly K and Na (Ca is dominated by calcite dissolution). High Na in boreholes around Yeovil are considered to be due to ion exchange. The high B, which correlates with Na, in these boreholes is difficult to explain. Although an anthropogenic source is possible, it is likely that these groundwaters are relatively old and they abstract partly or totally from the Pennard Sands. Further work is recommended in this area. Chloride concentrations are generally low and thought to be mainly derived from mixing with remnant formation water.

Water-rock interaction and mixing are also the dominant controls on minor and trace element concentrations e.g. Sr is derived from dissolution of calcite and feldspar and Ba from barite or K-feldspar. Redox processes are an important control on some metal species: Fe and Mn are high in the more reducing groundwaters but in oxidising parts mobility is limited by solubility controls. Most metals are present at concentrations below drinking water limits although locally elevated concentrations occur. Arsenic, for example, is generally low (typically < 1 µg l^{-1}) but one groundwater contained As at a concentration of 12 µg l^{-1}, slightly above the EU/UK drinking water standard of 10 µg l^{-1}.

Although the range in Cl concentrations is considered to be largely natural, some anthropogenic influences are likely, either from road salt application or urban and agricultural pollution.

Anthropogenic influences on the chemistry of the aquifer water are evidenced by elevated nitrate concentrations. Unfortunately there are no long term records and it is difficult to establish the baseline directly for the area. A regional plot of nitrate in groundwaters is shown on Figure 7.1, which indicates that the northern sector contains the highest NO_3 concentrations, but also displays a very wide overall range. The higher concentrations in the northern area may reflect increased urban inputs (e.g. leaking sewers) as well as agricultural inputs. There is a distinct change in populations on the cumulative probability plot (Figure 5.3) at around 5 mg l^{-1}, but this may simply be a control by denitrification which masks any true change in population. It is thus difficult to estimate what the natural baseline for nitrate is with current data; a concentration of 1-3 mg l^{-1} is likely if comparing to other regions. It is possible that old historical data exists but none were available for this study. It is probable that other solutes, including K, Cl, SO_4, NH_4 and Na are modified locally by anthropogenic inputs. The highest K concentration of 10.5 mg l^{-1} is undoubtedly anthropogenic (the sample also has high nitrate) but the 97.7 percentile (5.0 mg l^{-1}) represents a good estimate of the upper baseline excluding this data (5.1 mg l^{-1}). Table 5.1 highlights elements which may be modified locally by anthropogenic inputs, but which lie within the range of the regional baseline, therefore local baselines may need to be established to answer specific problems.

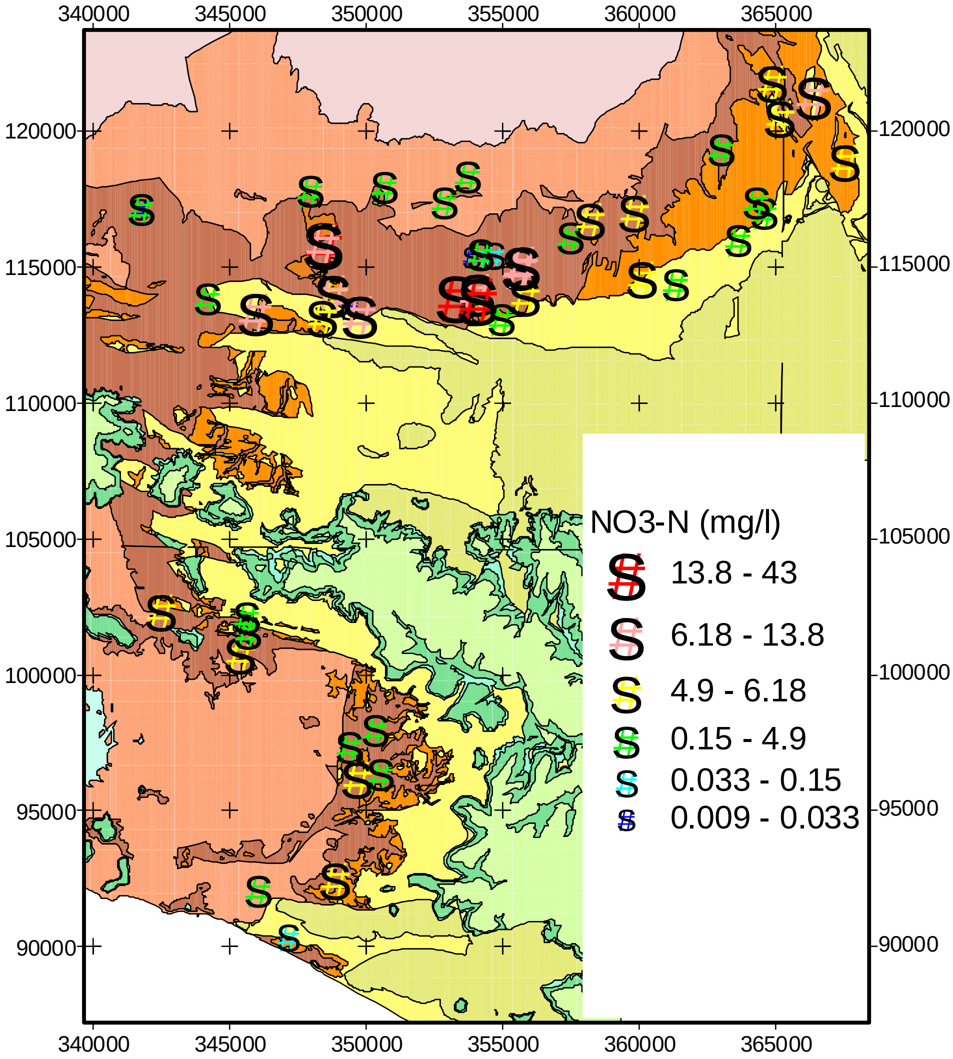


Figure 7.1 Regional variations in NO_3-N in groundwaters of the Bridport Sands.

The spatial variations in solute concentrations may be large over relatively short distances in the Bridport Sands and care should be taken extrapolating baseline concentrations across the aquifer. Such heterogeneity is caused by variations in geology (faulting), hydrogeology (different flow systems) and mineralogy throughout the aquifer. The aquifer is relatively poorly understood and further work would be useful to characterise such variations.

8. SUMMARY AND CONCLUSIONS

The hydrogeological characteristics of this aquifer are poorly known, but are likely to be complex due to the variations in facies and mineralogy and the extent of faulting. The Bridport Sands are strongly interbedded with alternating clay-rich sands and harder calcite cemented sands. This undoubtedly causes significant heterogeneity in terms of transmissivity and it is probable that horizontal hydraulic conductivity is much greater than vertical hydraulic conductivity. Fracture flow is likely to be important in the aquifer. It likely that the aquifer is compartmentalised with distinct groundwater units and flow systems. The aquifer comprises mainly Bridport Sands, but some boreholes also abstract from the underlying Pennard Sands and the overlying Inferior Oolite where they are treated as one aquifer unit.

The groundwaters are mainly of Ca-HCO_3 type although Na-HCO_3 types occur around Yeovil. It is considered the latter is due to ion-exchange reactions of Ca for Na, with the Na-rich compositions being derived from waters in the Pennard Sands at depth. These Na-HCO_3 type waters are also enriched in B, but it is not clear whether this is due to natural or anthropogenic influences. Further work is recommended in this area to establish the most likely source. Relatively high dissolved concentrations of Fe and Mn were present in some waters due to reducing conditions. Trace metals are typically low, especially in the more oxidising groundwaters, and below drinking water limits but may be enhanced locally. Elevated Cl concentrations in some waters are considered to be largely natural, although it is likely that there is some anthropogenic influence (The lack of time series data make it difficult to establish the baseline for some elements). Some groundwater sources in the Bridport Sands contain relatively high nitrate concentrations which are most likely the result of agricultural activity. Long-term time series data for the Bridport Sands were not available.

The spatial variations in solute concentrations may be large over relatively short distances in the Bridport Sands and care should be taken extrapolating baseline concentrations across the aquifer. The lack of knowledge of the hydrogeology, flow systems and residence times make it difficult to assess the baseline in detail and further work is recommended to address these issues.

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