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The Chalk aquifer of the Wessex Basin

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BRITISH GEOLOGICAL SURVEY

RESEARCH REPORT RR/11/02

The Chalk aquifer of the Wessex Basin

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Preface

This study was undertaken as part of the National Groundwater Survey (NGS), which aims to provide a comprehensive description of the major British aquifers and their groundwater resources. This includes the characterisation of the physical and chemical properties and processes that govern groundwater flow and pollutant transport and attenuation, in both the unsaturated and saturated zones. The NGS has commenced with a study of regions of the Chalk aquifer.

Although much work has been undertaken on the Chalk Group of the Wessex Basin, there is a need for current knowledge to be brought together into a convenient format that is in the public domain. The study aims to summarise available hydrogeological information and current understanding of the aquifer. This report is intended as a source of reference that will benefit and interest researchers, students and those in the water industry (suppliers, regulators and consultants) as well as the general public.

In order to meet the objectives of the study, information has been collected from a variety of sources, including British Geological Survey data, publicly available literature, information from the water industry and the Environment Agency and academic institutions. The information has been reviewed and summarised from a variety of standpoints; geological, hydrogeological and hydrochemical. Given the large area covered by the aquifer across the basin the approach taken has been to provide both basinwide overviews and catchment-specific discussions. The outcome of such an approach has resulted in a report which encompasses a broad range of aspects of the hydrogeology of the aquifer at a variety of scales.

The British Geological Survey has collaborated with the Environment Agency, and a number of water companies. An Advisory Panel comprising members of the above organisations ensured that the work was relevant to them, as well as contributing much valuable information and acting as reviewers. Work on this report commenced in the early 2000s and was mainly complete by 2011. Staff changes delayed publication. The maps and data presented thus reflect that period and more up-to-date versions may now be available elsewhere. Minor revisions of the management chapter were undertaken in 2015.

Acknowledgments

This study has relied on the work of a number of current and former members of BGS staff in addition to the named contributors. In particular the geological basis of the study has incorporated the work of D T Aldiss, C M Barton, K A Booth, C R Bristow, D J Evans, A R Farrant, and P M Hopson. The work was also helped substantially by the members of the Project Advisory Board, which comprised the following:

Giles Bryan (Environment Agency)*
Tina Dijkstal (Southern Water Technology Group)
Jim Grundy (Environment Agency)
Alison Matthews (Environment Agency)*
Mike Packman (Southern Water)
Paul Shaw (Environment Agency)*
Paul Stanfield (Wessex Water Services)*

(Those asterisked also provided written contributions to the report).

In addition we would like to thank Roger Harrington (Bournemouth and West Hampshire Water), and Mike Hedges (Portsmouth Water) for useful and fruitful discussions.

We would like to acknowledge the Environment Agency (Southern and South West Regions), Portsmouth Water, Southern Water and Wessex Water for the provision of hydrochemical data. Digital terrain model and river data used in the report were sourced from the Centre for Ecology and Hydrology (CEH) (Morris and Flavin, 1990, 1994; Moore et al., 1994). Other data are referenced in the text.

Maps and illustrations were prepared by J E Cunningham, P Sapey, P Lappage and I Longhurst. Page-setting was by P Sapey, D Rayner and A Hill. Additional editing was undertaken by J E Thomas.

Carole Sharratt has supported the production of this and many other reports with patience and supreme levels of organisation.

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Executive summary

The geological structure known as the Wessex Basin occupies a substantial area in southern England and contains deposits ranging from Permian to Cretaceous in age. The basin stretches from Devon eastwards to the Weald, flanks the southern side of the London Platform and extends south under the English Channel. Within this larger geological structure, the onshore Chalk of the Wessex region covers large parts of the counties of Hampshire, Wiltshire and Dorset and stretches from the Weymouth region in the west to near Chichester in the east and from the south coast towards Newbury in the north, with an outcrop area of approximately 4650 km^2.

The area of study is characterised mainly by Chalk downland that dominates over a core of forest and heath terrain associated with the outcrop of the Palaeogene sediments. The Downs, which reach elevations of around 270 m, are characterised by undulating topography consisting of steep-sided escarpments with long, gentle dip slopes and rounded hills. The climate is typically mild and rainfall over most of the region averages between 750 and 900 mm annually.

The Wessex region is drained by a number of rivers, the most significant of which generally have headwaters in the Chalk uplands around the edge of the basin; these then flow across the Chalk and Palaeogene deposits towards the south coast, discharging along the coastline between Poole Harbour and the Solent. From west to east the main catchments are those of the Frome and Piddle, Stour and Allen, Avon, Test and Itchen. In addition, smaller rivers drain the Chalk of East Hampshire and the Isle of Wight.

Water usage varies across the region but includes agriculture, public water supply, spray irrigation, industry, private domestic supply, gravel washing, fish farming and watercress production. Most of the licences are for agricultural practises such as farming and spray irrigation, but these are for relatively small volumes compared to public supply. Much of the water used is obtained from groundwater sources, which principally utilise the Chalk aquifer.

The distribution of the Chalk in the region results from two main tectonic stages in its history. During the Permian to Cretaceous, basins were subsiding and infilling with sediment under a regime of regional crustal extension and, apart from a few local variations, the Cretaceous Chalk was deposited as a uniform blanket across the central parts of the Wessex Basin. During the Cenozoic, crustal extension was replaced by south to north-directed compression related to the Alpine mountain building event. Sedimentary rocks that had accumulated within the basins were pushed upwards as the movement on bounding faults changed from normal to reverse and compression led to the development of east–west trending folds. The geographical distribution, geological structure and geomorphology of the Chalk is largely a function of Cenozoic compression and folding. The exposed Chalk uplands to the north of the Palaeogene lowlands of the Hampshire Basin are broadly anticlinal in structure, while beneath the Palaeogene deposits of the Hampshire Basin, the Chalk forms a syncline.

Palaeogene strata, characterised by alternating sand and clay formations, cover significant areas of the central and southern parts of the Wessex region and are separated from the Chalk by a major hiatus of some 15 million years; however, the two highly contrasting units are largely structurally conformable, both being folded during the main Miocene inversion event. The major hiatus between the Chalk and the Palaeogene was a time of regional uplift, sea level fall and subaerial erosion of the exposed Chalk surface under subtropical climatic conditions.

The aquifer properties of the Chalk in the Wessex Region are determined both by its intergranular (matrix) hydraulic properties and by the nature and distribution of fractures. The porosity of Chalk varies between about five per cent and 45 per cent and depends on stratigraphy. For example, the upper part of the White Chalk Subgroup of southern England has an average porosity of 39 per cent, the lower part of the White Chalk Subgroup an average porosity of 28 per cent and the Grey Chalk Subgroup a porosity of 23 per cent. Local contrasts in porosity are due to variations in the nature of the original sedimentation: generally, lower porosities are associated with more clay-rich chalks and with nodular and hardground seams. In addition, porosity tends to reduce with depth. Despite high values of porosity, the storage characteristics of the Chalk aquifer are poor as a result of small pore sizes and low values of specific yield are normal. The hydraulic conductivity of the Chalk depends principally on the occurrence of fractures, the matrix values being very low (of the order of 10^{-3} m d^{-1}) as a result of the small pore throat sizes. In general terms, the highest transmissivities and storage coefficients are found in valleys, with lower values towards interfluves. Hydraulic conductivity also rapidly decreases with depth.

Pumping test data suggest that the aquifer properties of the Chalk vary widely in the Wessex region, with transmissivity values ranging from virtually zero to several thousands of square metres per day and with storage coefficients ranging from the order of 10^{-5} to around 0.06. Mean values of transmissivity from pumping tests are around 1500 m^2 d^{-1} for much of the basin (with a bias to valley sites), falling to around 200 m^2 d^{-1} in south Dorset (probably as a result of the local tectonic hardening of the Chalk). Groundwater models have used transmissivities that commonly vary from a few hundred square metres per day on interfluves to several thousand square metres per day in valleys. Mean values of storage coefficients from pumping tests were of the order of 0.005. Storage coefficients used in models have tended to be larger, with values ranging from 0.003 to 0.05, with the higher values characterising Chalk at shallow depths in valleys.

The significant variability in the aquifer properties of the Chalk reflects a diverse range of matrix and fracture characteristics and the wide range of geological and hydrogeological processes that have contributed to the development of the aquifer. For example, in the Wessex region, where the Chalk has been affected by Alpine tectonics, there is a greater structural complexity in the aquifer than in other regions of England. Large folds and faults are present, which affect the hydrogeology of the region, while smaller structural features exert more subtle influences on the local hydrogeology. Although the area was not glaciated, it was significantly affected by periglacial processes and clay-with-flints deposits cover large parts of the aquifer on higher ground. Both the periglacial processes and acidic drainage from Palaeogene cover rocks have contributed to the local development of the aquifer, leading to the development of karst features in some areas.

Recharge to the aquifer through the unsaturated zone may have both vertical and horizontal flow components and may involve both the Chalk matrix and fractures. The recharge is influenced by the presence of permeable or impermeable horizons within the Chalk and the nature of overlying Palaeogene and Quaternary deposits. The heterogeneous nature of these deposits means that impermeable units may promote run-off, whilst the more permeable units may allow direct recharge to occur. However, the presence of impermeable deposits may also concentrate flow from certain areas and hence locally increase the amount of recharge to the underlying aquifer. Long-term average annual modelled recharge values in the basin vary from around 200 mm to around 500 mm. In general, modelled values in the Bourne, Upper Avon and Test catchments are around 250 to 350 mm per annum (a^{-1}).

The principal groundwater flow mechanism in the saturated zone is along fractures, which are often enlarged by solution, rather than through the Chalk matrix. Subsurface evidence for the location of groundwater flow horizons and their relationship with aquifer lithology is obtained primarily from the interpretation of geophysical borehole logs. Formation and fluid logging of boreholes penetrating the Chalk shows that water normally flows into a borehole at only a few specific points and these are often associated with certain stratigraphical horizons (which are commonly located at flint, marl and hardground surfaces) at shallow depths.

While the locations of flow horizons often appear to be controlled by lithologically distinct stratigraphical horizons such as Chalk hardgrounds, the hydraulic and chemical influence on their development is such that the main flow horizons generally develop within a few tens of metres of the Chalk surface. This is because the Chalk is soluble and groundwater tends to develop permeability pathways as it moves towards surface discharge points. In the Wessex region, groundwater flow is generally inwards from the edges of the basin towards the coast and is therefore broadly in the direction of dip. Generally, hydraulic gradients are shallower than the dip of the strata and groundwater flow in the shallow, solution-enlarged fracture systems will tend to be transferred from lower to higher stratigraphical horizons as it moves down a catchment.

Interaction between surface streams and groundwater is very common across the Wessex region and most of the surface watercourses are fed substantially by groundwater, with baseflow indices commonly high, of the order of 0.8 or more. The low specific yield of the Chalk results in winterbourne behaviour (involving streams drying in their upper reaches during summer) being very common in the Chalk groundwater-fed streams. However in the Wessex region many streams do not follow the classic winterbourne model of a simple gradational drying down to the stream's perennial head in summer and commensurate wetting from the perennial head in winter, but exhibit much more complex behaviour. For example, it is not uncommon for streamflow to increase from the stream head, then to decrease for a section (and in extreme cases to dry completely) before increasing again further down. Some streams exhibit even more complicated behaviour with, periodically, a succession of flowing and dry sections above the perennial head. There are a number of causes for this complex behaviour, which can include abstraction and lithological effects.

The major element chemistry of the Chalk groundwaters is controlled by the carbonate system and the groundwaters in the outcrop areas are of Ca-HCO_3 type. Mixing with remnant formation water (probably within the chalk matrix) has led to an increase in salinity in the deepest, oldest waters. Ion exchange of Na for Ca in these waters has led to a trend intermediate between that of Na-HCO_3 and Na-Cl types. The largest changes in water chemistry are found where the aquifer becomes confined beneath the overlying Palaeogene sediments. A redox boundary occurs close to this boundary and beyond this zone the groundwaters are reducing and contain low concentrations of nitrate. The reducing nature of the system leads to an increase in Fe and Mn. There are limited data on trace metals over much of the aquifer but the available information indicates that concentrations are generally low, a notable exception being fluoride which generally exceeds the EU-MAC for drinking water in confined parts of the aquifer. The large chemical differences between the unconfined and confined groundwaters in the Wessex region are consistent with differences in residence time and suggest that they may be controlled by different flow systems.

Groundwater management is very important in the Wessex region, where groundwater from the Chalk aquifer represents a major source of water supply (and often forms a large percentage of river water). There are a number of issues that are important to the management of the groundwater resources of the region: for example increasing demand, protection of habitats, the problems of drought and conversely of groundwater flooding, and, in the longer term, the effects of climate change.

Urbanisation, industrial growth and intensive agricultural activity can have a serious impact on groundwater quality. The rate of groundwater movement through the Chalk is generally slow and the effects of historical pollution may take a significant time to appear. Conversely, where the Chalk is karstic, pollutants such as pathogens may move rapidly from the ground surface to groundwater sources. In the Wessex region, initial characterisation for the Water Framework Directive showed that almost all of the groundwater bodies in the Chalk aquifer in the eastern part of the basin were 'at risk' as a result of diffuse pollution pressures (principally nutrients and pesticides) and groundwater bodies in the western part were classified as 'probably at risk'.

A thorough understanding of the hydrogeology of the Chalk of the Wessex region and the influences on Chalk groundwater is therefore essential for effective resource management. It is hoped that this report will fulfil part of that need.

1 Introduction

1.1 THE WESSEX BASIN CHALK AQUIFER

The geological structure known as the Wessex Basin occupies a substantial area in southern England and contains deposits ranging from Permian to Cretaceous in age. The basin extends from Devon eastwards to the Weald, flanks the southern side of the London Platform and extends south under the English Channel. Within this larger geological structure, the onshore Chalk Group of the Wessex Basin covers large parts of the counties of Hampshire, Wiltshire and Dorset and stretches from the Weymouth region in the west to beyond Portsmouth in the east and from the south coast towards Newbury in the north (Figure 1.1). The area covered by the Chalk Group at outcrop is approximately 4650 km^2.

The term Wessex Basin is used in two ways in this Research Report. In a geographical/hydrogeological sense it is the region of south central England drained by the generally southward and eastward flowing rivers of Dorset, east Wiltshire, Hampshire and the Isle of Wight. In a geological sense the Wessex Basin structure is more extensive, covering much of southern England south of the Variscan Front and including strata of Permian to Cretaceous age. A younger Hampshire Basin is a more restricted, eroded remnant founded on Palaeogene strata of east Dorset, southern Hampshire and northern Isle of Wight.

For the purposes of this report, the Chalk aquifer of the Wessex Basin is delineated by a number of natural boundaries within the total area underlain by the Chalk Group. The eastern limit of the aquifer is the groundwater divide between Portsmouth and Chichester, which has been taken as the western limit of the South Downs[1] Chalk aquifer (Jones and Robins, 1999). The northern limit is taken to be the surface water divide to the south of the Thames Valley, and the Vale of Pewsey. The western boundary is the edge of the outcrop and the southern limit is the line of outcrop of the Chalk Group along the Isle of Wight–Purbeck monocline. The sea forms the southern limit of the landward aquifer system, although the Chalk continues to dip beneath the English Channel. The Isle of Wight, although isolated from the mainland, is part of the same basin and contains steeply dipping Chalk strata that are connected underneath the Solent to the mainland.

The base of the Chalk Group forms the base of the aquifer. However, the Upper Greensand lying directly below the Chalk is often considered to be in hydraulic connection and may affect the response of the overlying aquifer. Furthermore, even though the majority of the units in the Chalk sequence may contain groundwater and the thickness of the Chalk Group reaches 450 m in places, only the uppermost few tens of metres of the saturated Chalk in a given locality are generally considered to constitute an aquifer in terms of a viable groundwater resource. Thus the Chalk aquifer is not synonymous with the Chalk Group. The central-southern portion of the Chalk in the basin is overlain by a sequence of younger Palaeogene sediments: these strata are generally considered to be poor aquifers or non-aquifers, but are important because they influence processes that occur on, and within, the Chalk.

1.2 TOPOGRAPHY AND LAND USE

The Wessex region rises from sea level to heights approximating 300 m above Ordnance Datum (AOD) around the basin periphery (Figure 1.2). The area of study is characterised mainly by Chalk [1]downland, which predominates around the edges of the basin and forest, and heath terrain associated with the southern and central outcrop of the Palaeogene sediments. Figure 1.3 illustrates the main types of land cover across the region. The Chalk forms a broad belt of country running from the coast of south Dorset through the North Dorset Downs to Salisbury Plain to the north of Salisbury. East of Salisbury, the Chalk covers a large area between Winchester and Basingstoke, with the outcrop extending eastward, to the north of Portsmouth. The Downs are characterised by undulating topography consisting of steep-sided escarpments with long, gently sloping dip slopes and rounded hills. In the west, the landscape consists of rounded hills that are intersected by a complex system of valleys and combes. In south Dorset, the Downs rise to a maximum elevation of 274 m at Bulbarrow Hill and over 220 m on Cranborne Chase (to the west and north of Blandford Forum respectively), with somewhat lower elevations over Salisbury Plain to the north-east of Salisbury. In the east of the Wessex Basin, the Downs rise to a maximum elevation of 271 m at Butser Hill to the north of Portsmouth.

The Isle of Wight is topographically dominated in the centre by two offset, steep-sided, narrow, east–west trending ridges connected by a broad central downland area, the region rising to elevations of 100–200 m. In the south of the island are the Southern Downs, characterised by steep landslipped margins, which attain about 240 m to the north of Ventnor.

The most notable habitats of the Wessex region include chalk grasslands, chalk rivers and woodlands with smaller areas of meadow land and wetland habitats that support a wide variety of associated species. The Chalk Downs were formerly well wooded, but now only scattered plantations are to be found. The Downs form characteristic rounded summits where they are uncultivated and have a springy turf of fescue grass with distinctive vegetation, including rare orchids and fauna. Agricultural technological advances have now made it possible to cultivate all but the steepest slopes allowing crops to grow on the land on which sheep used to graze. In the central and southern parts of the Wessex region there is an area of heathland and forest (associated with the Palaeogene sands and clays) that is generally lower lying and flatter than the Chalk downland.

In the western part of the region, in Dorset and Wiltshire, the main land use is for agriculture, although this accounts for only a small percentage of the counties' employment. The main towns in south-east Dorset are Dorchester, Wareham and Poole and the area's industrial developments tend to be located around Poole Harbour. On the Chalk uplands large farms concentrate on crop production and dairy farming,

[1] The name 'down' derives from the Saxon English 'dun' meaning 'hill'.

Figure 1.1 Geology of the Wessex Basin.

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while steeper land accommodates large flocks of sheep. The Frome and Piddle catchments, for example, are predominantly rural and modern agricultural methods have converted previously grazed pasture to arable land. In these catchments, around 70 per cent of the area is farmed. On the Palaeogene mixed sand and clay areas in south-east Dorset, agricultural enterprises are varied. Pig and poultry production is practiced, as is some horticulture, and forestry now plays an important role. In the Purbeck District, the Portland Stone and Purbeck Marble are renowned as building materials and Dorset also has one of the last mines in the country working ball clay, which is important in the ceramics industry. Offshore and onshore oil and gas resources are exploited in south Dorset, particularly to the south of Poole Harbour. The majority of west Dorset is considered an Area of Outstanding Natural Beauty and tourism is a major industry in the area.

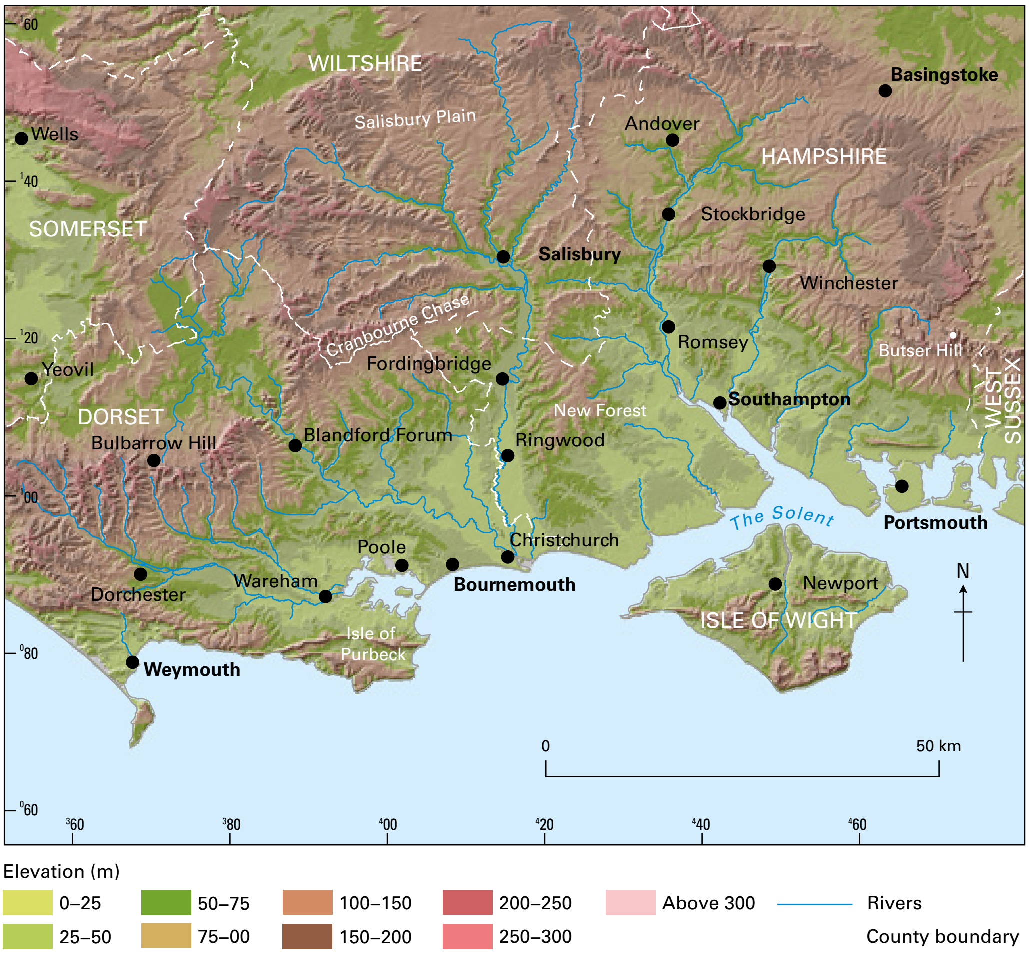

Figure 1.2
Topography of the Wessex Basin.
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Approximately 75 per cent of the Hampshire Avon area (Environment Agency, 1998a) is farmed, with cereal, cattle and sheep farming the dominant activities. There are also a number of sand and gravel extraction pits in the Ringwood area and chalk and sandstone quarries in the vicinity of Salisbury. Industry is mainly light in nature and situated in the towns; in addition there are several major military establishments on Salisbury Plain. Tourism forms a significant industry, particularly in Salisbury, Fordingbridge and Christchurch, and the area is also of high archaeological and historical importance. Abandoned water meadows are characteristic of all the river valleys, resulting from past agricultural practices.

The New Forest area is predominantly rural and the enclosed forest is classified as a Site of Special Scientific Interest (SSSI) and includes Forestry Commission plantations for both soft and hard woods, and enclosures for agricultural small holdings. The main urban areas are in the south-west and these include industries such as petrochemical and power generation. Tourism is also a major industry in this area.

The Test and Itchen valleys stretch north–south from the Chalk downlands, on the Berkshire border, to the meadows and the valleys of the rivers that discharge into Southampton Water and the Solent. The topography of the catchments comprises small hills and shallow valleys. Whilst the catchments are predominantly rural areas, with significant agricultural activity, they also have an economy based on industrial and commercial communities, principally in and around the main towns. Agriculture has always played a large part in shaping the local landscape that, historically, would have been covered with trees. In the thirteenth century, land was parcelled up into smaller fields, enclosed by many of the banks, hedges and ditches visible today. Medieval land use still survives in places like Stockbridge in the Test Valley, where the old water meadows by the river are now common land.

The valley of the Test has supported a variety of industries in the past, such as tanning leather and milling flour, but the majority of these industries have declined resulting in disused mill leats and backwaters. The river is used extensively for trout and salmon fishing. While the catchment is predominantly rural with significant agricultural activity, it includes the urban areas of Andover, Romsey and part of Southampton.

The landscape of east Hampshire is characterised by distinctive coastal and inland areas. The main urban and industrial zones lie along the coast, especially around the low-lying areas. The coastal strip contains important conservation areas, such as broad estuaries with tidal mud flats, wetland, marshland and open coastline, some of which have been designated as important conservation sites. Inland from the coastal zone lies rolling open countryside that is predominantly rural and used chiefly for agriculture. Watercress production is an important industry in this area, accounting for some 70 per cent of the total production in the UK. In addition to river valleys, there are also a number of dry valleys on the Chalk.

On the Isle of Wight, the Chalk downs are characterised by rolling pasture and arable land with pockets of unimproved grassland on steeper areas. Heathland/acidic pasture can be found on the Greensand between the two ranges of Chalk downs. Dairy farming, creating lush, irregular fields bounded by mature hedgerows and coppiced woodland, dominate

Figure 1.3 Land cover map for the study area (showing aggregate 1 km grid-square averages).
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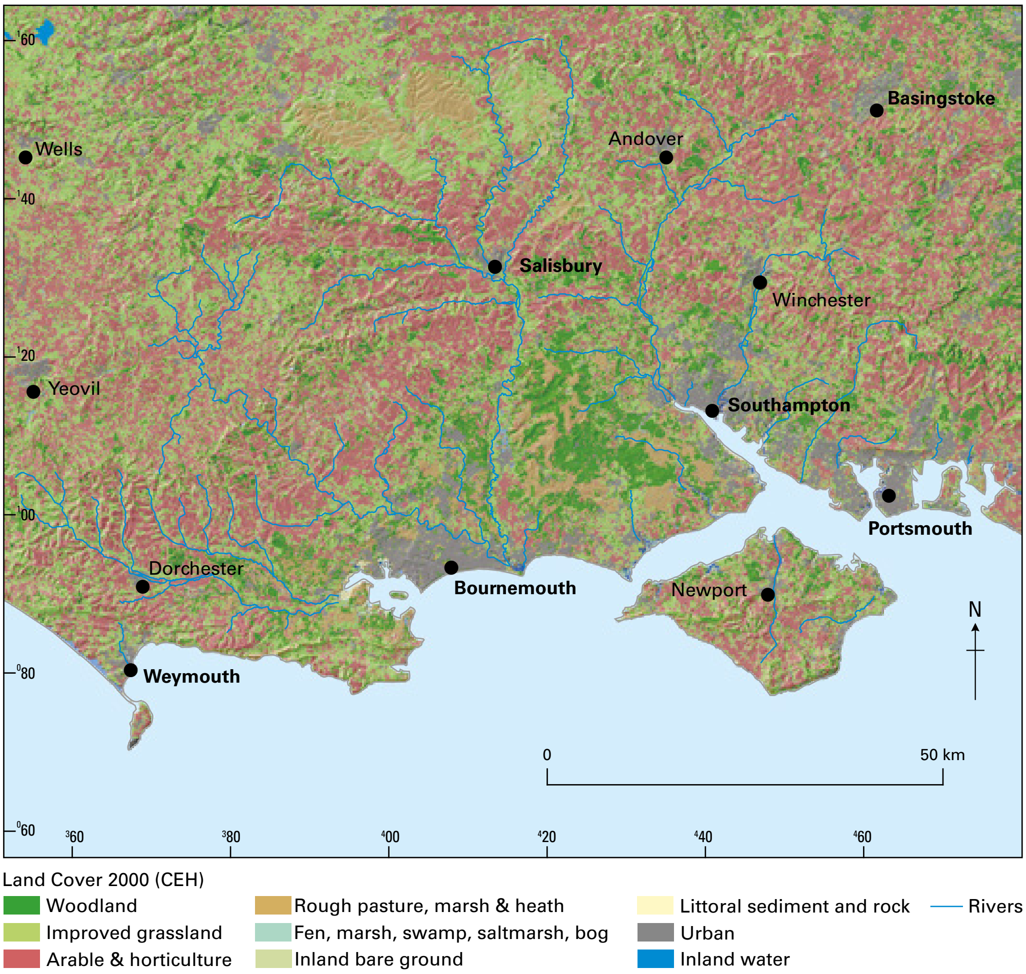

the northern pastures. Along the north coast are numerous harbours, creeks, salt marshes and tidal mudflats fringed by woodland. The southern coastal plain is dominated by an intensively managed arable farmland with large open fields and few trees. Land use is predominately rural with mixed farming over most the area and intensive horticulture in the Eastern Yar valley. There is a small industrial sector, mainly in aerospace, but tourism and the leisure industry dominate the island's economy.

1.3 CLIMATE

Temperatures in Wessex are typically mild, with averages ranging from 1°C in winter to 22°C during the summer (Table 1.1). Rainfall (Figure 1.4) varies from less than 700 mm per year in north-east Hampshire and along the coast near Portsmouth to over 1100 mm on the higher ground west of Blandford Forum in Dorset, although over most of the region the annual average is between 750 and 900 mm. The highest rainfall is observed in the south-western part of the region in the upper parts of the Frome and Piddle catchments where a rainfall average (Met Office data, 1969 to 1990) of 1033 mm a^{-1} has been recorded. Other areas of higher rainfall are in west Wiltshire and the eastern edge of the basin in Hampshire. The driest areas tend to occur around the coastline to the south from Portsmouth towards Bournemouth. Other notable dry areas with rainfall less than 750 mm a^{-1} are in the catchments of the River Avon and Bourne north of Salisbury and in the upper parts of the Test catchment around Andover.

1.4 DRAINAGE

1.4.1 Drainage pattern

The Wessex Basin is drained by a number of rivers (Figure 1.5), the most significant of which generally have headwaters in the Chalk uplands around the edge of the basin. These then flow and converge over the Palaeogene deposits towards the south coast, discharging along the coastline between Poole Harbour and The Solent.

In the south-west of the region the River Frome (Figure 1.6) rises from springs in the Upper Greensand near the village of Evershot on the West Dorset Downs. The River

Table 1.1 Long-term average (1971 to 2000) climate data recorded by the Met Office for four sites across the Wessex Basin (www.metoffice.gov.uk).

	Yeovilton	Bognor Regis	Everton	Boscombe Down
Max. temperature (°C) July/Aug	21.7	20.7	20.8	21.7
Min. temperature (°C) February	1.3	2.5	2.3	1.0
Daily sunshine (hours) Annual average	4.2	5.2	4.8	4.6
Annual rainfall (mm)	725	717	764	736

Figure 1.4 1961–90 gridded rainfall data for the Wessex Basin (data supplied by CEH, Wallingford).

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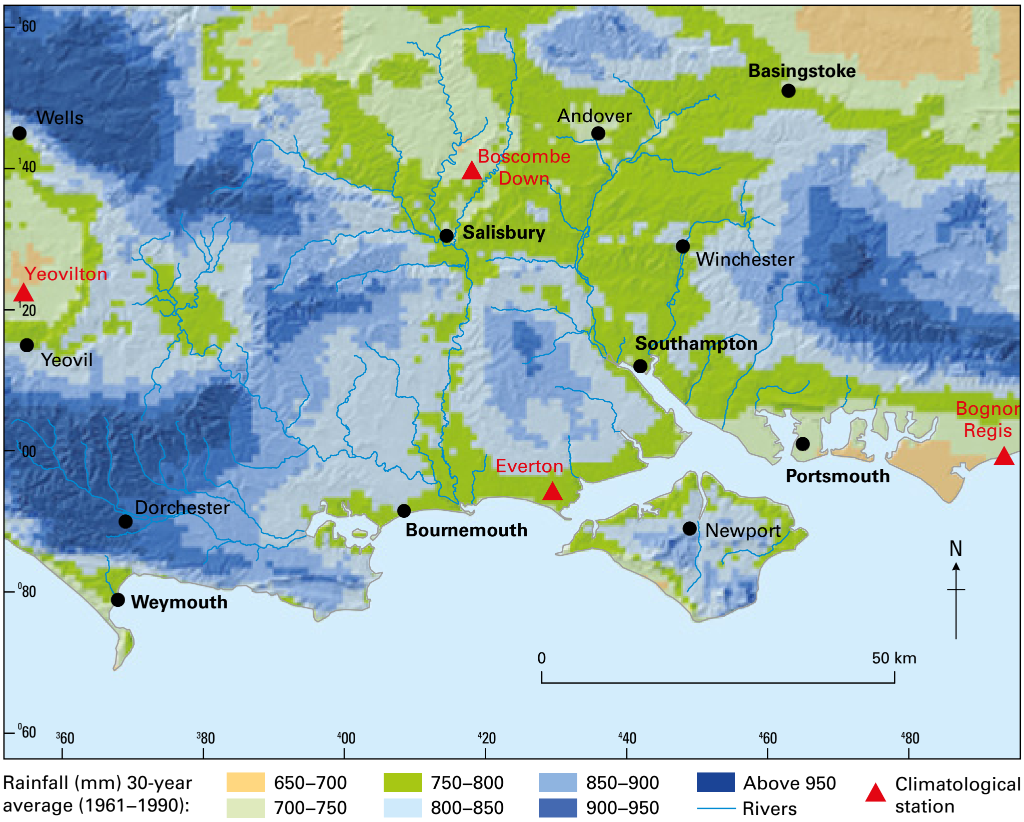

Frome and its tributaries form the southernmost major Chalk river in England. From its source, the River Frome flows south across Chalk and is joined by the Wraxall Brook north of Cattistock and then by the River Hooke at Maiden Newton, both draining land to the west. From Maiden Newton the Frome flows south-east to Dorchester, being joined on the way by two small streams, the Sydling Water and the River Cerne, which flow from the north. Below Dorchester it passes over the Palaeogene deposits and flows mainly eastwards. The Frome is soon joined by the South Winterbourne at West Stafford, flowing from the south-west. After the confluence with the South Winterbourne the

Figure 1.5 River network of the Wessex Basin.

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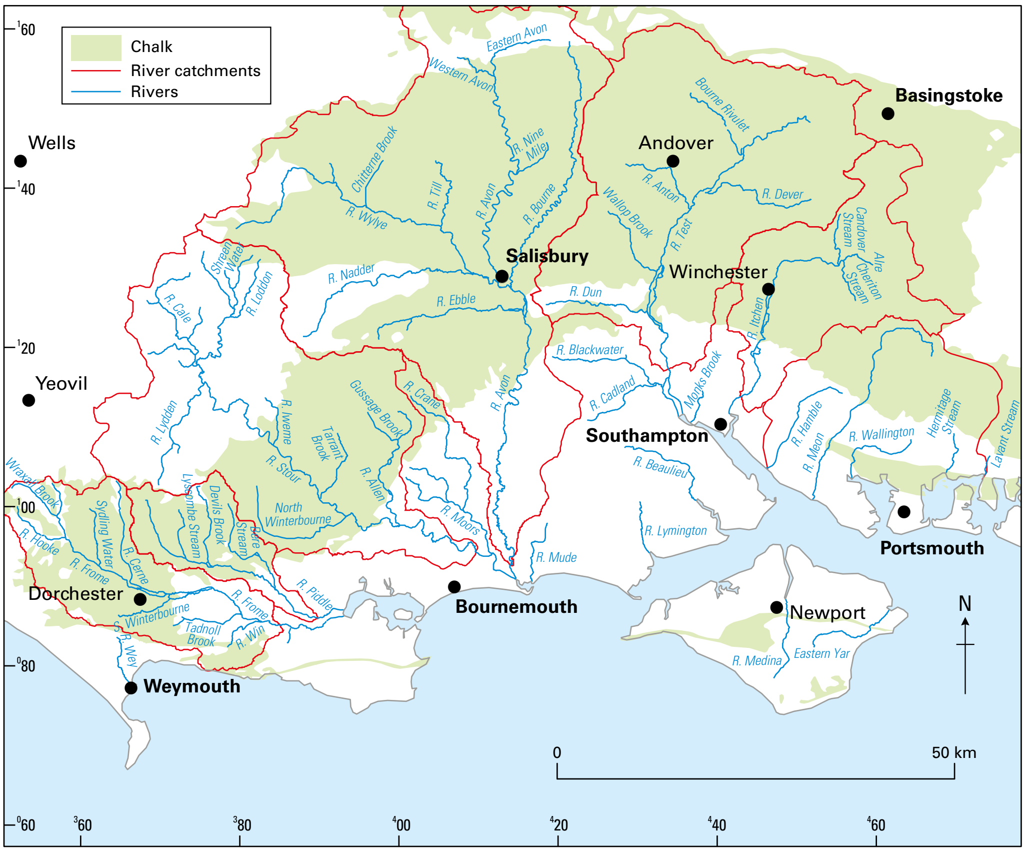

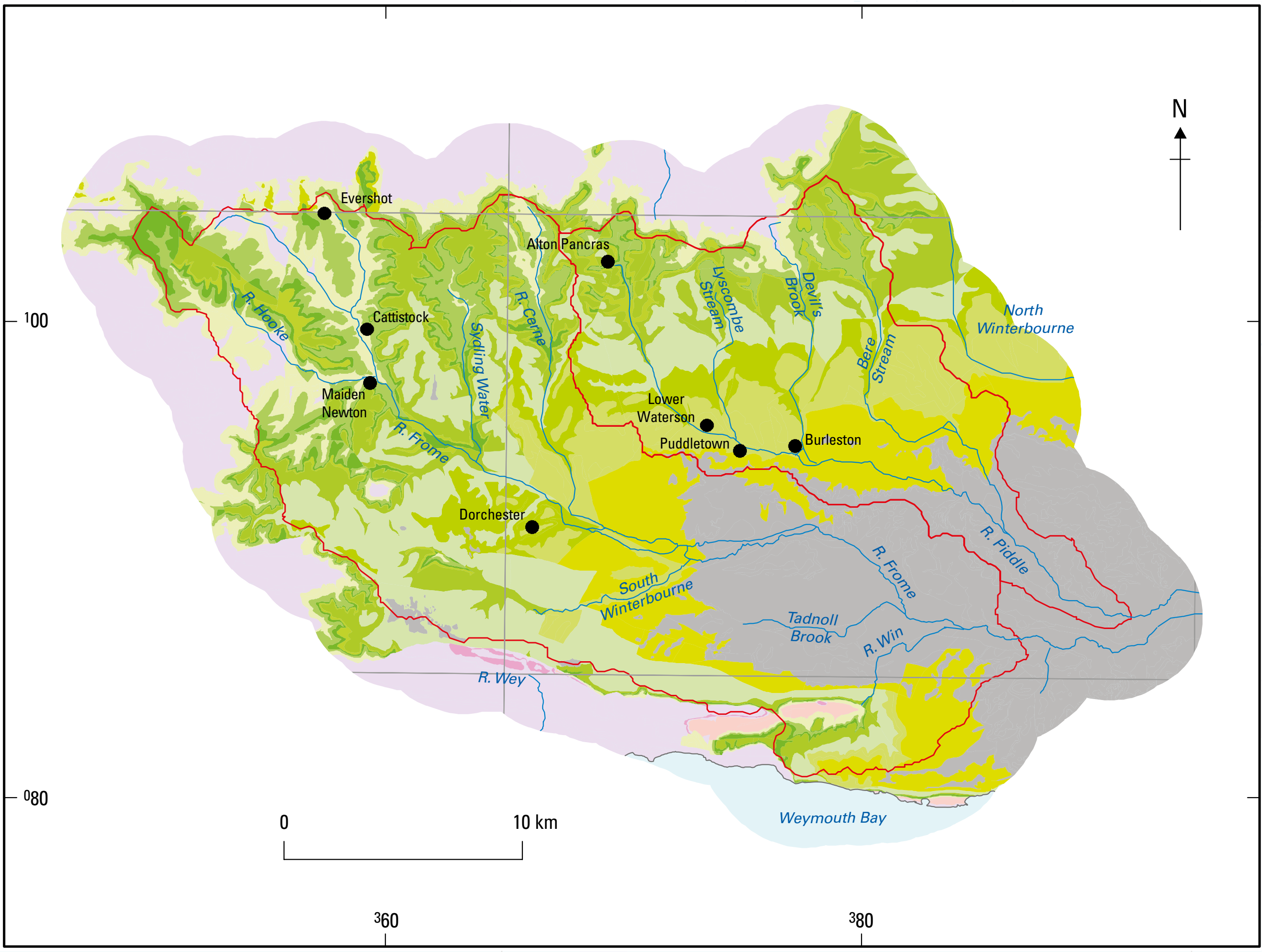

Figure 1.6 River Frome and River Piddle catchment area (see Figure 1.1 for key).

Frome flows over Palaeogene deposits eastward towards Wareham, being joined on the way by minor tributaries, the largest of which are the Tadnoll Brook and the River Win, which join from the south. The Frome finally discharges into Poole Harbour at Wareham where it is joined by the River Piddle. The middle and lower sections of the Frome have braided river features, many of which are the relics of historical water meadow systems but also include flood relief channels as well as natural channels (National Rivers Authority, 1996).

The River Piddle rises at springs near Alton Pancras and initially flows south and then eastwards from Puddletown towards Poole Harbour (Figure 1.6). There are three major tributaries; the Lyscombe Stream (which has a confluence with Piddle near Lower Waterston), The Devil's Brook (which joins the Piddle at Burleston) and the Bere Stream (with a confluence with the Piddle at Warren).

The River Stour rises in the Upper Greensand of Blackmoor Vale at Stourhead, a few kilometres north-west of Mere, and flows south-east to the sea at Christchurch (Figure 1.7). The Stour drains a catchment of 1300 km^2 (predominantly in Dorset, but including parts of Somerset and Wiltshire) and over the 96 km of its course it falls approximately 230 m (Environment Agency, 1997). From its source the Stour initially flows south to Gillingham where it is joined by two tributaries, the River Lodden and Shreen Water, which drain the Kimmeridge Clay. As it flows further south, towards Sturminster Newton, the other clay-influenced tributaries join the Stour (principally the Cale and Lydden which mainly drain Oxford Clay) the tributaries forming a dense drainage network. Below Sturminster Newton the river flows mainly south-east towards Blandford Forum and then to Wimborne Minster. In this reach, which is predominantly underlain by Chalk, there are fewer tributaries, and these include the Iwerne, Tarrant, North Winterbourne and finally the Allen, which joins the Stour at Wimborne Minster. The River Allen, which drains a catchment of 177 km^2 above Walford Mill Gauging Station rises from seasonal Chalk springs near Monkton Up Wimborne; the perennial head of the river is further downstream, at springs near to Wimborne St Giles, from where it flows approximately 18 km to its confluence with the Stour. From Wimborne to the sea, the Stour flows over Palaeogene deposits and shortly before reaching Christchurch the river is joined by the Moors River (known as the Crane in its upper reaches where it flows over Chalk). Finally, the Stour discharges into Christchurch Harbour.

The River Avon tributaries, the Wylye and Bourne and confluent streams, drain a large area of Salisbury Plain. The source of the River Avon is in the Greensand of the Vale of Pewsey, however most of the flow is gained from the Chalk, either directly to the Avon or via its tributaries as the river flows in a southerly direction over Salisbury Plain (Figure 1.8). Above Salisbury the river is called the Upper Avon and above Upavon it is divided into two tributaries, the Eastern Avon and Western Avon. These streams are themselves formed from several smaller watercourses, making the true

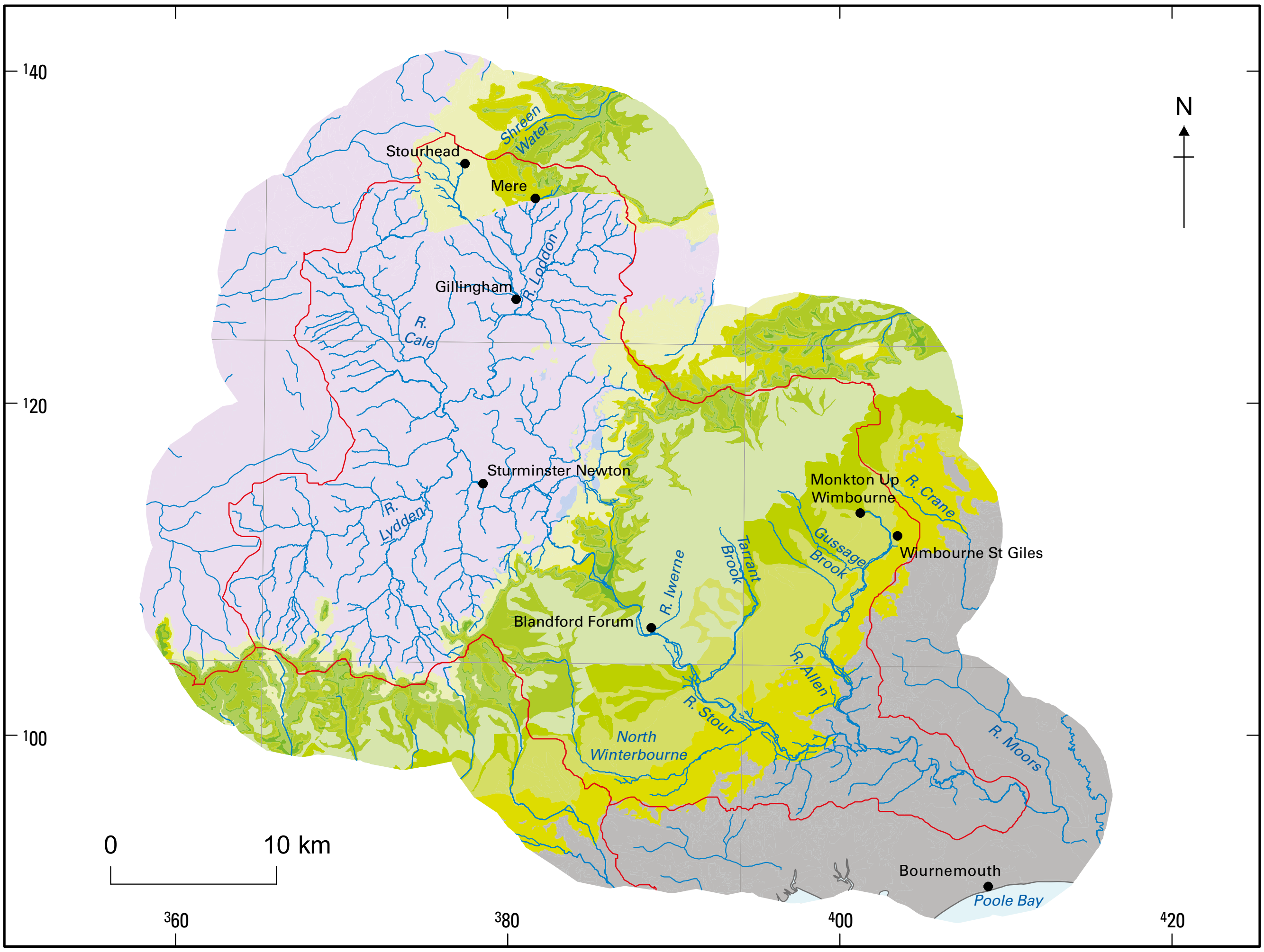

Figure 1.7 River Stour and River Allen catchment area (see Figure 1.1 for key).
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source of the Avon difficult to establish. Streams at Bishops Cannings are generally considered to comprise the source of the Western Avon, with the Eastern Avon rising near Easton Royal. From Upavon towards Salisbury, the Upper Avon meanders strongly over narrow meadowlands in a steeply confined valley and is joined from the east by the Nine Mile River north of Amesbury. There are numerous dry valleys, some of which contain springs. At Salisbury, there are confluences with the rivers Bourne and Wylye, which drain the Chalk of Salisbury Plain.

The River Wylye (Figure 1.8), with a catchment area of around 460 km^2, rises from Upper Greensand springs near Maiden Bradley. The Wylye is joined by two tributaries that originate on the Chalk of Salisbury Plain: the Chitterne Brook, which joins at Codford St Mary and the River Till, with a confluence at Stapleford. The River Till has its winter source near Tilshead some 12 km from its Wylye confluence (Halcrow, 1996).

The Wylye tributary is itself joined at Wilton, near to Salisbury, by the Nadder, a spring-fed river that drains the escarpment of the Chalk Downs of south Wiltshire and the Kimmeridge Clay of the Wardour Vale. The River Ebble, a small river, joins the Avon to the south of Salisbury and flows continuously downstream of Broad Chalke but behaves as a bourne above this point. Below Salisbury the valley widens, with several watercourses in places, but there are few towns near the riverbanks. Below Fordingbridge the Avon is joined by a number of tributary rivers that have their sources on the Palaeogene deposits of the New Forest area: these can contribute significant quantities of floodwaters. The Avon finally drains into Christchurch Harbour, where it is joined by the Stour and the Mude. The total catchment area of the Avon is approximately 1700 km^2, with a total fall from Pewsey to the sea of 110 m and with an average gradient south of Salisbury of 1:1000 (National Rivers Authority, 1994).

The River Bourne (Figure 1.8) drains the Chalk of the eastern edge of Salisbury Plain, forming a valley between the Avon to the west and the Test to the east. The river flows entirely over Chalk bedrock, rising in the north from springs in the lower formations of the Chalk Group. The River Bourne normally rises in winter near to Burbage and then flows south and south-west for over 40 km towards its confluence with the Avon at Salisbury. The river is perennial below major springs at Idmiston.

To the east of the Avon Catchment, the River Test (Figure 1.9) drains a large portion of the northern and north eastern area of the Wessex region. The River Test rises near the village of Ashe and flows south-west and then south across youngest formations of the Chalk Group to discharge at Southampton. There are a number of tributaries. The Test is joined by the Bourne Rivulet at Hurstbourne Priors and further downstream by the spring-fed Dever, Anton, Wallop Brook and Somborne Brook. Downstream of Mottisfont, the Test flows off the Chalk outcrop onto Palaeogene deposits.

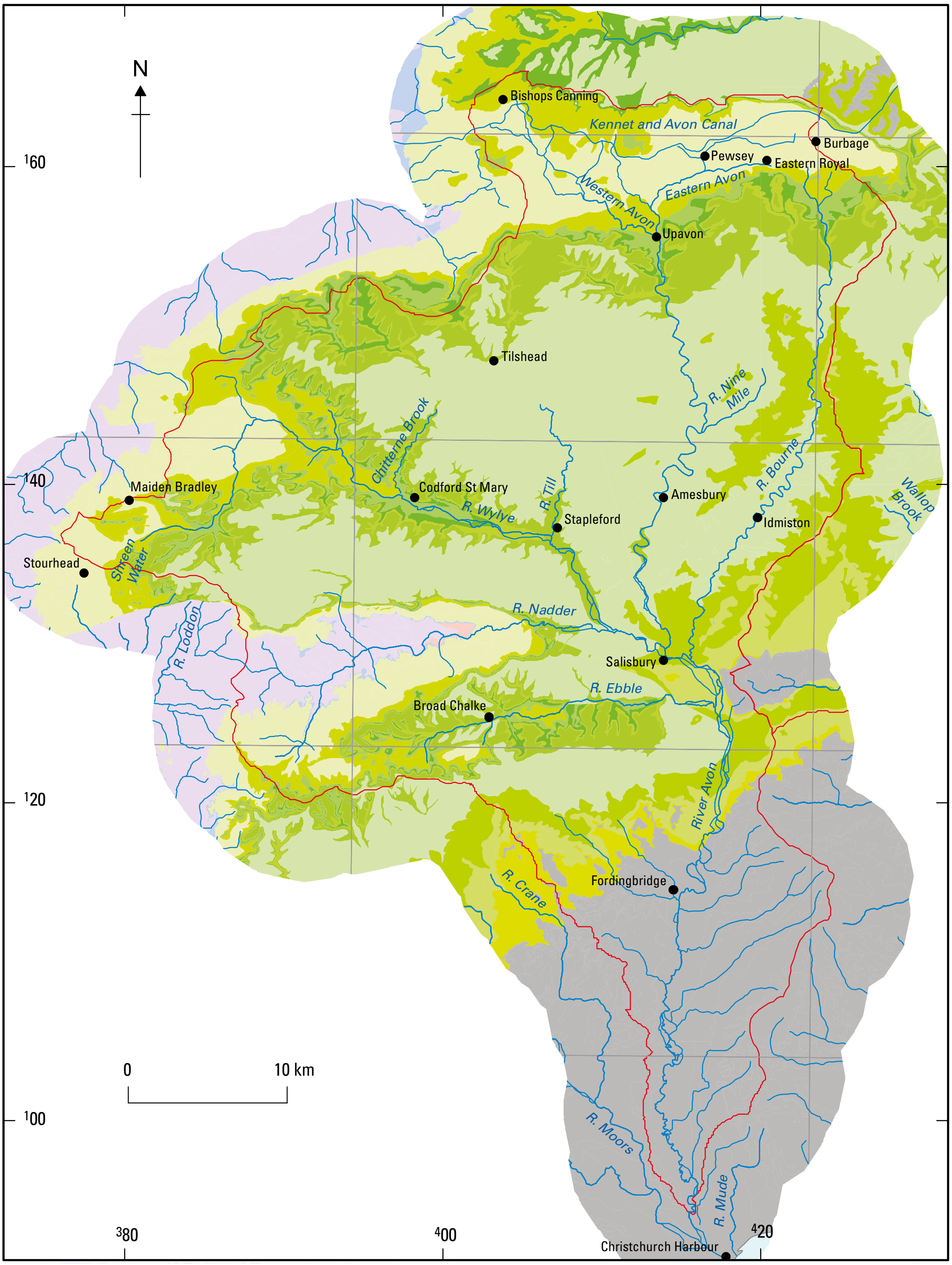

Figure 1.8 River Avon catchment area (see Figure 1.1 for key).

The River Dun joins the Test from the west just south of this point, and flows across both London Clay and the Chalk, receiving water both via Chalk baseflow and surface run-off from the clays. The River Blackwater joins the River Test south of Broadlands. Its catchment, founded on variable sand and clay strata of the Palaeogene, gives the stream a 'flashy' flow regime. The Test is not truly a natural river in its current form. Along most of its length, the river is split into two or more channels with sluices to regulate flows.

The River Itchen (Figure 1.10) rises on the Chalk near Alresford in the Hampshire Downs. Three tributaries feed the upper Itchen — the Candover Stream, the Cheriton Stream (also called Tichbourne) and the Alre. In general, the Candover Stream rises at Brown Candover and the Cheriton Stream normally rises at springs just south of Cheriton, however, the sources of both these tributaries recede in dry years (Entec, 2002). The Alre has three tributaries, two of which now start in watercress beds and fish farms where the natural spring flow of the river is supplemented by artesian or pumped borehole discharge. The third rises at a spring near Bishops Sutton which can run dry when groundwater levels are low.

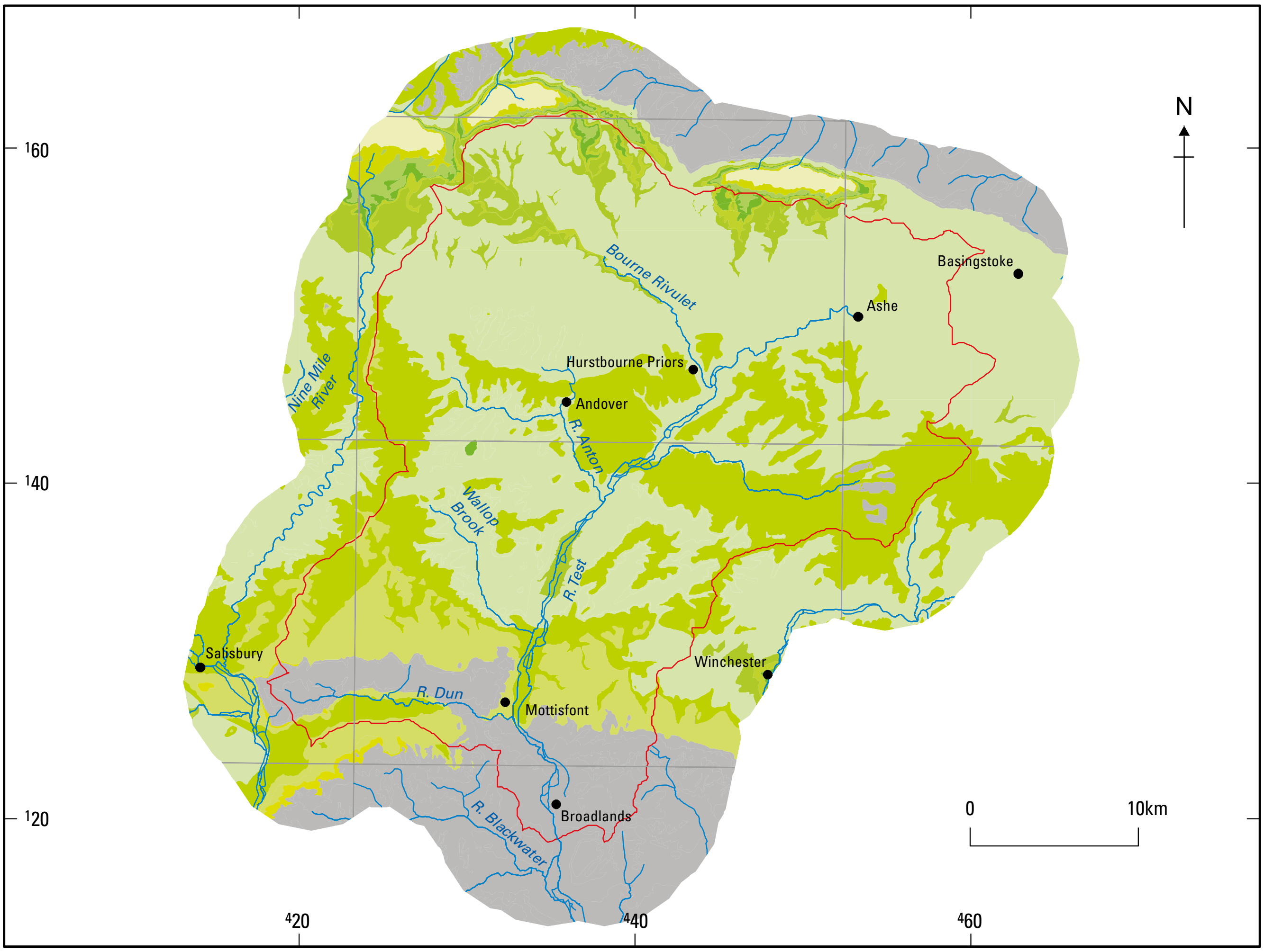

Figure 1.9 River Test catchment area (see Figure 1.1 for key).
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From the confluence of the Cheriton, Alre and Candover streams near Alresford, the River Itchen flows initially west and then it turns to flow south through Winchester to the edge of the Chalk outcrop at Otterbourne. The river then passes over Palaeogene cover through Eastleigh and Southampton towards its mouth on the north bank of Southampton Water. A further tributary, Monks Brook, which drains a mainly urban area, joins the Itchen just downstream of the tidal limit at Woodmill. For the majority of its length, the Itchen is divided between two or more separate channels that run parallel to each other. This is because of the past use of the river to provide water for milling, to supply water meadows, and for the development of navigation.

The area of the surface water catchment of the River Itchen to Otterbourne is approximately 360 km^2. However, the groundwater catchment extends significantly to the north-east (Entec, 2002) beneath the surface catchment of the River Wey (part of the extended River Thames Catchment) east of New Alresford. The larger size of the Chalk groundwater catchment that feeds the upper Itchen is reflected in high baseflows, particularly in the Alre.

The most easterly catchments of the Wessex Basin lie in Hampshire and are drained by the Rivers Meon, Hamble and Wallington, together with numerous other smaller tributary rivers that feed into the three large harbours of Portsmouth, Langstone and Chichester and into the Solent (Figures 1.5 and 1.11). The area extends from Emsworth and Hayling Island in the east to the Hamble estuary in the west. The River Meon is the longest and most significant river in the area and is sourced from Chalk springs near East Meon. The river initially flows north-west, and then west before turning south to cut through the downs towards the coast. The River Hamble rises near to the juction between the Palaeogene strata and the Chalk outcrop, as does the River Wallington and the two rivers to the east of Portsmouth, the Hermitage Stream and Lavant Stream. Dry valleys exist throughout the Chalk outcrop of the Hamble and Wallington catchments where run-off only occurs during exceptionally wet periods.

The two principal rivers of the Isle of Wight (Figure 1.11), the Medina and the Eastern Yar, originate at the south-east end of the island. The River Medina flows northward through a gap in the central downs and the Eastern Yar flows in a north/north-easterly direction, cutting through the Sandown Pericline at Brading. In addition, a number of smaller rivers drain the region, often rising on the Palaeogene deposits and running to discharge at the coast.

1.4.2 Winterbourne behaviour

A winterbourne is a stream that is commonly dry in its upper reaches in summer, while flowing over its maximum length in winter or early spring. This behaviour occurs when the stream is in good hydraulic continuity with an underlying aquifer and where the summer streamflow depends

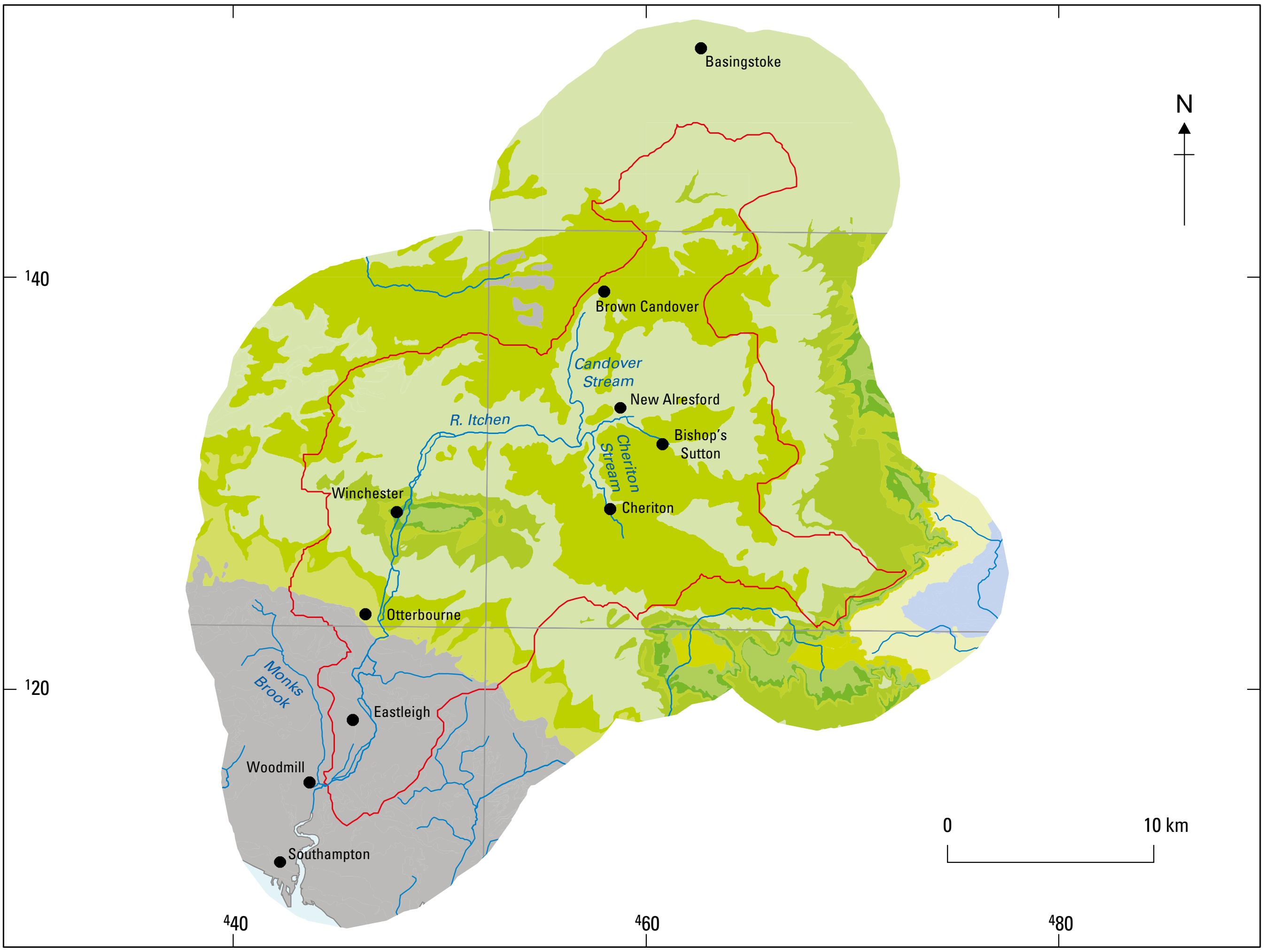

Figure 1.10 River Itchen catchment area (see Figure 1.1 for key).
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largely (perhaps almost entirely) on the contribution from groundwater. Thus as the water table in the aquifer rises and falls annually, so the stream lengthens and shortens along the river valley. Since, for a given amount of recharge, the annual variation in water table elevation is inversely proportional to the specific yield of an aquifer, the effect is particularly noticeable in streams fed by an aquifer having a low specific yield, such as the Chalk. Thus, in a classic winterbourne, the head of the stream would be expected to migrate in a predictable and relatively smooth manner upstream from its perennial location as groundwater levels rose, with the stream reaching its maximum length as groundwater levels peaked, and would then return in a predictable way to the perennial head position as the water table fell. It would also be expected that flow downstream from the migrating stream head would steadily increase as more groundwater discharge was accepted by the stream from the aquifer.

In fact, as is discussed in Chapter 3, many streams and rivers in the region do not follow the simple winterbourne model outlined above. In some rivers, for example the Piddle, flows increase downstream from the stream head, then commonly decrease over a section of the stream, before increasing again further down. In extreme cases, such as the River Bourne, the river often flows for a section, then dries, sometimes for a considerable length, then flows again further downstream (commonly at its perennial head). Some streams exhibit even more complex behaviour with, periodically, a succession of flowing and dry sections.

There are a number of possible causes for this complex behaviour. In some cases a local lowering of the water table, and concomitant reversal of effluent (gaining) streams to influent (losing) systems over certain reaches, may be caused by abstraction. Natural causes (principally lithological and karstic effects) are also likely to be involved, such as the influence of hardgrounds (see Section 3.2.2).

1.4.3 The development of drainage and landscape in Wessex

The drainage of the Wessex Basin originally consisted of a system of rivers flowing towards a longitudinal trunk stream that is now dismembered but formerly flowed along the basin axis from west to east, discharging to the south of the Solent. This drainage system parallels that of the larger London Basin as drained today by the Kennet–Thames. These two river systems, the former Frome–Solent system and the modern Kennet–Thames, are separated by a longitudinal watershed that runs broadly from west to east across the northern edge of Wessex towards the Weald. Today, almost all the Wessex region drainage is southwards towards the Frome–Solent and the English Channel (Figure 1.5). As a consequence, most of the major rivers flow across all the structural complexities of the basin.

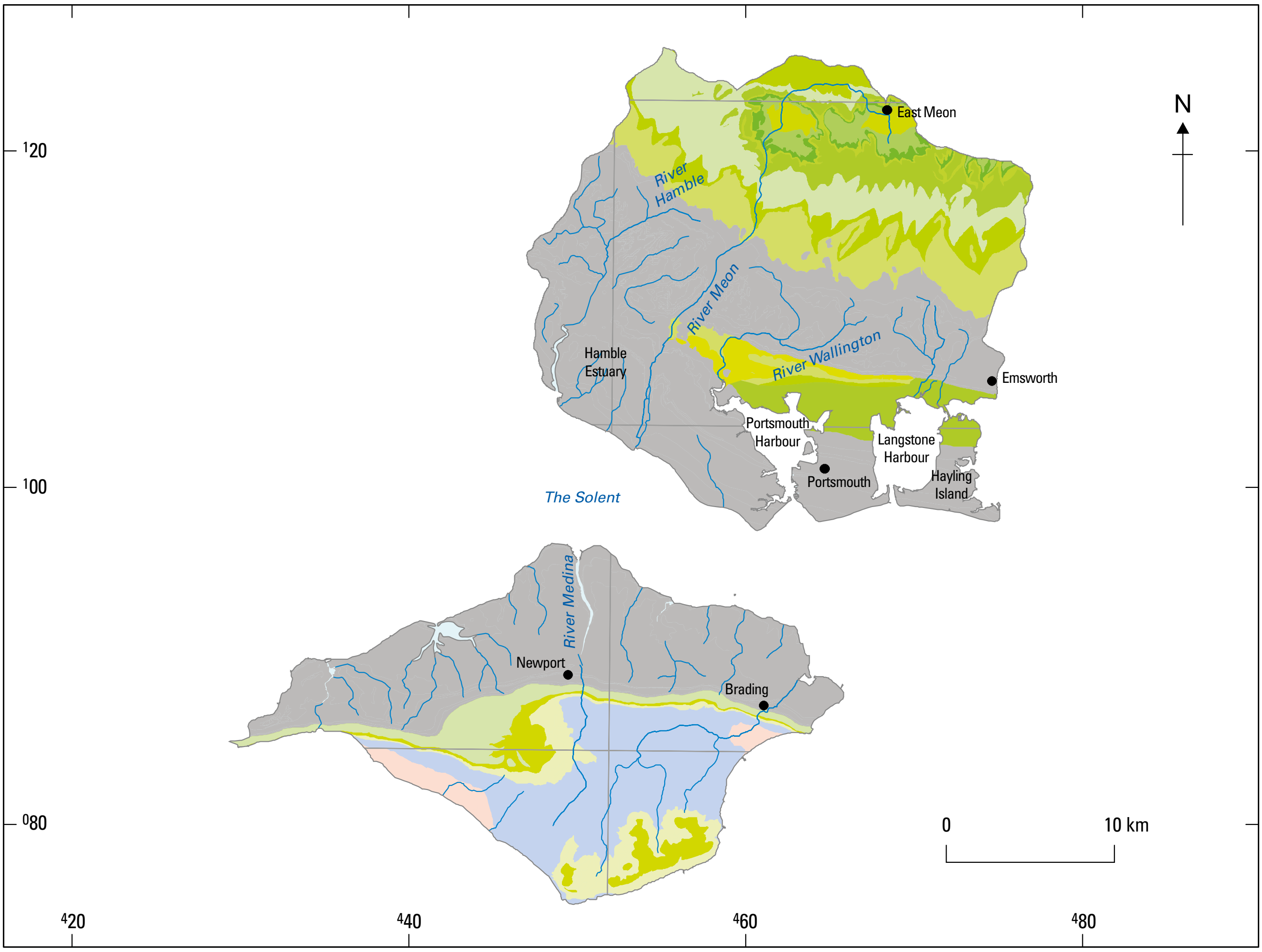

Figure 1.11 East Hampshire and Isle of Wight catchment areas (see Figure 1.1 for key).

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The geomorphology of the chalklands of southern England has been extensively investigated, but there is still great uncertainty related to the development of the landscape, and hence the underlying aquifer, in these areas (Jones, 1999). Wooldridge and Linton (1955) described the development of discordant drainage in the Wessex area as a series of discrete events as follows:

1. During the Miocene, rivers developed on the post-Alpine folded surface of the Chalk and broadly reflected the east–west trending fold and fault lineations in the underling Chalk.
2. The Pliocene sea inundated the uplifted Wessex uplands producing a peneplaned surface.
3. Following the Pliocene, the area was uplifted and a superimposed drainage developed on the tilted peneplaned surface. The drainage had a dominant southward direction and the distribution of rivers that developed on the peneplaned surface formed the basis of the present day drainage pattern.
4. As the superimposed drainage network developed, local accommodation of the river system led to some outgrowth of rivers into east–west tributaries. Trunk streams cut down into the Chalk and the water table fell. As the streams continued to cut down into the Chalk some lateral tributaries and eventually some main trunk streams dried up from perennial head downwards, leaving the system of rivers and dry valleys we see today.

More recently, however, such a simple model of landscape evolution has been questioned (Jones, 1999) on a number of grounds. For example, a model involving the development of anteconsequent streams rather than a 'superimposition model' is currently favoured. More importantly, from the viewpoint of aquifer development, instead of modelling landscape development as a series of discrete events Jones (1999) has emphasised the continuity of landscape (and by inference aquifer) evolution. He also notes that geological and geomorphological events often occur as pulses rather than distinct episodes, for example, pulsed uplift or sedimentation.

Finally, the concept of structural compartmentalisation into morphotectonic regions has been developed and Jones (1999) speculates that in southern England there may be evidence for up to 200 m of Pleistocene differential uplift. This is important as it removes the need for uniformity in landscape (and hence aquifer) evolution over large regions. Part of the cited evidence for compartmentalisation of chalklands into morphotectonic regions is the work of Edmonds (1983) and Farrant (2008) who described the distribution and density of karst features. Edmonds suggested that karst is more prone to development in areas where recent deposits are most extensive (e.g. the London Basin) and where erosion surfaces between the Chalk and overlying deposits are preserved, and are least developed where superficial deposits are generally thin and where erosion surfaces are relatively poorly preserved due to dissection. Jones (1999) notes that the Pewsey–London Platform inversion appears to be an important structural divide separating the London Basin from the Wessex Basin and may mark the boundary between two areas with differential Pleistocene uplift.

1.5 DEMOGRAPHY

The demography of the Wessex region is largely controlled by land use and, particularly along the coast, by the tourism industry. There are a number of towns and cities with populations exceeding 100 000 people (Table 1.2).

The population of Dorset is 390 986 (2001 Census). Outside the main towns of Bournemouth, Poole, and Weymouth, many people live in small towns with populations of around 10 000. The largest agricultural centres of the district are centred around Shaftesbury, Blandford Forum, Dorchester and Salisbury in Wiltshire. There has been substantial urban development along the coastline in response to demands from the tourist industry, concentrated in the four districts of Christchurch, Bournemouth, Poole and Weymouth and Portland.

The population of Hampshire is 1 240 032 (2001 Census). The most significant centres of population are along the coast, principally Southampton, which is an important English Channel port, and Portsmouth, a major naval base. Inland, important centres are Winchester, Andover, Basingstoke, Farnborough and Aldershot.

The resident population for the Isle for Wight is 132 719 (2001 Census). This figure approximately doubles in the summer holiday season. The main towns of Ryde, Newport and Cowes are located along the coast or rivers.

Table 1.2 Some of the main towns and cities of Wessex and their populations based on the 2001 Census (www.statistics.gov).

Location	Population
Weymouth and Portland	63 665
Bournemouth	163 441
Poole	138 229
Salisbury	114 614
Basingstoke and Deane	152 583
Winchester	107 213
Southampton	217 478
Portsmouth	186 704

1.6 WATER USAGE AND THE IMPORTANCE OF GROUNDWATER

Water usage varies across the region but includes agriculture, public water supply, spray irrigation, industry, private domestic supply, gravel washing, fish farming and watercress production. Most of the licences are for agricultural practises such as farming and spray irrigation, but these are for relatively small volumes compared to public supply. For example in the Test and Itchen catchments, industry and agricultural uses combined made up only three per cent of the total volumes licensed, despite a large number of abstraction licences (Environment Agency, 1999a).

A large proportion of the abstraction licences across the Wessex Basin are for groundwater, underlining the fact that the Chalk is the most important aquifer in Britain and in particular in southern and eastern England, supplying over half the nation's groundwater-abstracted drinking water. In the Wessex region groundwater provides a major source of water used for both public and private supplies. For example in the Stour and Allen catchment, groundwater comprises 49 per cent of the total annual licensed abstractions (Environment Agency, 1997); similarly in the Avon catchment groundwater makes up approximately 45 per cent of the total (Environment Agency, 1998a). On the Isle of Wight, an area which has historically suffered from water supply problems, 68 per cent of the total licensed abstractions are from groundwater (Environment Agency, 2003). In the East Hampshire CAMS area groundwater accounts for 98 per cent of all licensed abstraction (Environment Agency, 2002a).

The majority of groundwater sources used for water supply are sited along the river valleys in the Wessex Basin, both because of the shallower depth to the water table in these locations and as a result of the tendency for the Chalk aquifer to have higher values of transmissivity in valleys. Groundwater is used widely across the basin for both private and public water supplies, with the volumes abstracted for public water supply significantly exceeding other abstractions. For example on the Isle of Wight 86 per cent of all licensed groundwater abstractions are for public water supply (Environment Agency, 2003). Of the groundwater abstracted only 1.5 per cent is used for agriculture and 1.4 per cent for industry. (Environment Agency, 1999b).

2 Geology

2.1 INTRODUCTION

2.1.1 Basin structure

The Wessex Basin comprises a series of structurally controlled sedimentary basins and intrabasinal highs filled with strata of Permian to Cretaceous age and covers southern England and adjacent offshore areas (Underhill and Stoneley, 1998). Onshore, the geographical region, also termed the Wessex Basin, covers an area of Hampshire and Dorset together with parts of east Devon, Somerset and Wiltshire and this approximates to the ancient Kingdom of the West Saxons. The geological units present in this basin were affected by later tectonic events of mid-Miocene age. The present structural configuration results from two main tectonic stages in the history of the Wessex Basin (Chadwick, 1993):

1. During the Permian to Early Cretaceous, sub-basins were subsiding and infilling with sediment under a regime of regional crustal extension. Initially driven by differential block faulting, the subsidence became thermally driven and more regional during the Cretaceous. Apart from a few local variations, the Chalk was deposited as a uniform blanket across the central parts of the basin.
2. During the Cenozoic, crustal extension was replaced by south to north-directed compression related to the Alpine mountain building event. Sedimentary rocks that had accumulated within the basins were pushed upwards as the movement on bounding faults changed from normal to reverse. Compression led to the development of east–west trending folds.

The distribution of the chalk within the Wessex region and the Palaeogene preserved in the Hampshire Basin syncline are shown in Figure 2.1. The geographical distribution, geological structure and geomorphology of the Chalk is largely a function of Cenozoic compression and folding and erosion up to the present day. The exposed Chalk uplands to the north of the Palaeogene lowlands of the Hampshire Basin are broadly anticlinal in structure. However, the detailed morphology of this area owes much to the existence of numerous subsidiary fold axes of Tertiary age, and developed as reactivations of older structures, including the Wardour, Dean Hill and Portsdown anticlines, which are offset along a diagonal belt (Figures 2.1 and 2.2). The Hampshire Basin syncline preserves a thick succession of Palaeogene strata and overlies the similarly folded Chalk. The conspicuous variation in the outcrop width of the Chalk reflects structural control, with a narrow ridge developed where dips approach vertical along the Purbeck–Isle of Wight Monocline and broader cuestas formed where regional dips are shallow.

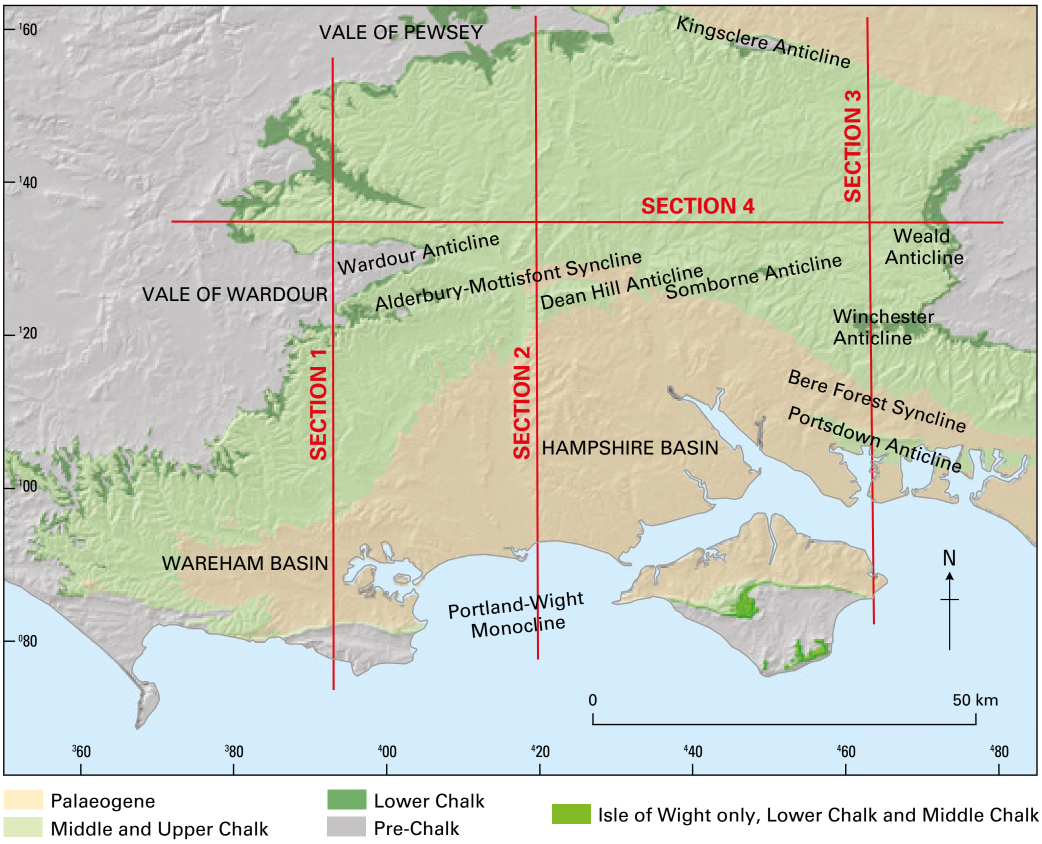

Figure 2.1 Geology of the Wessex Basin showing the locations of cross-sections. *contains OS data © Crown copyright and database rights 2017 Ordnance Survey [100021290 EUL]. Use of this data is subject to terms and conditions.*

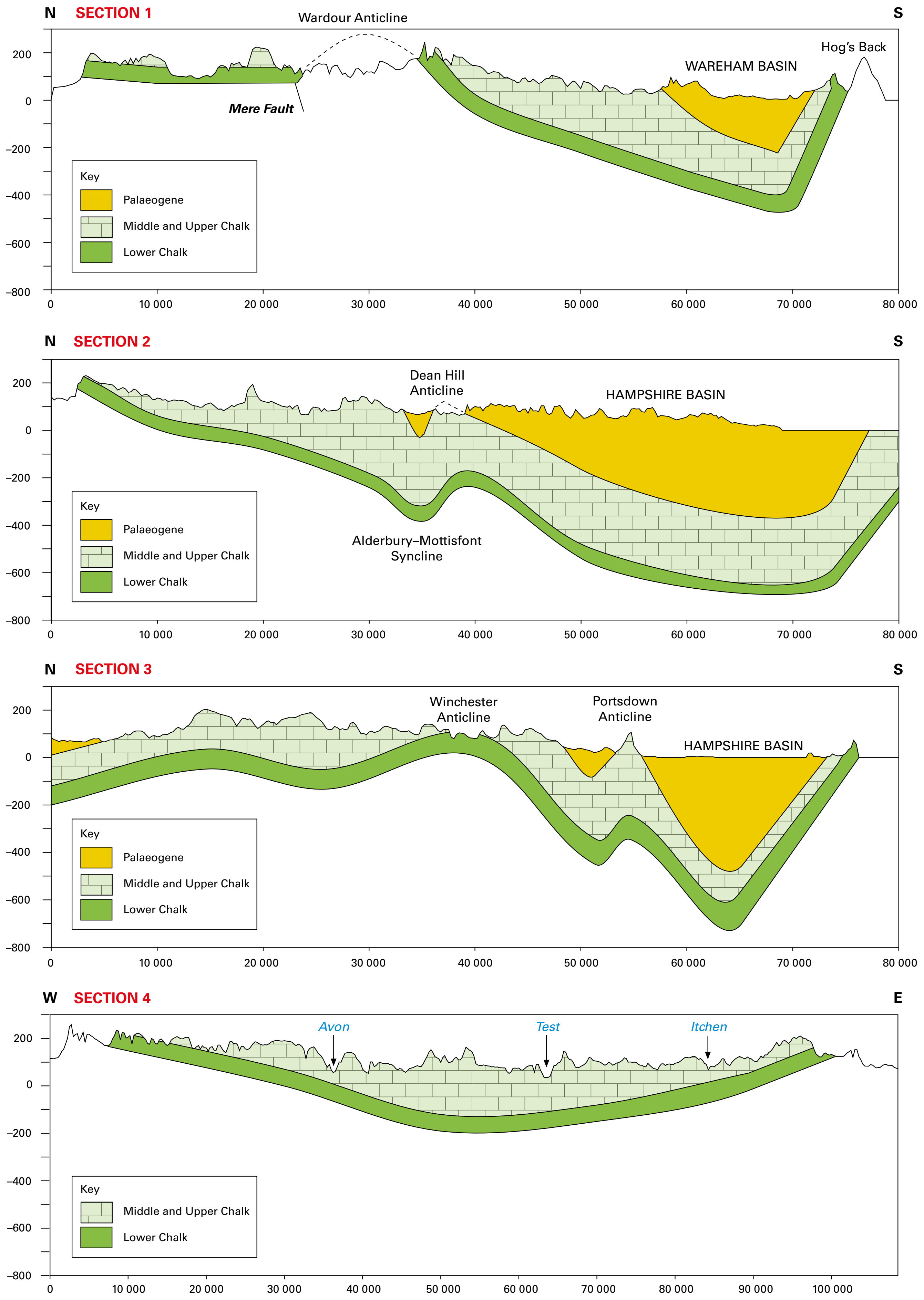

Figure 2.2 Geological cross-sections through the Wessex Basin (vertical axis metres AOD, horizontal axis metres). For locations see Figure 2.1.

Table 2.1 Chalk stratigraphy of southern England (after Bristow et al., 1997).

Stage	Traditional southern England subdivisions *		Southern England Hopson (2005)	
Campanian (pars)	Upper Chalk		White Chalk Subgroup	Portsdown Chalk Formation
Campanian (pars)	Upper Chalk		White Chalk Subgroup	Culver Chalk Fm: Spetisbury C M
Campanian (pars)	Upper Chalk		White Chalk Subgroup	Culver Chalk Fm: Tarrant Chalk Member
Santonian	Upper Chalk		White Chalk Subgroup	Newhaven Chalk Formation
Coniacian	Upper Chalk		White Chalk Subgroup	Seaford Chalk Formation
Coniacian	Upper Chalk	Top Rock	White Chalk Subgroup	Lewes Nodular Chalk Formation
Turonian	Upper Chalk	Chalk Rock	White Chalk Subgroup	Chalk Rock Member
Turonian	Middle Chalk	Spurious Chalk Rock	White Chalk Subgroup	New Pit Chalk Formation
Turonian	Middle Chalk	Melbourn Rock	White Chalk Subgroup	Holywell Nodular Chalk Formation (Melbourn Rock Member)
Cenomanian U	Lower Chalk	Plenus Marls	White Chalk Subgroup	(Plenus Marls Member)
Cenomanian U/M	Lower Chalk	Grey Chalk	Grey Chalk Subgroup	Zig Zag Chalk Formation
Cenomanian M/L	Lower Chalk	Chalk Marl	Grey Chalk Subgroup	West Melbury Marly Chalk Formation
Cenomanian L	Lower Chalk	Glauconitic Marl	Grey Chalk Subgroup	(Glauconitic Marl Member)
Upper Albian (pars)	Upper Greensand		Upper Greensand	

*Traditional Chalk subdivisions after Jukes-Browne and Hill (1903, 1904, for example)

2.1.2 Chalk Group

For nearly a century following Jukes-Browne and Hill (1903; 1904) the Chalk of southern England had a simple threefold lithostratigraphy with Lower, Middle and Upper divisions. Today the Chalk Group of southern England is divided into nine laterally persistent formations that are defined on the basics of contrasting, subtle lithological variations and give rise to broad topographical features in the landscape. The distribution of these formations can be further justified on the basis of their included macro-and micropalaeontology and by characteristic downhole geophysical log traces (Bristow et al., 1997; Rawson et al., 2001; Hopson, 2005). The terms Lower, Middle and Upper Chalk are abandoned in the most modern scheme (but see Bristow et al., 1997) but are still used in the literature as a 'convenient' shorthand. In this report, while the new stratigraphical nomenclature takes precedence, the old informal names are frequently employed. This is necessary, principally because the historical hydrogeological studies on which much of the report is based used the old nomenclature, and to a minor extent because a limited area still remains to be surveyed

BOX 1 CHALK COMPOSITION

Chalk is a white to greyish white, very fine-grained, microporous limestone. It is composed predominantly of coccoliths (microscopic, calcareous skeletal remains of planktonic algae), but coarse-grained, bioclastic material derived from bivalves, echinoderms and other shelly invertebrates is also present, although this typically forms less than 10 per cent of the Chalk (Hancock, 1993). Further lithological variation in the Chalk is produced by the inclusion of:

Marly Chalk and marl seams. Marly Chalk is a mixture of chalk and clay, while marl seams are more horizon-specific concentrations of clay.

Nodular chalks and chalkstones. Chalks display a continuous range of lithification from discrete nodules of hard chalk through to fully lithified chalkstone.

Omission surfaces. Unlithified 'discontinuity surfaces' are identified by contrasts in colour and texture between successive sediments and are usually penetrated by Thalassinoides burrows.

Hardgrounds. Fully lithified omission surfaces are called hardgrounds and are characterised by the presence of borings and encrusting organisms and green glauconitic or brown phosphatic mineralisation. Surface morphology can be planar, hummocky or convolute. Nodular chalks and hardgrounds are products of early diagenetic cementation that took place just beneath the seafloor and are generally associated with reduced sedimentation rates or hiatuses. They are best developed in thin basin-margin successions in the northwest of the Wessex Basin.

Flints. Flints form a continuum from nodules to more or less continuous sheets. They also occur in a range of styles including paramoudra, Zoophycos, sheet flint and the common thalassinid horn-flints.

BOX 2 GEOPHYSICAL PROPERTIES OF THE CHALK

A significant amount of geophysical logging has been undertaken in the Wessex Basin, principally for oil and gas exploration, geothermal investigations and water boreholes. It is possible to subdivide the Chalk lithostratigraphically based on the gamma ray, sonic and resistivity log profiles. The example shown in Figure 2.3 shows some of the main properties.

- The clayey Grey Chalk Subgroup, below the Plenus Marls, has high gamma-ray values relative to the White Chalk Subgroup where the gamma-ray values are low and uniform. The upward decreasing clay and silt content as the West Melbury Marly Chalk passes into the Zig Zag Chalk is usually clearly expressed as a steady decrease in gamma-ray values.
- Conspicuous peaks in the gamma-ray log occur at the Glauconitic Marl and Plenus Marls and, where well-developed, the Chalk Rock Hardgrounds at the base of the Lewis Nodular Chalks. The thicker marl units can generally be detected by a coincidence of the higher gamma-ray values and lower sonic velocities.

The Holywell Nodular and Lewis Nodular chalks have a significantly higher sonic velocity than the other chalk formations. In the White Chalk Subgroup there is generally an overall decrease in sonic velocity corresponding to the tendency of softer Chalks to occur towards the top. The curve is moderately serrated, however, reflecting the alternation of hard and soft chalks with interbedded marls and flints. In general, the resistivity curve follows that of the sonic log.

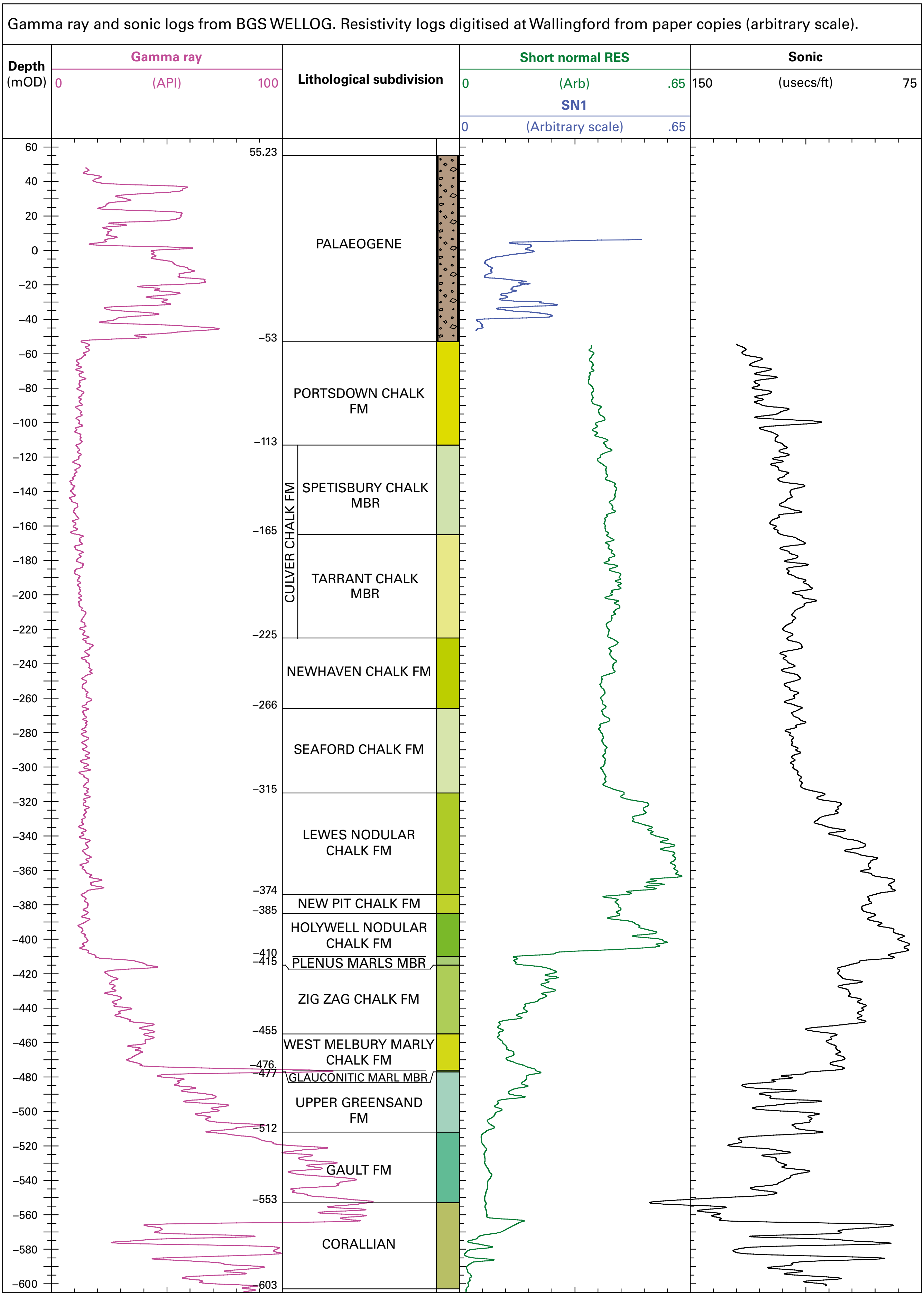

Figure 2.3 Geophysical logs showing the stratigraphical subdivision of the Chalk, Wessex Basin.

using the new system. Table 2.1 shows the relationship between the old and new terms. Where possible the new stratigraphical divisions are shown on Figures 1.6 to 1.11.

The principal subdivision into two subgroups is made at the base of a prominent mudstone interval, the Plenus Marls Member. Below the Plenus Marls, the Grey Chalk Subgroup (Lower Chalk) comprises thin argillaceous and marly grey and greyish white chalks, while the overlying White Chalk Subgroup (Middle and Upper Chalk) comprises thick units of white and nodular chalks with or without flints (Table 2.1 and Box 1).

2.1.3 Chalk thickness variation

The thickness of the Chalk Group varies depending on the original sedimentation conditions and the scale of post-Cretaceous erosion. A maximum of 473 m of Chalk has been recorded beneath Palaeogene sediments in the Hampshire Basin (in the Lymington Borehole [SZ 30 96]), however, even below this protective cover there is significant variation partly related to pre-Palaeogene erosion that removed the youngest Chalk formations. At outcrop to the north of the Hampshire Basin, the Chalk is generally less than 300 m thick, thinning progressively toward the primary escarpment as the erosion level cuts deeper into the stratigraphy. This general pattern is complicated by thinning over anticlinal axes in the centre of the basin (e.g. the Winchester Anticline), cumulating in the total removal of Chalk over the Weald and Wardour anticlines (Figure 2.4)

Comparison of geophysical logs (see Box 2) from deep boreholes demonstrates a general regional thinning of a number of the constituent formations from Sussex north and westward into Hampshire and Wiltshire, reflecting the move from basinward thicker successions in the south to areas characterised by thinner 'shelf' deposition. Figure 2.5 shows the thickening of the Chalk units from the Wessex shelf to the Sussex trough.

2.2 CHALK GROUP LITHOSTRATIGRAPHY

2.2.1 Grey Chalk Subgroup

The Grey Chalk Subgroup, with the exclusion of the Plenus Marls Member, is broadly equivalent to the Lower Chalk of the traditional scheme. Where fully developed, the Grey Chalk Subgroup is divided into two formations, a lower, West Melbury Marly Chalk Formation and an upper, Zig Zag Chalk Formation. In the field, the boundary between the two units is marked by a sharp negative break in slope with the more resistant Zig Zag Chalk being relatively upstanding compared with the more easily weathered, softer West Melbury Marly Chalk below.

Throughout most of the Wessex Basin, the base of the Chalk Group is traditionally taken at the base of the Glauconitic Marl. However, in south-west Wiltshire the hiatus is marked by glauconitic calcareous sandstones and the base of the Chalk Group is taken at the base of the marl-poor Melbury Sandstone Member that is the local equivalent of the Glauconitic Marl Member. Over the 'Mid Dorset Swell', the West Melbury Marly Chalk is absent and the base of the Chalk Group is diachronous and coincides with the Cenomanian Basement Bed.

In the west, the thickness of the Lower Chalk ranges from 26 m at Batcombe to over 70 m in the Salisbury area, but for the most part, the thickness is between 40 and 50 m. The formation is up to 90 m thick east of Winchester and up to 95 m thick on the scarp overlooking the Weald in the Alresford area.

2.2.1.1 West Melbury Marly Chalk Formation

The West Melbury Marly Chalk consists of rhythmically layered alternations of off-white to creamy marls, greyish Chalks and pale grey to brown limestones. The top of the member is taken at the top of the Tenuis Limestone where

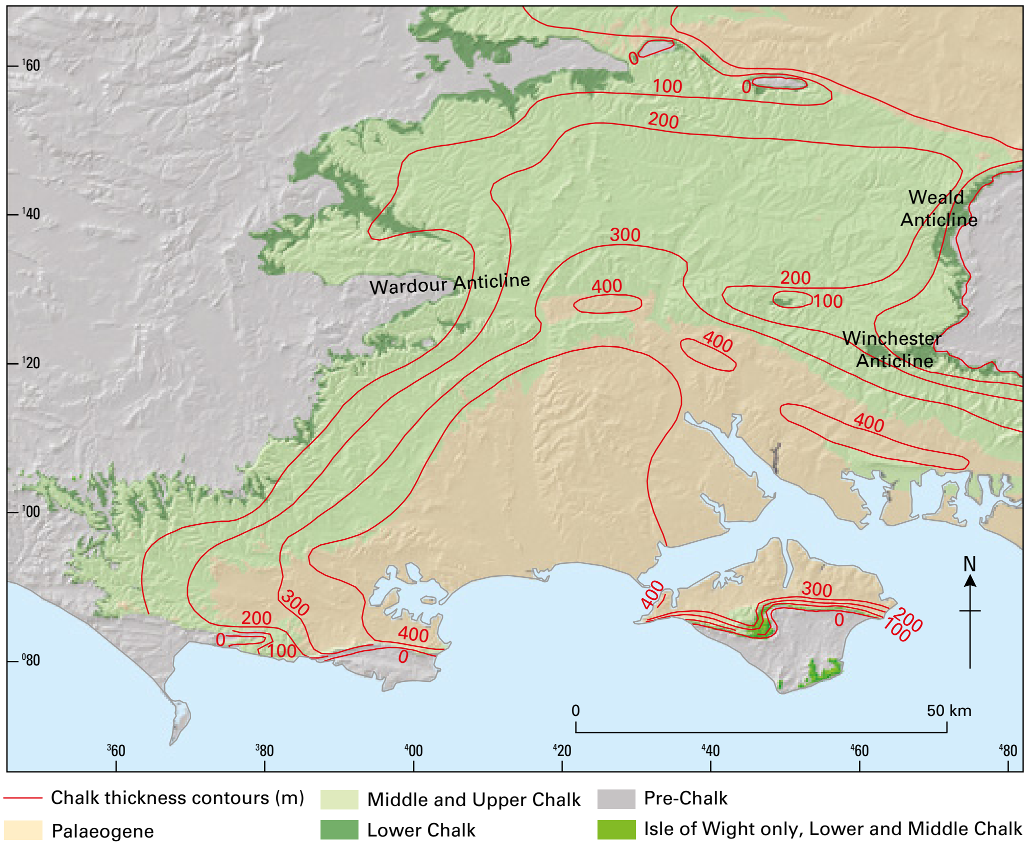

Figure 2.4 Chalk thickness (metres) in the Wessex Basin. *contains OS data © Crown copyright and database rights 2017 Ordnance Survey [100021290 EUL]. Use of this data is subject to terms and conditions.*

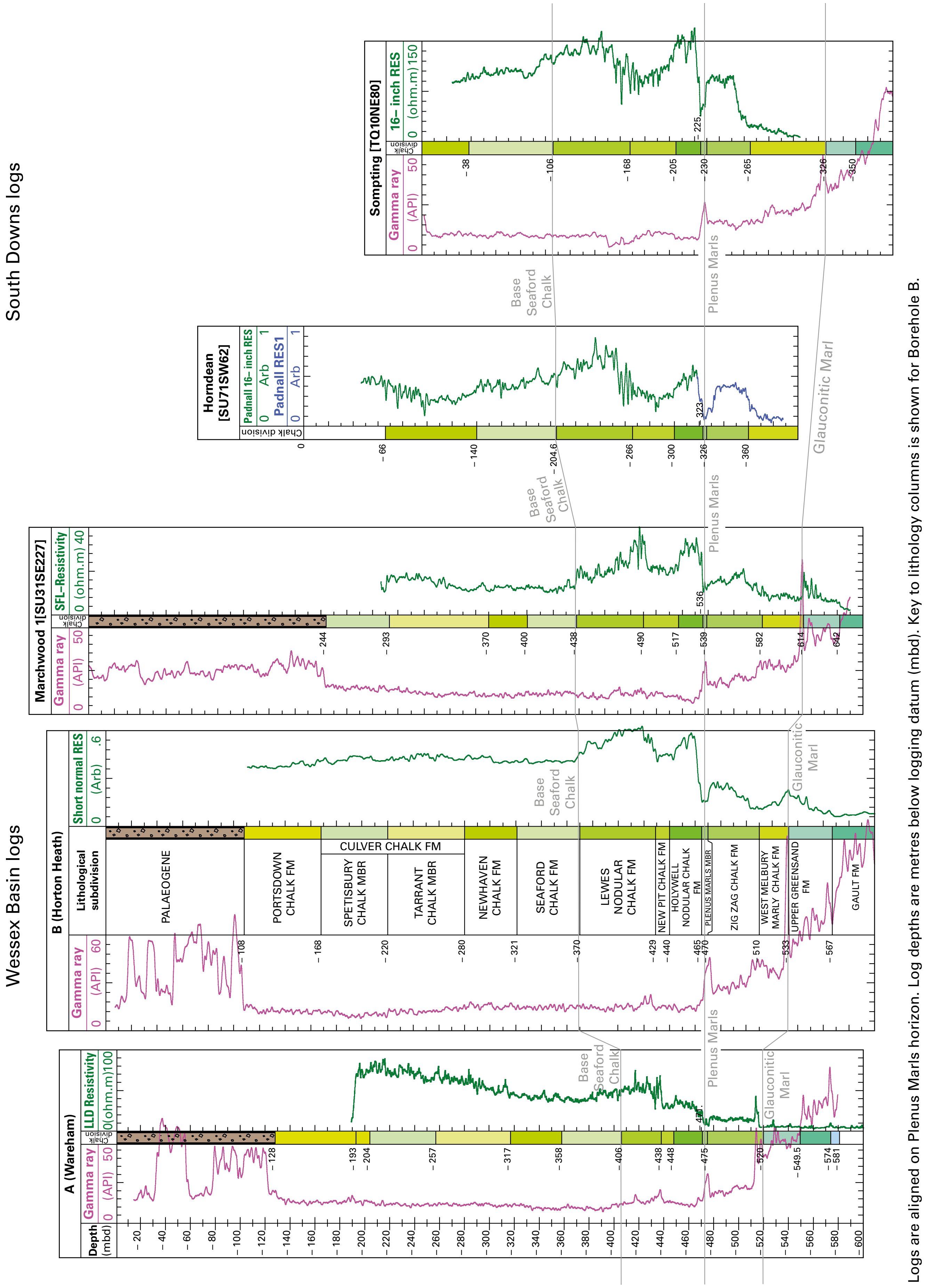

Figure 2.5 Gamma ray and resistivity logs showing expansion of Chalk units from the Wessex Basin to Sussex (after Bristow et al., 1997).

this is present, or at the erosion surface beneath the Coast Bed of the overlying Zig Zag Chalk Formation. The West Melbury Marly Chalk is absent over the Mid Dorset Swell, where it is represented within a phosphatic, ammonite-rich conglomerate (Cenomanian Basement Bed or 'Bookham Conglomerate') at the base of the overlying Zig Zag Chalk.

2.2.1.2 Zig Zag Chalk Formation

The Zig Zag Chalk comprises soft to medium hard, greyish blocky chalk with marl–limestone rhythms in the lowest part. The base of the formation is placed at the base of the Cast Bed that overlies the preceding Tenuis Limestone in full successions; the base of the Plenus Marls Member marks the top. The Plenus Marls are present along the whole outcrop of the Lower Chalk. They range from 2 to 6 m thick and consist of an alternating sequence of blocky, white chalks and silty marls up to 0.5 m thick (Bristow et al., 1995). The marls give a high gamma-ray response and are readily recognisable on geophysical logs.

The Zig Zag Chalk ranges from 20 m thick in south Dorset to 75 m thick in the east of the basin around Winchester. The lower part of the Zig Zag Chalk was not deposited over the Mid Dorset Swell and the formation rests unconformably on the pitted and phosphatised top of the Upper Greensand; its base is marked by the Cenomanian Basement Bed (Drummond, 1970) on the coast, which is the equivalent of the Bookham Conglomerate of the Shaftesbury district (Bristow et al., 1995).

2.2.2 White Chalk Subgroup

The White Chalk comprises white chalks and nodular chalks, with or without flints, divided into seven formations. It encompasses the traditional Middle and Upper Chalk with the addition of the Plenus Marls Member at the base. The Holywell Nodular Chalk and smooth chalks of the New Pit Chalk form a readily identifiable succession across the whole of southern England. These two formations, which are generally flint free, are for the most part equivalent to the Middle Chalk. The Lewes Nodular Chalk and younger smooth white chalk (Seaford to Portsdown) without significant flint and marl seams are equivalent to the Upper Chalk of the traditional scheme.

In Dorset, the Middle Chalk maintains a fairly constant thickness of 25 m, thickening eastwards to 65 m east of Winchester and up to 80 m on the western scarp of the Weald. The Upper Chalk is thickest in the south of the Wessex Basin, where it is up to 365 m thick. The general northwards and north-eastwards thinning is mostly a result of pre-Palaeogene erosion. The Upper Chalk forms two prominent outward-facing escarpments around much of the outcrop.

2.2.2.1 Holywell Nodular Chalk Formation

The Holywell Nodular Chalk comprises hard nodular chalks with abundant shell debris and greyish green wispy (or flaser) marl seams separating the nodules. The Melbourn Rock Member and the Plenus Marls Member form the base of the Holywell Nodular Chalk. The Melbourn Rock forms a marked lithological contrast to the underlying Plenus Marls and is one of the easiest of the Chalk boundaries to map in the field and to recognise on geophysical logs. The Holywell Nodular Chalk thickens across the basin from 15 m at the western outcrop to 35 m in the east.

2.2.2.2 New Pit Chalk Formation

The New Pit Chalk comprises smooth, firm, white chalks with marl seams. The upper part of the newly defined New Pit Chalk includes the Glynde Marls, which are of great value for identifying the top of the New Pit Chalk on geophysical logs. The New Pit Chalk is 10 to 16 m thick in the west and up to 45 m in the east of the basin.

2.2.2.3 Lewes Nodular Chalk Formation

The Lewes Nodular Chalk comprises hard to very hard nodular chalk and hardgrounds with interbedded soft to hard gritty chalks. The base of the Chalk Rock Member within the Lewes Nodular Chalk is the traditional base of the Upper Chalk. However, strong nodularity and flint seams occur lower in the succession, in the thicker, basinal parts of the Wessex Basin, and the base of those units forms the base of the Lewes Nodular Chalk.

The basal Lewes Nodular Chalk becomes condensed towards the western margin of the depositional basin and the nodular chalks are replaced progressively by chalkstones, mineralised hardgrounds and marl seams of the Chalk Rock which are best developed in Wiltshire, Berkshire and the Chilterns (Bromley and Gale, 1982). Individual hardgrounds within the Chalk Rock are recognisable by hardground surface morphology and colour and have been named and correlated over large areas by Bromley and Gale (1982). Hardgrounds at the base of the Chalk Rock (Ogbourne and Pewsey hardgrounds) are present across much of the western Wessex Basin in Wiltshire, Dorset and Hampshire, while those at the top (Fognam and Hitch Wood hardgrounds) show a significant geographical shift to the north and east (Figure 2.6).

The Hope Gap Hardground occurs 5 to 10 m above the top of the Chalk Rock; it is another well-developed hardground (the 'Upper Rock' of White, 1923), but not so strongly mineralised and correlates with the Top Rock of East Anglia. The Top Rock/Hope Gap Hardground is succeeded by up to 30 m of hard, nodular flinty chalk and chalkstone, locally porcellanous, but with some interbeds of firm, white chalk. The nodularity and hardness decrease upwards and there is a transitional zone of a metre or two with the overlying Seaford Chalk.

The Lewes Nodular Chalk is about 25 to 40 m thick over much of the Wessex Basin, but reaches a thickness of 50 m near Blandford Forum. In the Wytch Farm boreholes, the thickness varies from 20 to 26 m. In the Winchester, Fareham and Alresford districts, the Lewes Nodular Chalk is estimated to be 60 to 65 m thick. At the western end of the Isle of Wight, the thickness is about 40 m.

2.2.2.4 Seaford Chalk Formation

The Seaford Chalk is a firm, white, flinty chalk with few marl seams (except near the base), overlain by similar chalk with common marl seams, the Newhaven Chalk. At the type locality in Sussex, the base of the Seaford Chalk is taken at the base of Shoreham Marl 2 (Mortimore and Wood, 1986). Conspicuous, semi-continuous bands of large nodular flints are a feature of this member. The member consists of at least 80 m of firm, white chalk with regular courses of flint nodules. Flints in the basal part of the member are typically carious. The upper boundary is delimited upwards by the entry of marl seams marking the base of the succeeding Newhaven Chalk. In a limited area south of Dorchester, however, the succession differs, perhaps reflecting the continuing influence of the Mid Dorset Swell structure and the undivided Seaford and Newhaven Chalk, together with part of the Tarrant Chalk, consists of an alternating sequence of hard, nodular chalk and firm, blocky chalk. In that area, the three units have not been separated and are mapped as one unit, the so-called Blandford Chalk.

Figure 2.6 Distribution of hardgrounds in the Chalk Rock in the Wessex Basin (after Bromley and Gale, 1982.

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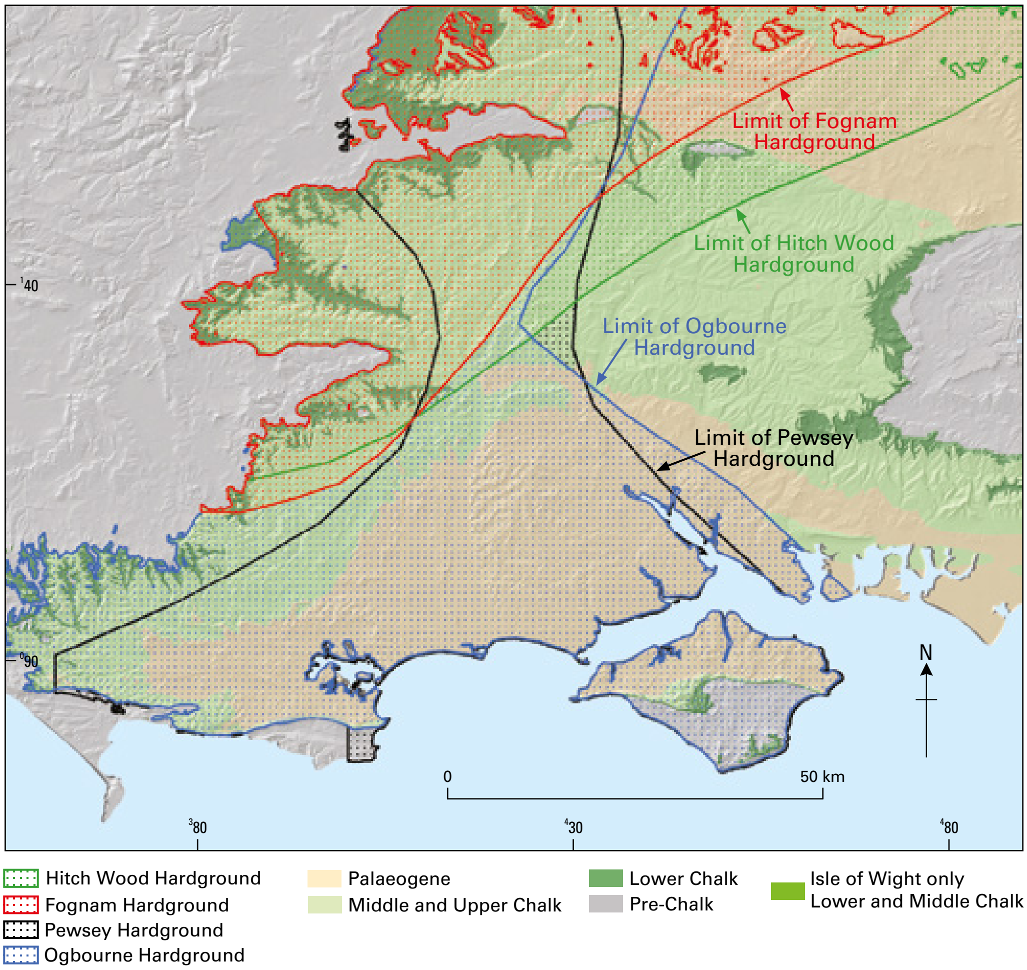


2.2.2.5 Newhaven Chalk Formation

The Newhaven Chalk is a unit of firm, white, predominantly marly chalk with widely spaced flints and common marl seams. At the type locality at Seaford Head, Sussex, the base is taken at the base of Buckle Marl 1 (Mortimore and Wood, 1986). This stratotype section, however, is situated close to a positive feature where marl seams are either relatively poorly developed or may virtually disappear (Mortimore and Wood, 1986). In trough areas, such as around Salisbury and Brighton, not only are marl seams better developed, but additional strong marl seams occur higher in the sequence (Mortimore, 1983; Mortimore and Wood, 1986). In such situations, the upper limit of the Newhaven Chalk is sharply defined both in field sections and in boreholes. In the field, the base of the member is taken at a negative feature break. Locally (western side of the Dorchester district) the boundary between the Seaford and Newhaven Chalks is taken at a positive feature within the *Marsupites testudinarius* Zone (Westhead, 1992) even though the base of the Newhaven Chalk is at a slightly higher level than in the type area. In south Dorset and in particular the coastal exposures, the Newhaven Chalk is commonly nodular and has only weakly developed marl seams. South of the Purbeck–Isle of Wight Monocline in Dorset, the chalk is extremely hard. The Newhaven Chalk ranges from 40 to 80 m thick.

2.2.2.6 Culver Chalk Formation (Tarrant Chalk Member)

The Tarrant Chalk comprises firm, white chalk with relatively widely spaced, large flint bands. Along the Purbeck structure, the steeply dipping Tarrant Chalk is extremely hard and has not been distinguished lithologically from the Newhaven Chalk below or the Spetisbury Chalk above. South of Dorchester, the succession differs. There, the Tarrant Chalk consists of an alternating sequence of hard, nodular and firm, blocky chalk that has not been separated from the combined Seaford and Newhaven Chalk. The thickness of the Tarrant Chalk is mostly in the range 50 to 60 m, but in the east, in the Fareham district, the thickness is only 30 to 40 m. At outcrop at the western end of the Isle of Wight, the member is about 36 m thick, but appears to be 57 m thick in the Wilmingham Borehole [SZ 36 87].

2.2.2.7 Culver Chalk Formation (Spetisbury Chalk Member)

The Spetisbury Chalk consists of firm, white chalk with large flints, including the tabular form, in the lower part and *Zoophycos* flints in the higher part. The exact stratigraphical level of the feature-forming beds has not been established in the type area, but, in Sussex, is inferred to occur at about the level of the Whitecliff Flint, i.e. at the boundary between the Sompting and Whitecliff Beds (Mortimore and Wood, 1986; Mortimore, 1986). The Spetisbury Chalk is equivalent to the upper part of the Culver Chalk (i.e. the Whitecliff Beds of Mortimore and Wood, 1986). The member has a characteristic sonic velocity log signature (Figure 2.3), which suggests that its top is marked by a hardground or prominent layer of flints. Both at outcrop and at depth across the Wessex Basin, the member is generally between 60 and 70 m thick, but is only some 40 m thick in the east.

2.2.2.8 Portsdown Chalk Formation

The Portsdown Chalk is the youngest member of the Upper Chalk. It crops out from beneath Palaeogene strata in an arc across the central, south-western and southern parts of the district. It consists of up to 90 m of soft to firm, white chalk; flints are sparse in the lower part of the member, and there are some large intervals (exceeding three metres) without flints. Marl seams are common in the lower part of the member, and it is presumably their relatively common occurrence in the lower part of the sequence, associated with softer chalks, that give rise to the steep scarp face that characterises the Portsdown Chalk.

2.3 PALAEOGENE STRATA

Palaeogene strata cover significant areas of the Wessex Basin (Figure 2.1); for example in the synclinal Hampshire Basin they comprise a layered succession, up to 652 m thick, of weakly consolidated sands and clays, with minor limestone, lignite and flint gravel. The Palaeogene deposits are separated from the Chalk by a major time gap of some 5 to 15 million years, but the two highly contrasting units are largely structurally conformable, both being folded during the main Miocene inversion event. The major time gap between the Chalk and the Palaeogene was a period of regional uplift, sea-level fall and subaerial erosion of the exposed Chalk surface under subtropical climatic conditions. Basal Palaeogene deposits infill valleys and solution holes cut into the upper surface of the Chalk. The complexities of Palaeogene stratigraphy result from deposition in fluctuating nonmarine and shallow-marine environments during successive coastal transgression and regressions. The stratigraphy is best known from the spectacular coastal outcrops at Alum Bay and Whitecliff Bay on the Isle of Wight. Inland, exposures are few but numerous boreholes, many of which have geophysical logs, provide stratigraphical control. The gamma-ray log is particularly effective at discriminating the alternating sand and clay formations that characterise the Palaeogene (e.g. Figures 2.7, 2.8 and 3.18).

2.3.1 Thickness trends and structure

The Hampshire Basin is an elliptical, highly asymmetrical, west–east trending syncline with a vertical southern limb and a gently dipping northern limb. Palaeogene deposits attain a maximum thickness of 652 m in the Sandhills Borehole on the Isle of Wight [SZ 45 90] and thin progressively toward the western and northern margins of the outcrop as the present-day erosion level cuts deeper into the stratigraphy. Folding associated with the Portsdown and Dean Hill anticlines complicates this general structural pattern.

2.3.2 Reading Formation

The Reading Formation reaches a maximum thickness of 80 m and is a highly variable succession of red-mottled clays, sands and gravels resting on a glauconitic sandy base. The formation thins to the west and is not present west of Wareham, where the London Clay rests directly on the Chalk.

2.3.3 London Clay Formation

The London Clay has a fairly wide outcrop on the northern and western margins of the basin, but in the south, because of either steep dip or faulting, its outcrop is narrow or absent. The formation consists predominantly of clays and sandy clays with minor interbedded sand. The sand content of the London Clay Formation generally increases upwards with the upper 30 to 50 m developed as a sequence of thinly interbedded sands and clays. The formation thins from around 100 m in the eastern part of Hampshire to around 50 m or less in the west. Around Wareham, in the west, the London Clay rests directly on Chalk and the base of the group is developed as a sand overlain by reddened clays of the West Park Farm Member that were previously mapped as ‘Reading Beds’ (Figure 2.8).

2.3.4 Bracklesham Group

The Bracklesham Group encompasses the strata between the top of the London Clay and the base of the Barton Group. In the western half of the Hampshire Basin, the group is dominated by the thick sands of the Poole Formation and Branksome Sand. The Poole Formation reaches up to 160 m thick and in general consists of four separate sand members separated by clays. The Branksome Sand is around 70 m thick and consists of alternating clean sands and thinly bedded sands and clays. The Bracklesham Group changes facies in the eastern half of the Hampshire Basin where it consists of thinly laminated sands and clays, glauconitic shelly sand and fine-grained clayey sand subdivided into the Wittering, Earnley, Marsh Farm and Selsey formations.

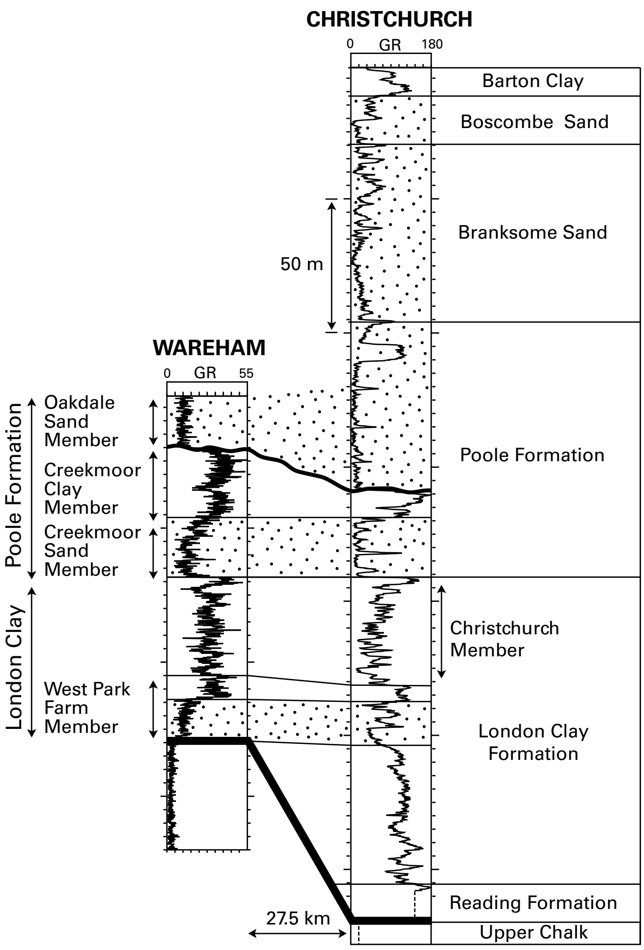


Figure 2.7 Palaeogene correlation using gamma-ray logs, Wareham Basin, Dorset.

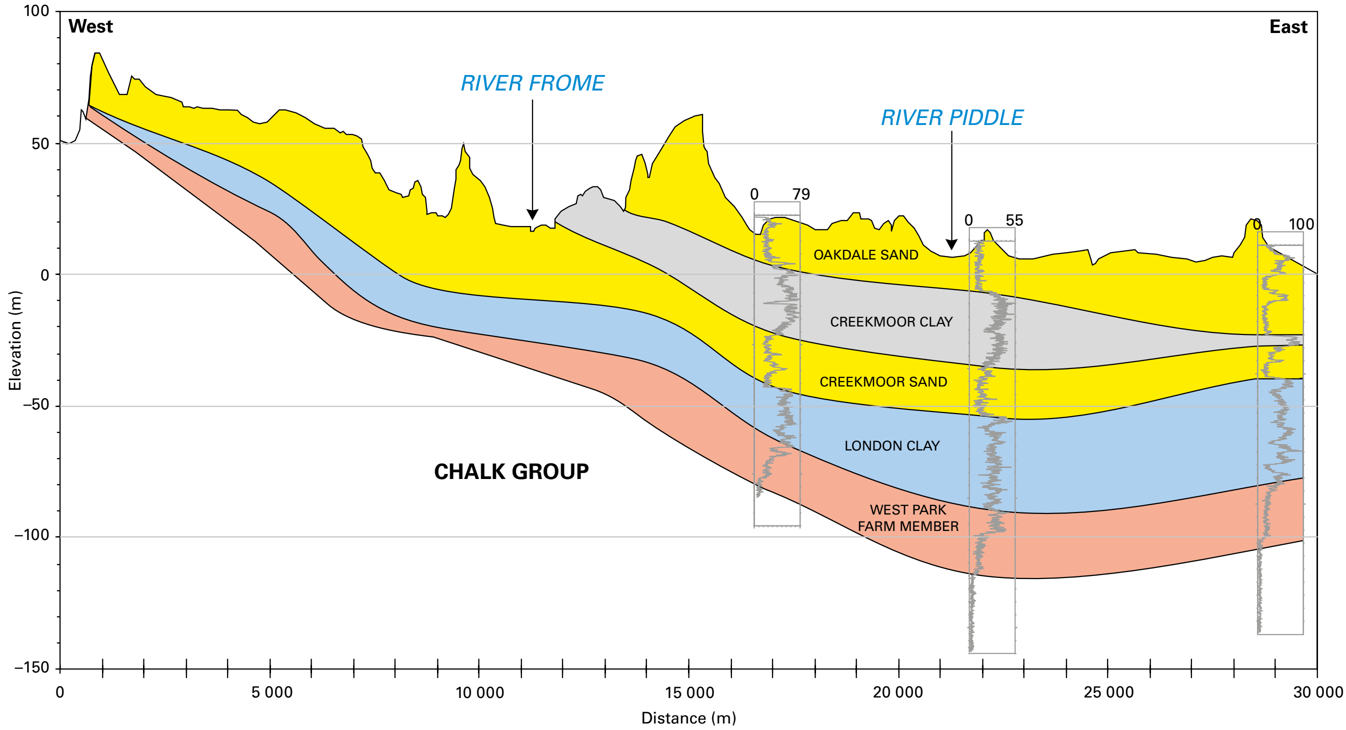


Figure 2.8 West–east section through the Palaeogene deposits of the Wareham Basin based on correlation of borehole gamma ray logs.

2.3.5 Barton Group

The Barton Group outcrops widely in the central part of the Hampshire Basin. Over most of its outcrop, the lower part of the group (Barton Clay) consists of glauconitic sandy clays with a large molluscan fauna. In the upper part there is a transition through the clayey fine-grained sands of the Chama Sand to the relatively clay-free sands of the Becton Sand that forms the top of the Barton Group. The Barton Clay varies in thickness from about 50 to 90 m, and the combined thickness of the Chama Sand and Becton Sand can vary from about 30 to 100 m (Edwards and Freshney, 1987).

2.3.6 Solent Group

The Solent Group is around 130 m thick and is subdivided into three formations, the uppermost of which just extends into the Oligocene. The Headon Hill Formation forms the base and is a 90 m thick succession of shelly sands, muds, marls, lignites and thin limestones. The overlying Bembridge Limestone Formation is a 8.5 m- thick sequence of pale brown, freshwater limestones, marls and muds. The uppermost Bouldner Formation is a thick unit of clays and silts, with occasional thin sands, marls and limestones up to 34 m on the mainland and as much as 90 m is preserved on the Isle of Wight.

2.4 QUATERNARY

The Quaternary Period saw many oscillations of climate. During several of the colder episodes extensive ice sheets pushed southwards across England, but they did not reach the Wessex Basin, and so there are none of the till sheets that elsewhere prove valuable in unravelling the Quaternary sequence. Instead, the Quaternary record is preserved primarily in river terraces, in records of high sea levels at several points along the coastline and in evidence of intense periglacial activity in the form of soliflucted sediments. There is a considerable time gap, broadly corresponding to the Neogene, between the deposition of the youngest Palaeogene strata and the oldest Quaternary deposits in the Wessex Basin. During this interval the Chalk and its Palaeogene cover was folded, uplifted and extensively eroded. Superficial deposits in the Wessex Basin are shown in Figure 2.9.

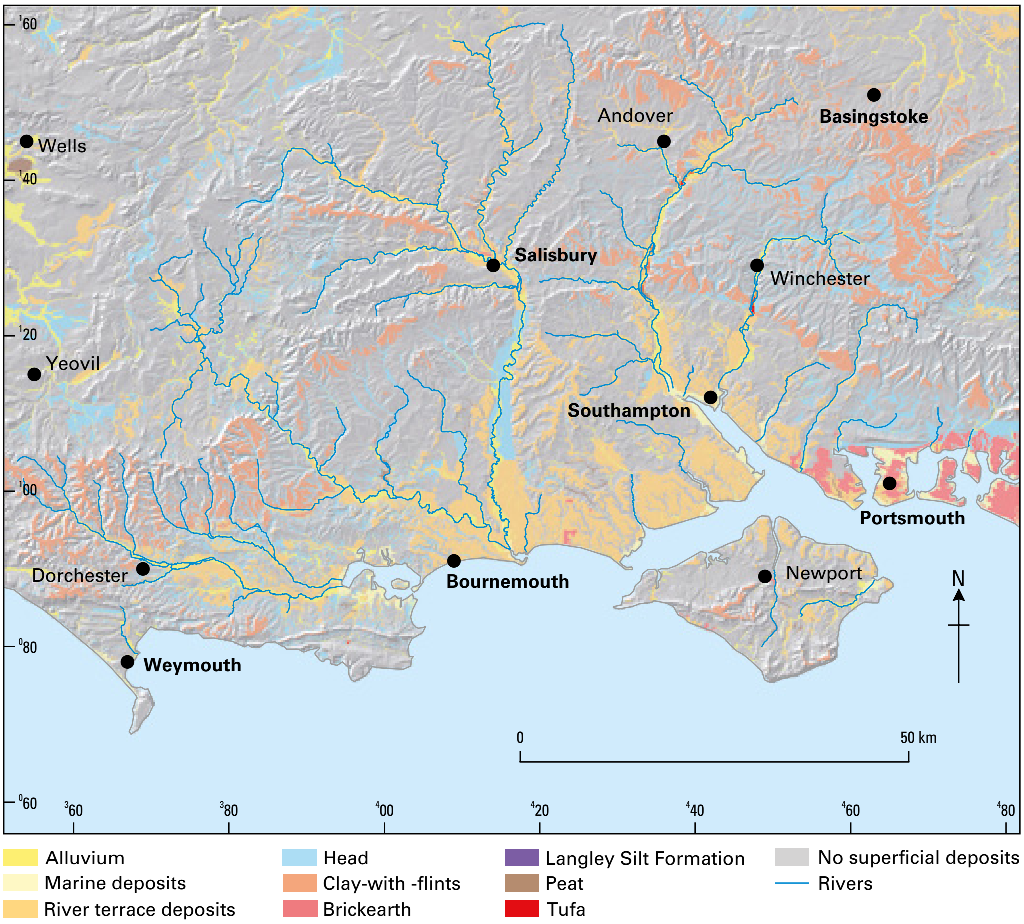
2.4.1 River terrace deposits

River terrace deposits occur along the flanks of the major rivers. They typically parallel the channels of the present rivers and fall only very gently downstream. The terrace deposits are generally less than 5 m thick and consist dominantly of gravels made up from angular, with some rounded, flints and sand. High-level terraces typically form flat-topped or gently inclined caps to interfluves. Many cannot be related to the modern drainage system, with those bordering the Solent being used to support the former existence of an easterly flowing 'Solent River' which pre-dates breaching of the Purbeck–Isle of Wight Monocline and present-day marine flooding. High-level terraces have undergone weathering and degradation by crytobation and may have an appreciable clay content.

2.4.2 Head

Head is a heterogeneous group of superficial deposits that have accumulated by solifluction, hillwash and hillcreep. Essentially it is a very gravelly, silty, sandy clay to clayey sandy gravel, with variable proportions of coarser granular material. The clasts are primarily of large nodular and coarse gravel-sized flint. It is regarded as a periglacial deposit resulting from the solifluction of Chalk, Palaeogene and clay-with-flints material.

Figure 2.9
Map of superficial deposits in the Wessex Basin.



2.4.3 Clay-with-flints

Clay-with-flints is primarily a deposit created by modification of the original Palaeogene cover and solution of the underlying Chalk. It is typically composed of clays and sandy clays containing abundant flint nodules and pebbles. In general it forms the flat top to hills and long dip-slope spurs. Deposits are estimated to be between 2 and 8 m thick, but will be much thicker over the solution pipes that may extend 10 m or more into the underlying Chalk.

3 Groundwater flow in the Chalk aquifer

3.1 HYDRAULIC PROPERTIES OF THE AQUIFER

3.1.1 Matrix characteristics

Chalk is a predominantly soft, fine-grained limestone formed from the shells of marine organisms and can be composed of up to 99 per cent calcium carbonate. Other shells, detrital quartz grains and chert nodules (in the form of flint) contribute small amounts of silica to its composition. Small proportions of clay minerals, glauconite and calcium phosphate are also present.

Chalk porosity varies between about 5 per cent and 45 per cent and is related to stratigraphy (Price, 1987; Bloomfield et al., 1995). For example, the Upper Chalk of southern England has an average porosity of 39 per cent, the Middle Chalk an average porosity of 28 per cent and the Lower Chalk a porosity of 23 per cent (Bloomfield et al., 1995). Changes in porosity are also reflected in differences in the intact dry densities of the Chalk. In southern England, the average dry density of the Upper Chalk is 1650 kg m^{-3}; in the Middle Chalk it is 1910 kg m^{-3} and in the Lower Chalk it is 2080 kg m^{-3} (Bloomfield et al., 1995). Figure 3.1 illustrates the reduction in average porosity with depth in the Chalk at the Totford Borehole [SU 57 38] determined by core sample analysis. At Totford, porosity reduces by about 1.5 per cent every 10 m below ground level. Local contrasts in porosity are due to variations in the nature of the original sedimentation. Generally, lower porosities are associated with more clay-rich chalks and with nodular and hardground bands such as the Melbourn Rock. However, the overall reduction in porosity with depth is due to differences in the degree of diagenetic compaction, with the older sediments subject to greater maximum overburden and so to a greater degree of mechanical and chemical compaction (Bloomfield, 1997).

Despite its commonly high porosity, pore sizes in the Chalk are generally very small. Matrix (intergranular) hydraulic conductivity is controlled by pore throat size and this is typically less than one micron (Price et al., 1976). This results in very small values of matrix hydraulic conductivity. For example, an average value of hydraulic conductivity of 6.3×10^{-4} m d^{-1} was determined from measurements on over 900 UK Chalk samples, of which around 99 per cent had values of less than 10^{-2} m d^{-1} (Allen et al., 1997).

3.1.2 Hydraulic conductivity, transmissivity and storage

Investigations of aquifer properties in the Wessex Basin have used many different techniques, for example pumping-test interpretation, groundwater-recession curve analysis, groundwater-model calibration, water-level data interpretation and tracer-test analysis. Most of the following regional discussion however is based on the results of pumping-test analysis. Further interpretations from catchment groundwater modelling are included in Chapter 4.

From a review of literature, it is notable that aquifer properties data are not distributed evenly over the Wessex Basin. For example, parts of south Dorset and the Candover and Alre catchments in Hampshire have been investigated in detail, while information is lacking on the aquifer properties of other areas, such as on Cranborne Chase and the Dorset Downs. Much of the following discussion is based on the data and analysis in Allen et al. (1997).

3.1.2.1 South Dorset

The Chalk of south Dorset is the most deformed in England. The Purbeck Monocline, which is the dominant structure in the area, and associated faults and folds (which extend over the outcrop of the Chalk) are significant in controlling the aquifer properties of the area.

Laboratory work, including porosity tests, has shown that the Chalk porosity varies with stratigraphical dip, highly folded chalk having a lower porosity and intergranular permeability than undisturbed chalk (Alexander, 1981). Mimran (1976) studied the structure of the Purbeck Monocline and suggested that up to 30 per cent compaction might have taken place, with a resulting porosity of only 5 per cent (compared with average porosity values of 35 to 44 per cent). It is evident therefore that folding has changed the chalk from a soft, highly porous material into harder limestone.

In the Mimran (1976) study, it was observed that, generally, where the Chalk has been tectonically hardened, values of transmissivity and storage coefficient are reduced, suggesting that the fracture distribution within the Chalk has also been altered. The mechanism for this is unknown but is possibly a result of chemical and mechanical diagenetic processes closing the fractures. However, faulting associated with the folded Chalk appears to have

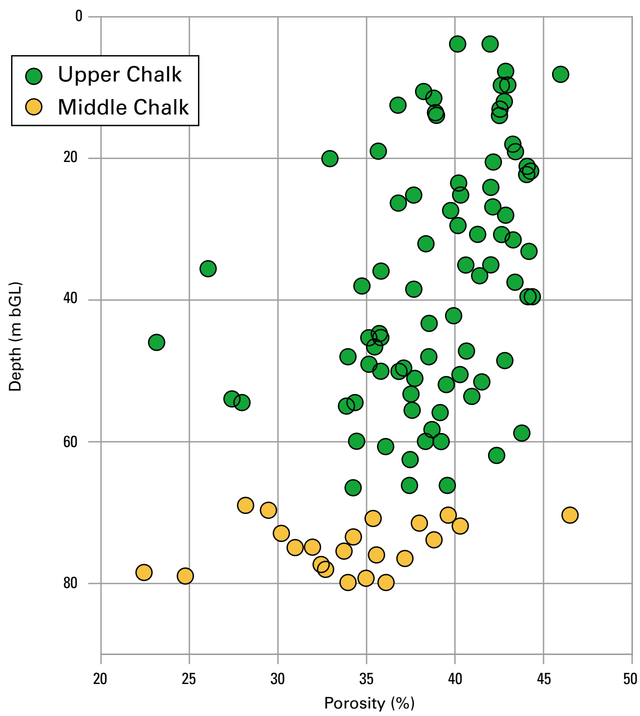


Figure 3.1 Porosity profile for the Totford Borehole.

a significant effect in increasing transmissivity locally. The faults have provided a preferential zone for rapid groundwater flow, which has been further enhanced by dissolution. An example of faulting increasing the aquifer transmissivity is seen in the Lulworth area (Houston et al., 1986).

In the Allen et al. (1997) study, pumping test data were collected from 28 locations in the south Dorset area. Thirty-eight pumping tests were recorded, giving 38 estimates of transmissivity and 19 of the storage coefficient.

Transmissivity data varied from 0.8 to over 3000 $m^2 d^{-1}$, with a geometric mean of 210 $m^2 d^{-1}$ and median of 330 $m^2 d^{-1}$. Storage coefficient data varied from 9 x 10^{-5} to 0.064 with a geometric mean of 0.003 and median of 0.0039. The majority of the Chalk data were from the unconfined area, although Pleistocene deposits in the outliers resulted in confined conditions. The high storage values were believed to have been influenced by the Upper Greensand aquifer in hydraulic continuity with the Chalk.

The effective base of the aquifer locally is taken to be the middle of the Upper Greensand, at the top of the Exogyra Sandstone. This horizon is well cemented and has a low permeability. The Chalk Marl (West Melbury Marley Chalk Formation and basal Zig Zag Chalk Formation) at the base of the Lower Chalk (Grey Chalk Subgroup) also has low permeability (Robins and Lloyd, 1975; Alexander, 1981), but the lack of springs emerging at the top of the marls implies a large component of vertical leakage to the Upper Greensand. On the scarp slopes, most of the springs emerge from within the Upper Greensand at the top of the Exogyra Sandstone. The Chalk Rock and Melbourn Rock can also be important flow horizons when near to the water table and minor flows can be detected when these horizons are found at depth. As found in other chalkland areas, the groundwater does not appear to circulate deeply within the aquifer; rather, the most important flow horizons are within the top 50 metres of the water table where fractures and bedding planes have been enlarged by solution. However, sea level changes during the Pleistocene induced large water table fluctuations near the coastlines where up to 100 m of effective aquifer may now exist (Edmunds et al., 1992).

Lulworth

The transmissivity distribution in the Chalk to the east of the Lulworth area is strongly controlled by geological structure. As a consequence of the tectonic hardening of the Chalk and associated reduction in intergranular porosity, permeability and open fractures, the general transmissivity and storage of the Chalk has been reduced. Transmissivity values from pumping test sites generally vary from around 250 $m^2 d^{-1}$ to about 1000 $m^2 d^{-1}$ with typical values from 300 to 500 $m^2 d^{-1}$ (Allen et al., 1997). The calculated storage coefficient for various tests is very low, usually about 1 x 10^{-4}. There are no pumping test data from the Purbeck Hills on top of the monocline. However, it is likely that the aquifer properties will be poor as a result of the steep inclination of the bedding planes and the low water levels.

In certain areas, where fracture zones have been enlarged by solution processes to form groundwater conduits, significantly enhanced transmissivity is observed. Pumping tests in high transmissivity zones indicate values ranging from around 1500 $m^2 d^{-1}$ to in excess of 2500 $m^2 d^{-1}$ and storage coefficients of 0.0025 to 0.04.

Frome and Piddle catchments

The Frome and Piddle catchments lie to the north of the structurally complex Lulworth area and the aquifer becomes rather more predictable. Groundwater levels are a reflection of topography and transmissivity reverts to a more classical model of low values in the interfluves and high values in the valleys. Transmissivity data from valley sites indicate values ranging from several hundred to over 3000 $m^2 d^{-1}$ and storage coefficients of 2 x 10^{-4} to 0.06 (Allen et al., 1997). A range of small pumping tests have been carried out on interfluve locations throughout the west of the south Dorset areas (Alexander, 1981). Although these tests are probably unreliable due to their short duration, they do give a general indication of the variation of aquifer parameters. Transmissivity values ranging from 0.04 to 340 $m^2 d^{-1}$ have been measured, although typically values were less than 50 $m^2 d^{-1}$.

In the West Knighton area (south-east of Dorchester), where the Chalk becomes confined by Palaeogene deposits, high transmissivity values have been recorded (>2000 $m^2 d^{-1}$). Low hydraulic gradients are associated with the high transmissivity, and it is possible that the aggressive water from the Palaeogene through-flow has enhanced the solution of fractures and led to the development of high transmissivity. It is anticipated that transmissivity will reduce with increasing degree of confinement.

3.1.2.2 Cranborne Chase and the Dorset Downs

The Allen et al. (1997) study of aquifer properties obtained data from 11 locations in the Cranborne Chase area. Sixteen pumping tests were recorded, giving 16 estimates of transmissivity and eight of the storage coefficient. Transmissivity data varied from 0.2 to 20 000 $m^2 d^{-1}$, with a geometric mean of 1600 $m^2 d^{-1}$ and median of 2800 $m^2 d^{-1}$. Storage coefficient data vary from 2 x 10^{-4} to 0.057 with a geometric mean of 0.0044 and median of 0.0055. The area had very few data points to describe the aquifer properties and this limited information is very biased towards high values in the valleys, therefore the statistics should be treated with caution.

The lack of hydrogeological data for Cranborne Chase and the Dorset Downs makes it difficult to assign an effective aquifer thickness to the Chalk. As with other areas of the Chalk, the most productive sections are probably in the top 50 m of the aquifer where the most significant fractures are present.

The distribution of the hydraulic properties of the Chalk appears to conform with the topographical model of high transmissivity and storage in the valleys, with lower values on the interfluves. The unsaturated zone is quite thick in this area and the water table is situated in the Middle/Lower Chalk (basal White Chalk/Grey Chalk subgroups). Solution-enhanced fracture development may therefore be somewhat inhibited. It is believed that the transmissivity of the Chalk is better developed at the periphery of the Palaeogene deposits where acidic run-off has developed fracture arrays.

Between Shaftesbury and Westbury, the Boyne Hollow Chert occurs intermittently at the top of the Upper Greensand, beneath the Lower Chalk (Grey Chalk Subgroup) and can act as a horizontal drain to vertical leakage through the less permeable marls.

3.1.2.3 Salisbury Plain

In this area, transmissivity data collected by the Allen et al. (1997) study varied from 50 to 8200 $m^2 d^{-1}$, with a geometric mean of 1400 $m^2 d^{-1}$ and median of 1600 $m^2 d^{-1}$. Storage coefficient data varied from 1 x 10^{-4} to 0.05 with a geometric mean of 0.0052 and median of 0.0099. Insufficient data were obtained to enable the relationship between transmissivity and specific capacity for the area to be described.

A study conducted by the Avon and Dorset River Authority and others (1973), as part of the Upper Wylye investigation, used borehole geophysics to investigate the aquifer properties. The results of this study showed that 90 per cent of the flow came from the top 47 m of a borehole that included Middle as well as Upper Chalk (lower White Chalk Subgroup). Again, as observed in other areas, the most productive section of the aquifer appeared to be the uppermost 50 m or so. The Chalk Marl (lower Grey Chalk Subgroup) appears to be unproductive and may define the base of the Chalk aquifer.

From the limited dataset analysed by Allen et al. (1997), it appears that boreholes located in the Lower Chalk (Grey Chalk Subgroup) have a lower transmissivity than those located in the Upper and Middle Chalk (White Chalk Subgroup). Valley pumping tests in the Upper and Middle Chalk yielded transmissivity values ranging from around 450 to nearly 7000 $m^2 d^{-1}$, with most results between 700 and 1000 $m^2 d^{-1}$. Pumping tests carried out in the Lower Chalk and Upper Greensand indicate transmissivity values ranging from around 100 $m^2 d^{-1}$ to 1500 $m^2 d^{-1}$ but most results were within the range 100 to 300 $m^2 d^{-1}$.

Halcrow (1992) calculated transmissivity and storage coefficient as part of a modelling programme to investigate the effects of groundwater abstraction on river flows in the Upper Hampshire Avon. From this study, the transmissivity was estimated to range from 250 $m^2 d^{-1}$ in the interfluves to 2500 $m^2 d^{-1}$ in the valleys. The storage coefficient varied from 0.001 over the interfluves to 0.15 in the valley bottoms.

3.1.2.4 Hampshire

Data from 29 locations in the Hampshire area were obtained during the Allen et al. (1997) study. Many of these locations had been researched intensively during previous investigations. Consequently, 63 pumping tests had been undertaken giving 63 estimates of transmissivity and 53 of the storage coefficient. Transmissivity data varied from 0.55 to 29 000 $m^2 d^{-1}$, with a geometric mean of 1600 $m^2 d^{-1}$ and median of 2600 $m^2 d^{-1}$. Measurements of the storage coefficient varied from 7 x 10^{-5} to 0.06 with a geometric mean of 0.008 and median of 0.009.

A number of studies in Hampshire have discussed the vertical variation of aquifer properties. These are summarised in Section 3.2.1.

The distribution of aquifer properties in the Hampshire Chalk is complex. Lithology is an important control and the hydraulic properties of the aquifer are influenced by the presence of hardgrounds, flint and marl bands and their effect upon fracturing. Generally, the Upper Chalk is considered a better aquifer than the Middle and Lower Chalks, although solution can increase the hydraulic properties of the Middle Chalk where it is near the surface. The Lower Chalk is generally a poor aquifer due to its generally higher marl content and poor fracture development. Where groundwater flow is predominantly through the Lower Chalk, as in east Hampshire towards the Weald, transmissivity is thought to be usually less than 500 $m^2 d^{-1}$. There is evidence to suggest that the Chalk and Upper Greensand in this area are not in hydraulic continuity (Giles and Lowings, 1990).

Topography is also believed to be an important factor; yields from the boreholes sited in the interfluve areas are generally less than in the valleys. Transmissivity values of 1000 $m^2 d^{-1}$ are considered to be common in the Upper Chalk in valleys but, together with storage coefficients, are thought to decrease away from the valley up onto the interfluves.

Geological structure may play both a direct and indirect role on the development of aquifer properties. Some valleys develop along the axes of synclines or faults (Southern Water Authority, 1979), and aquifer properties may develop there as in the typical topographical model. Giles and Lowings (1990) suggested that higher yields develop along the axes of denuded synclines rather than anticlines. This is evident on Figure 3.2, where groundwater contours are plotted with the trends of major fold axes. Groundwater mounds, indicating low transmissivity, are observed to correlate well with anticlinal axes.

Finally, the nature and extent of Palaeogene deposits will also influence the development of aquifer properties, for example fracture apertures in the Chalk will be small under significant Palaeogene overburden, resulting in lowered transmissivities.

In East Hampshire, across the groundwater divide towards the Weald, the aquifer properties are poorer and transmissivities are usually less than 500 $m^2 d^{-1}$. This reflects the stratigraphy, where groundwater flow is predominantly through the Lower Chalk, which is more clayey and less fractured than the Middle and Upper Chalk and has lower transmissivity and storage potential. However, in the north on the scarp slope facing the London Basin, the aquifer properties improve. Tests within valleys here show transmissivity and storage coefficients that are comparable to dip slope valley sites on Upper Chalk (approximately 1000 $m^2 d^{-1}$).

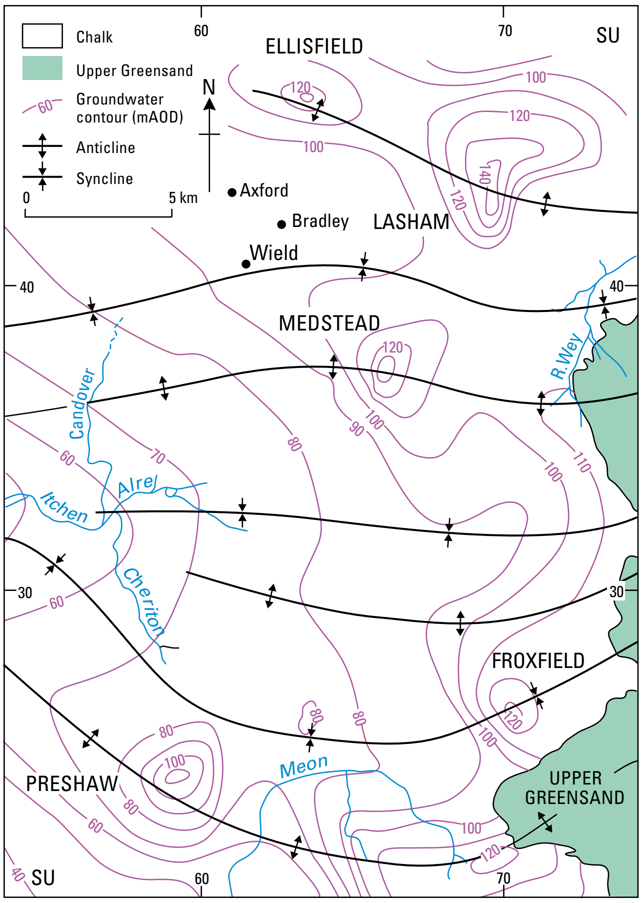


Figure 3.2 Groundwater levels and structure for the Upper Itchen catchment (after Giles and Lowings, 1990).

3.1.2.5 Isle of Wight

Little aquifer properties information exists for the Isle of Wight but can be expected to be strongly influenced by lithology, tectonically induced hardening and structural setting. Pumping tests within the Chalk indicate transmissivity values ranging from around 100 to over 300 $m^2 d^{-1}$ (Allen et al., 1997). The effective thickness of the Upper Greensand aquifer is generally 20 to 30 m and the hydraulic conductivity is approximately 1 m d^{-1}. The Plenus Marls at the top of the Lower Chalk and also the chert beds at the top of the Upper Greensand are both thought to have low hydraulic conductivities and may limit groundwater flow.

3.2 GEOLOGICAL CONTROLS ON AQUIFER PROPERTIES

As discussed above, the aquifer properties of the Chalk of the Wessex Basin are highly variable. They result from a diverse variety of matrix and fracture characteristics and reflect the wide variety of geological and hydrogeological processes that have contributed to the development of the aquifer. In the Wessex Basin, the Chalk has been affected by Alpine tectonics, leading to a greater structural complexity in the aquifer than in other regions of England. Large folds and faults are present which affect the hydrogeology of the region, while smaller structural features exert more subtle influences on the local hydrogeology. Although the area was not glaciated, it was significantly affected by periglacial processes and clay-with-flints deposits cover large parts of the aquifer on higher ground. Both the periglacial processes and acidic drainage from Palaeogene cover rocks have contributed to the development of the aquifer and locally have led to the development of karst features.

3.2.1 Variation in aquifer properties with depth

A characteristic feature of the Chalk aquifer is that significant permeability generally only exists near the top of the aquifer. Deeper in the aquifer the frequency and effective aperture of fractures reduces as a result of the increased overburden and general reduction in groundwater circulation and hence opportunity for development of the aquifer. Enlarged fractures may be particularly concentrated in the zone of water table fluctuation, and flow through these fractures provides a significant contribution to the overall transmissivity of the aquifer. Figure 3.3 is a schematic illustration of the variation in fracture density and style with depth.

Such trends in decreasing hydraulic conductivity with depth associated with changing fracture density and style have been recognised in a number of areas in the Wessex Basin, particularly in areas where the dip of the Chalk is relatively shallow and structural complexity does not dominate the hydrogeology. The following are some examples.

1. Packer tests were performed on three boreholes in the Itchen catchment in the Candover area at Abbotstone [SU 55 34], Itchen Down Farm [SU 54 33] and Totford [SU 56 38] along with laboratory permeability measurements on core samples taken from the boreholes (Price et al., 1977). The hydraulic conductivity of the matrix was found to be about 10^{-2} m d^{-1} at the water table, decreasing with depth by about an order of magnitude to 10^{-3} m d^{-1} at 80 m below the water table. The packer tests showed that zones of high hydraulic conductivity corresponded to fracture locations. Most of the saturated thickness of the Chalk had relatively low permeabilities, of the order of 10^{-1} to 1 m d^{-1}, with only a few fractures in each borehole providing a significant contribution to the overall transmissivity. These fractures were restricted to the top 40 to 50 m of the saturated zone.
2. Geophysical logging at Brixton Deverill, Heytesbury and Chitterne in the Upper Wylye (Avon and Dorset River Authority et al., 1973; Allen et al., 1997) demonstrated that even though fracturing was recorded to depths of up to 100 m below ground level, most of the flow (about 90 per cent) came from the top 47 m of the boreholes with the most productive features in the top 35 m.
3. Studies of artesian boreholes at watercress farms at Alresford in east Hampshire indicate that the majority of flow is focused in a narrow zone of 30 m near the top of the boreholes (Headworth, 1978).
4. As part of the Itchen augmentation scheme, a group pumping test was analysed to determine aquifer properties variation with drawdown. A strongly non-linear decrease in both transmissivity and storage coefficient was found with increasing drawdown (Southern Water Authority, 1979). Subsequent modelling of the shape and size of cones of depression in this area by Headworth et al. (1982) suggested that the highest transmissivities were associated with a layer about 6 m thick just below the water table.

In summary, various field investigations (principally in the Itchen catchment) have demonstrated the presence of a vertical gradient in the hydraulic properties of the aquifer controlled principally by a few enlarged fractures that tend to be developed near the water table.

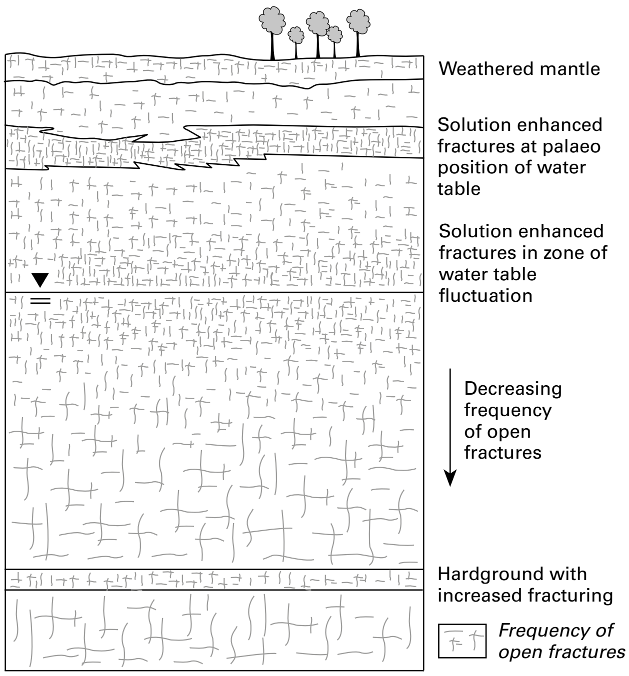


Figure 3.3 A schematic illustration of the variation of open fractures with depth in the Chalk (after Allen et al., 1997).

Vertical variations in hydraulic properties are not however ubiquitous in the Wessex Basin. In areas where karstic development of the aquifer has taken place, the depth distribution of aquifer properties is less predictable. In the Alre catchment in Hampshire, a neighbouring catchment to the Candover where vertical gradients in hydraulic properties have been described, karst has developed at various levels in the Upper and Middle Chalk (Allen et al., 1997). Maximum transmissivity from boreholes in this catchment is estimated to be as high as 30 000 $m^2 d^{-1}$ and high transmissivity is associated with localised karstic flow in the Middle Chalk.

In areas of structural complexity the depth distribution of aquifer properties is also less predictable. Where the Chalk has been tectonically hardened (i.e. matrix and fracture porosity has been reduced due to syn- and post-deformational compaction and cementation) and typically in areas where the dip of the bedding is steep (such as across the Purbeck monocline) the depth distribution of fractures is influenced by local tectonic structures. In such areas, fracturing associated with the release of overburden stresses is less important. Under these conditions there is only a limited potential for porosity development in the zone of water table fluctuation and flow is more likely to exploit and develop local tectonic structures. For example, rapid transport towards springs at Arish Mell [SY 85 80] in south Dorset has been attributed to flow through solution-enlarged fracture zones associated with faulting.

3.2.2 Lithological controls

The matrix properties of the Chalk aquifer, such as porosity and pore-throat size distribution, vary as a result of differences in primary sedimentological characteristics and diagenetic history (Scholle, 1977; Hancock, 1993; Bloomfield, 1997). This in turn may affect the fracture characteristics of the different Chalk formations so that lithology may be expected to influence both matrix and fracture properties of the aquifer. Mortimore et al. (1990) were able to identify characteristic fracture styles and frequencies for specific formations in the Chalk of Sussex and these characteristics have been related to aquifer potential (Jones and Robins, 1999). Similar correlations between lithology, fracture density and aquifer properties can broadly be made for the Chalk of the Wessex Basin, although less work has been done than in Sussex. As part of the Bourne and Nine Mile River study (Environment Agency, 2001), the spatial distribution of soft or hard units within the Chalk was identified as the principal factor in the development of relatively low or high hydraulic conductivity zones within the catchments. Relatively hard formations, such the Lewes Nodular Chalk Formation, are typically pervasively fractured and potentially provide pathways for groundwater flow and, at outcrop, they act as a focus for spring lines. Relatively softer chalks commonly deform more plastically and typically have fewer connected fractures. These formations are generally less hydraulically conductive and marl bands may act as semi-confining layers impeding down-gradient groundwater flow.

In the Wessex Basin the Upper Chalk is typically highly fractured and has numerous flints and marl bands that act to focus flow leading to secondary porosity development. Secondary porosity development has been recorded in the Bourne and Nine Mile River catchments on sheet flints (Culver and Seaford Chalk Formations) and on thicker marl seams (Newhaven Chalk Formation) (Environment Agency, 2001). Hardgrounds can also act as sites of localised flow. For example, throughout much of the basin the Chalk Rock near the base of the Upper Chalk may act as a preferential flow horizon when it is close to the water table, (Hopson et al. 2008). The outcrop of the Stockbridge Rock Member, a thin bed of very hard porcellaneous chalk in the Seaford Chalk Formation, determines the location of the perennial head of the Bowne, Wallop Brook, Pilhil Brook, and River Anton (Farrant et al. 2001; Bryan et al., 2004).

The Middle Chalk is much more lithologically variable and its poorer aquifer properties have been attributed to the greater frequency of marls (Southern Water Authority, 1979). The Plenus Marls Member (Holywell Nodular Chalk Formation) may locally support perched water tables and may also locally confine flow in the Bourne catchment, while the hard nodular Melbourn Rock Member supports flowing horizons (Environment Agency, 2001). The Lower Chalk (Grey Chalk Subgroup) is generally less permeable than the overlying Middle and Upper Chalks (White Chalk Subgroup) and the Chalk Marl at the base of the Lower Chalk is a particularly low permeability formation (Robins and Lloyd, 1975; Alexander, 1981) that may influence the drawdown behaviour of pumped wells (Allen et al., 1997).

The most direct evidence of relationships between lithology and the location of groundwater flow horizons is provided by the interpretation of geophysical logs. Examples of such evidence are provided in the section of this chapter discussing flow in the saturated zone.

Regional structure can have an important influence on the depth and outcrop location of flow horizons, and evidence of this has been found in recent studies of the Bourne (Environment Agency, 2001) and the Itchen (Entec, 2002) catchments. In addition, faults can provide important controls on spring locations (for example in the Piddle catchment).

Variations in Chalk lithology not only affect the aquifer's hydraulic properties but may also influence the bourne behaviour of some of the Chalk streams in the Wessex Basin. Stretches of some bournes may become perched for parts of the year where they pass over relatively impermeable formations and may lose flow where they pass over more permeable formations. For example, in the Upper Piddle there is only a limited loss of flow from reaches underlain by the relatively hard, nodular Holywell Chalk, whilst loss of flow from perched reaches of the river underlain by the New Pit Chalk ranges from about 2 to 13 $l\ s^{-1}$ and appears to be independent of flow. This loss is inferred to be controlled by the hydraulic conductivity of the New Pit Chalk outcropping on the river bed (Marcus Hodges Environment, 1999). This aspect of river–aquifer interaction is further discussed later in this chapter.

3.2.3 The relationship between topography, drainage development and aquifer properties

In southern England, relatively high transmissivities and storage coefficients have been reported within valleys and lower transmissivities and storage coefficients towards the interfluves so that aquifer properties generally reflect topography (Allen et al., 1997). Detailed discussions of why transmissivity and storage coefficients may have developed to broadly mirror topography can be found in Price (1987), Downing et al. (1993) and Price et al. (1993). Several important factors contribute to the topographical control on areal distribution of aquifer properties:

1. Valleys in the Chalk, including dry valleys, may follow structural lineaments or lines of structural weakness and may be the locus of increased fracture density.

2. Erosion along valleys can act to reduce effective stress and lead to the development of horizontal fractures at shallow depths (Price et al., 1993).
3. Concentration of groundwater flow towards discharge areas within the valley can contribute to the development of localised secondary fracture porosity and hence to increased transmissivity and storage coefficients in the valley (Price et al., 1993 and references therein).
4. Periglacial processes may further contribute to the development of enhanced hydraulic conductivity within the valleys due to repeated freezing and thawing and the opening of fractures in the top 20 to 30 m of the Chalk (Younger, 1989).

In the Wessex Basin, however, structural control on topography and hence hydraulic properties is much less clear. Many of the rivers in the basin cut across the predominant structural grain (Wooldridge and Linton, 1955) and the Chalk in south Dorset is extensively deformed so that relationships between the geomorphology, hydrology and hydrogeology of the area are complex and do not simply conform to the patterns observed in other chalkland areas (Allen et al., 1997).

Examples of discordant relations between surface drainage, topography and structure include:

1. central Hampshire where the two principal streams, the Itchen and the Test, flow southwards in a discordant fashion across anticlinal folds at Winchester and Stockbridge
2. the headwaters of the Itchen where both the Candover Brook and the Meon flow southwards over east–west trending fold structures (Giles and Lowings, 1990)
3. the River Avon where it cuts across the eastern end of the Warminster Anticline.

Despite these observations, there are areas where there is clearly structural control on topography and subsequent development of enhanced aquifer properties due to valley erosion, concentration of groundwater flow towards the valley and periglacial modification. For example, east–west trending anticlinal structures are associated with the Vale of Wardour, Wylye Valley and the Vale of Pewsey, and aquifer properties in these areas generally reflect the topography with transmissivity and storage tending to be highest in the valleys and lowest in the interfluves. This is taken to reflect the areal distribution of enlarged fractures (Allen et al., 1997).

In Hampshire, some rivers and dry valleys have developed along the axes of synclines and fault lineaments (Southern Water Authority, 1979). Giles and Lowings (1990) reported pumping test data indicating higher yields along the axes of denuded synclines than anticlines. They also investigated the relationship between groundwater levels and structure in the Upper Itchen catchment and found a positive correlation, with high groundwater levels associated with small anticlinal features and lower groundwater levels associated with small synclinal features (Figure 3.2). This was attributed to low transmissivity values resulting from relatively poor fracture development around the axes of the anticlines.

3.2.4 Karst

Solution features at the land surface are widespread in the Wessex Basin and in some areas karstification of the underlying Chalk aquifer is particularly prevalent, for example in parts of Dorset, around Salisbury and Mottisfont and in the Newbury area along the edge of Palaeogene. Both solution features and karst in the Chalk appear to be most common where the present land surface is close to the sub-Palaeogene peneplain. Solution features and karst may be of local hydrogeological significance as they can indicate areas where there may be particularly rapid or focused recharge and rapid, highly localised movement of groundwater in the saturated zone.

Solution features at the land surface, such as buried and subsidence sinkholes (or dolines), may reach densities of the order of 100 per km^2 in parts of Dorset (Sperling et al., 1977). Buried sinkholes (Culshaw and Waltham, 1987) are typified by pipe or cone-like cavities in the underlying Chalk but have no surface expression. The pipes are commonly filled with flinty, gravelly clay derived from superficial cover, usually clay-with-flints. Subsidence sinkholes are closed surface depressions, usually bowl-, pipe- or cone-shaped. They may be isolated features or may occur in groups, sometimes coalescing into large, composite dolines. Most are found in unconsolidated cover sediments up to 10 m thick, such as the clay-with-flints, for example on the scarp crest east of South Tidworth, at Collingbourne Wood near Ludgershall and between Everleigh and Sidbury Hill. The location of these solution features depends on a range of variables including lithology, fracture style, geomorphological setting, structure and occasionally even anthropogenic factors. The main control, however, is the geomorphological setting and proximity to the margin of Palaeogene cover. The highest densities of solution features are generally found along spring lines and valley floors — for example along the middle and upper reaches of the Bourne, between Collingbourne Kingston and North Tidworth — and near the margins of Palaeogene cover. An example of the latter can be found between the rivers Piddle and Frome in the Puddletown Heath, Southover Heath and Culpepper's Dish areas (Figure 3.4) where extensive solution features have developed on the margins of Eocene cover (Sperling et al., 1977). Although Allen et al. (1997) note that these solution features could permit rapid recharge to the aquifer, there is as yet no direct evidence linking such geomorphological features to zones of high transmissivity in this area.

Allen et al. (1997) considered that several factors could account for the high degree of solution activity associated with cover deposits. These are:

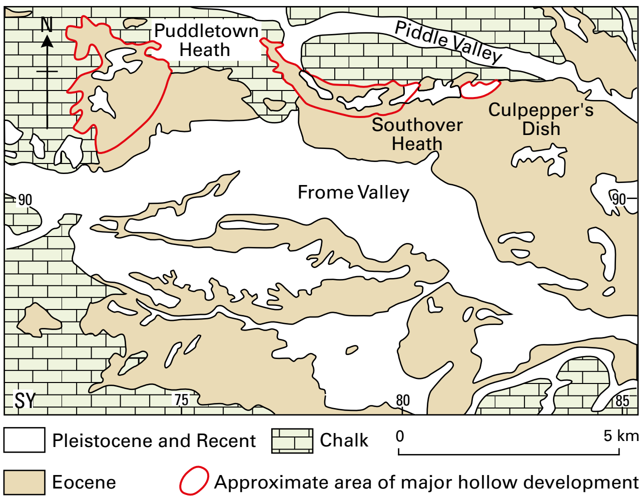


Figure 3.4 The distribution of solution features in the Chalk of the Dorset heathlands (after Sperling et al., 1977).

- soils associated with Palaeogene deposits and clay-with-flints tend to be quite acidic (Edmunds et al., 1992)
- chalk soils are generally permeable, but those associated with cover can be quite clayey and therefore concentrate run-off to discrete points
- as recharge waters drain through the cover, they remain undersaturated with respect to calcite until reaching the Chalk surface, thus allowing the acidic recharge to be channelled to discrete points.

The karstic features in the Chalk to the east of Dorchester may be the result of intense and localised solution activity promoted by highly acidic conditions under heathland vegetation (Sperling et al., 1977). In south Hampshire, significant hydraulic connections between swallow holes and springs in the Chalk were established, using groundwater tracing techniques, by Atkinson and Smith (1974) and were considered to be the result of solution activity caused by rapid run-off from the Palaeogene cover enhancing the transmissivity of the Chalk aquifer.

3.2.5 Role of Palaeogene

From a hydrogeological point of view, there are few regionally significant minor Palaeogene aquifers in the Wessex area. The outcrop of Palaeogene deposits is shown in Figure 2.1. In Figure 3.5 (from Jones et al., 2000) the principal sand-dominated units that comprise the minor aquifers are shown in relation to the major clay-dominated aquitards/aquicludes. The great vertical and lateral variation of the more argillaceous units may also give rise to minor aquifers where sand lenses are present.

In many areas, oxidation and percolation of groundwater has weathered sand-dominated sequences to depths of several tens of metres, which is likely to increase the permeability. Perched water tables have also frequently led to the development of thin, irregular layers of iron-cemented sands. Their cementation would impede vertical leakage and may reduce the scope for recharge to the Chalk.

The regional pattern of groundwater flow is from the edge of the basin towards the centre. Local groundwater flow may be hard to predict, however, due to the lateral discontinuity of the sandy beds. Perched water tables are common. The sand-dominated minor aquifers are interlayered with clay-dominated aquitards. Many of the Palaeogene minor aquifers will therefore be confined or semi-confined by overlying clay beds. Lithological variations may also result in sandy layers within a formation being bounded laterally as well as vertically by clay layers. In particular, in the Wessex Basin, the laterally discontinuous aquifers within the London Clay Formation such as the Whitecliff, Durley, Nursling and Portsmouth sands, are confined by the surrounding clay beds.

Brickearth, plateau gravels or valley gravels overlie Palaeogene beds in some areas. Only the brickearth is likely to inhibit recharge to the underlying minor aquifers.

Where the basal Palaeogene strata are arenaceous, the sands are in hydraulic continuity with the underlying Chalk, and the combined deposits are considered to be a single aquifer. The proportion of sand in these formations decreases to the west. Where clay predominates, the Palaeogene deposits provide an aquitard of regional extent, and a useful element of additional drainable storage overlying the Chalk aquifer. North of Southampton, borehole yields from the Reading Formation can be up to 200 $m^3 d^{-1}$, and this is thought to be partly due to upward recharge to the formation from the underlying Chalk.

3.2.6 Periglacial influences

During the Quaternary, the Chalk of southern England remained largely free of ice sheets but was significantly affected

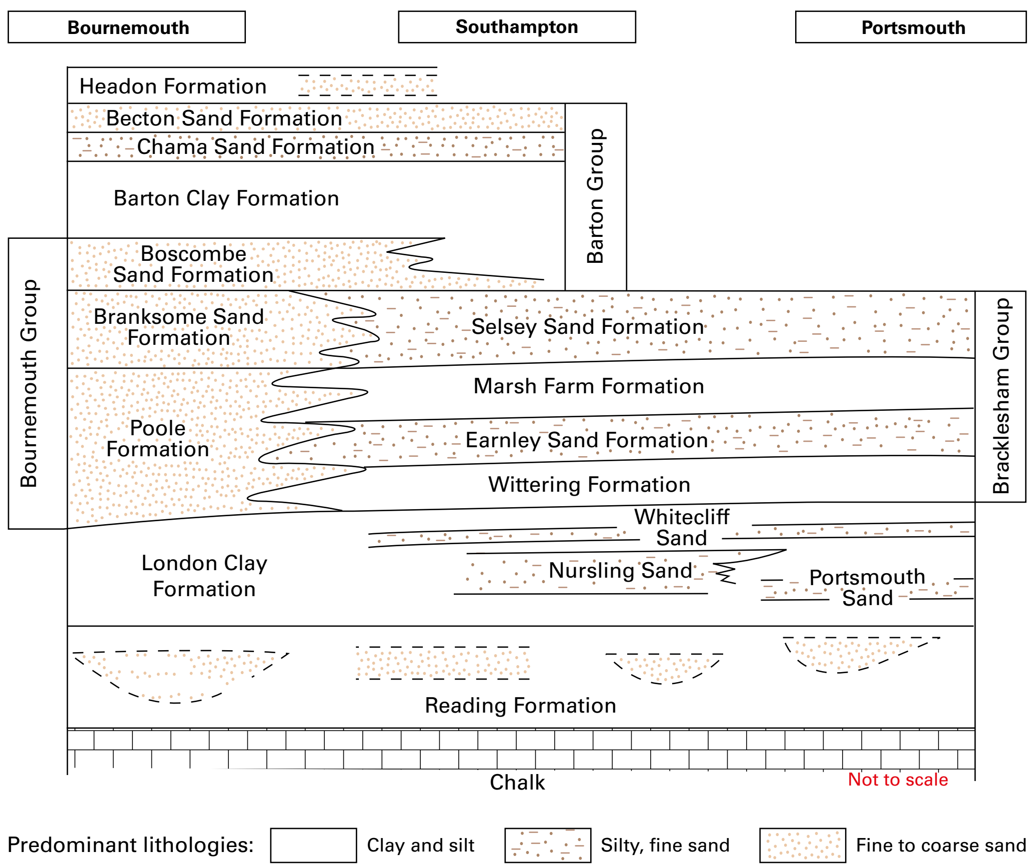


Figure 3.5 Relationship between Palaeogene minor aquifers in the Wessex Basin (not to scale) (from Jones et al., 2000).

by ground ice (periglaciation). The permanently frozen substrata were probably not seriously affected by periglacial activity. Close to the surface, however, the active zone underwent cycles of freezing and thawing that, over the whole of the Chalk outcrop, have produced a weathered mantle frequently 1 to 2.5 m thick consisting of broken, rubbly chalk (Williams, 1987). In some places, just below the subsoil, the Chalk is highly pulverised to putty chalk, which is generally structureless chalk with irregular sized blocks set in a soft to firm putty matrix. The main effect is a significant increase in fracture density in the top few metres of the Chalk. In some valleys, periglacial activity has led to fractures opening up to a depth of up to 20 or 30 m (Higginbottom and Fookes, 1971; Williams, 1987) and this may contribute to the development of enhanced permeability in valleys. Many of the present-day dry valleys in the region are possibly remnants of active stream valleys, formed at a time of different sea levels. The different sea levels may also have resulted in the maintenance of the water table at various levels and so allowed the development of subkarstic horizons of enhanced permeability throughout the vertical sequence of the Chalk (see Figure 3.3).

3.2.7 Role of drift – Pleistocene and Recent

Although most of the Chalk aquifer of Hampshire is unconfined, a number of different types of Pleistocene deposits are present over the Chalk outcrop in the Wessex Basin, the main expressions of which include clay-with-flints, plateau gravels/alluvium, brickearth and head deposits. However, there has been little work undertaken to investigate the effect of the drift on the hydrogeology of the Chalk in the Wessex region.

The clay-with-flints forms extensive deposits on the Chalk of the Hampshire Downs and to a lesser extent on Salisbury Plain, south Dorset and the Isle of Wight where these deposits are prominent only on the higher ground. The deposits range from about 0.5 to 10 m in thickness with an average of around 6 m (Klinck et al., 1998). It commonly forms the fill material in solution pipes in the Chalk where it can be up to 15 m in thickness. Klinck et al. (1998) conducted a series of laboratory and field experiments in order to characterise the porosity and permeability characteristics of the clay-with-flints in southern England. The deposits tend to show a trend of increasing porosity and decreasing hydraulic conductivity with depth, with an increase in hydraulic conductivity again near to the contact with the Chalk. Infiltrometer measurements for Dorset gave a mean hydraulic conductivity of around 1 m d^{-1}. The high values at the surface were attributed to cracking; the higher conductivity at the base due to the presence of closely spaced subvertical shearing adjacent to the contact with the Chalk. Plateau gravels and alluvium are observed lining valley sides up to 15 m above the present valley floors and are capped by the most recent river deposits present as alluvium.

3.2.8 Summary of geological events and their implications for the hydrogeological evolution of the aquifer

It is clear that a wide range of geological events and processes have contributed to the evolution of the Chalk aquifer. These events and processes and their corresponding hydrogeological implications are detailed in Table 3.1. Similar approaches have been adopted previously to describe the links between geological events and the geomorphological evolution of southern England (e.g. Wooldridge and Linton, 1955; Jones, 1999). The earlier model of landscape development was based on a sequential interpretation of events, while the later model (Jones, 1999) envisaged a more evolutionary interpretation of events. Although, for ease of representation, the hydrogeological evolution of the Chalk aquifer is presented in Table 3.1 as a series of discrete events, it is envisaged that many of the geological events or processes are likely to have occurred over more extended periods of time and will have overlapped and/or will have had cyclic characteristics. For example, there have been pulses of tectonic activity within and from the end of the Cretaceous through to the present day (Mortimore and Pomerol, 1991), and although the major phase of deformation was Miocene (Alpine compression) minor compressive events have continued to cause limited uplift since the Miocene. Another example is the uplift and erosion prior to deposition of the Palaeogene — it is thought that this uplift occurred as a series of pulsed events or episodes (Jones, 1999) rather than one or two discrete events.

3.3 THE AQUIFER IN THE WATER CYCLE

3.3.1 Unsaturated zone and recharge

The water table in the Chalk aquifer generally follows, in a subdued manner, the surface expression of topography: the unsaturated zone is thicker under hills and thinner in the valley areas. Given the variation in topography over the Wessex Basin, the thickness of the unsaturated zone can therefore vary considerably. In addition, annual variations in water level can be significant.

Flow through the unsaturated zone in the Chalk takes place either by fracture flow or matrix flow or a combination of both, and there are a number of lines of evidence for each. Recharge to the aquifer through the unsaturated zone may comprise both vertical and horizontal flow components. The dominating process of recharge is likely to be influenced by the presence of permeable or impermeable horizons within the Chalk. The overlying Palaeogene and Quaternary deposits also have an influence on the recharge process. The heterogeneous nature of these deposits means that the impermeable units may cause run-off, whilst the more permeable units may allow direct recharge to occur. However, the presence of impermeable deposits may also concentrate flow from certain areas and hence increase the amount of recharge to the underlying aquifer.

It has been postulated by some researchers that recharge through unsaturated Chalk takes place mainly via the fractures rather than through the matrix itself. The rapid response of water table levels to rainfall events seemed to indicate this to be the case (Headworth, 1972). There is also evidence from the bacterial contamination of groundwater (Maclean, 1969) that fissure flow can predominate in the unsaturated zone of the Chalk. However, the work of Smith et al. (1970) concluded that in fact only about 15 per cent of recharge occurs through the fissures; the remaining 85 per cent recharges the aquifer by a piston displacement model, i.e. water draining from above by gravity displaces water already in the intergranular rock matrix downwards. Daily rainfall in excess of a few millimetres appears to be stored temporarily in the soil and near-surface weathered Chalk. The delayed drainage is often at rates low enough to be conducted by the matrix alone (Gardner et al., 1990).

A number of study sites have been developed in the UK to examine how recharge processes vary in different rock types. One such site, at Bridget's Farm near Winchester

Table 3.1 Geological evolution of the Chalk aquifer in the Wessex Basin and its hydrogeological implications.

Geological events	Factors influencing chalk rock mass properties	Hydrogeological implications/significance
Chalk deposition	Primary lithological characteristics established, e.g. ratio of carbonate to clay minerals, hardground and flint development	The primary lithological nature of the Chalk aquifer has implications for the gross hydrogeological characteristics of different Chalk formations, particularly the development of hardgrounds
Chalk burial and diagenesis	Compaction and cementation. Initial physical compaction and, for more deeply buried chalks, chemical compaction. Lithification of the Chalk and flints and the development of burial joints as burial and lithification progresses	The location of marl seams, flaser marls, nodular chalks and flints, including tabular flints, within the Chalk sequence may later affect the development of flow heterogeneity at both catchment and local scales within the aquifer. Burial joints are the first stage in the development of the dual-porosity nature of the Chalk
Chalk uplift and erosion, and development of pre-Palaeogene drainage	Faulting, jointing and minor flexuring of the lithified Chalk to accommodate uplift. Faulting may be localised over structural lineaments in the pre-Cretaceous basement. Followed by karstic weathering and erosion and possible development of first drainage network on the eroded Chalk under a subtropical climatic regime	Further development of the dual porosity nature of the Chalk with the formation of faults, uplift joints and gentle folds. Erosion and possible pre-Palaeogene drainage development may lead to initial flushing of connate waters and possibly early development of enhanced (or secondary) porosity near the water table
Palaeogene deposition and burial	Marine transgression of the eroded Chalk surface and deposition of a thick sequence of Palaeogene deposits. Chalk burial was accommodated by re-activation (inversion) of earlier uplift faults and folds and the development of new burial joints. Potential additional chemical compaction of the deeper Chalk formations	Infill of irregularities on the eroded Chalk surface by Palaeogene deposits forms the starting point for future karstification of this surface with implications for groundwater recharge. Further modification of the dual porosity nature of the Chalk with possible inversion of faults, closure of existing joints and potential development of new burial joints
Progressive re-emergence of the sub-Palaeogene surface	Uplift of the Palaeogene associated with re-activation of existing faults and renewed uplift jointing. Re-establishment of a consequent drainage pattern on the exposed Palaeogene surface	Further development of dual porosity. Limited flushing of connate waters in the Chalk where groundwater can percolate through Palaeogene cover may lead to additional development of secondary porosity. Start of the removal of Palaeogene deposits. Karstification of the Chalk
Alpine deformation and development of Miocene drainage	Extensive deformation and uplift of the Chalk and Palaeogene deposits with the formation of tight folds and monoclines and associated accommodating jointing and faulting. Development of a Miocene drainage network associated with the uplifted landscape and start of the development of clay-with-flints	Major structural controls on hydrogeology initiated. Groundwater flow directions possibly controlled by Miocene drainage network and associated zones of groundwater discharge. Continued freshening of the aquifer. Continued removal of the Palaeogene deposits and karstification of the Chalk
Post-Pliocene transgression and planation	Minor transgression and limited planation of the post Miocene land surface. Removal of some of the Palaeogene deposits. Continued development of drainage network	Initiation of the present-day drainage network and hence control on present-day groundwater flow directions. Continued limited development of present-day karst with removal of Palaeogene cover
Quaternary periglaciation	Episodic pulses of periglaciation. Freeze-thaw and cryoturbation of the top few metres of the Chalk. Continued removal of the Palaeogene cover and development of clay-with-flints deposits during thawing episodes and development of head deposits. Deposition of river gravels (river terrace deposits)	Major modification of the shallow aquifer with formation of local putty chalks and thick weathered zones in valleys. Colder groundwaters are much more chemically aggressive so this may be the major phase of development of secondary porosity and karst (see Ford and Williams, 1989). 'Dry valley development' at times of relatively high sea-level stands
Recent erosion and ground-water circulation	Continued removal of the Palaeogene cover and formation of the clay-with-flints. Deposition of recent alluvium	Development of the aquifer in the zone of groundwater level fluctuation and in areas of recent groundwater discharge near river valleys. Present-day groundwater flow heterogeneity established as sea levels fluctuate and present-day drainage is established. Limited development of the Chalk aquifer covered by Palaeogene

in Hampshire, has been extensively used for this purpose. Wellings (1984a, b) concluded from the analysis of soil physics data that water moves predominantly through the fine pores of the Chalk matrix with only a minor component through the fissures.

The concept of delayed recharge may be of importance. Regional studies of the Chalk aquifer in the Thames catchment suggests that up to 50 per cent of recharge is still in transit in the unsaturated zone when the water table peaks (Lerner, 1997). This water drains to the saturated zone over the summer at a slower rate than groundwater discharges to rivers.

Darling and Bath (1988) analysed stable isotope data of ^{2}H and ^{18}O values in the unsaturated Chalk from Fleam Dyke in Cambridgeshire and at Bridget's Farm. A number of differences were observed between the vertical isotope profiles from the two sites. These differences were attributed to higher infiltration rates in southern England (>400 mm a^{-1}) than in eastern England (<200 mm a^{-1}) and also to different infiltration mechanisms. It was considered that differences in lithology, due to stratigraphical position in the Chalk sequence and postdepositional history, e.g. glaciation, could impose a major influence on the recharge mechanisms. For example, Wellings et al. (1982) reported that the matrix conductivity of Chalk at Bridget's Farm is approximately five times greater than at Fleam Dyke. However, the conductivity of fractured Chalk is likely to be orders of magnitude greater than unfractured Chalk, and so these differences in matrix conductivity may be less significant depending on the relative proportion of matrix/fracture flow. This last point highlights that the results of site-specific experiments on mechanisms of groundwater recharge should be generalised with caution.

A study into the mechanisms of water storage and flow in the unsaturated zone of the Chalk (Lewis et al., 1993) found that for the Lambourn and Kennet catchments in the Berkshire Downs, the volume of water flowing out of the catchment was substantially greater than could be accounted for based on the change in the level of the water table, unless an unrealistic value of specific yield was assumed. They concluded that the most likely explanation for this discrepancy was the slow release of water due to drainage of the Chalk in the unsaturated zone. It was calculated that a drainage of around 0.25 to 0.30 per cent of the volume of rock in the unsaturated zone was required to account for the anomaly. Price et al. (2000) concluded that this storage property of the unsaturated zone could be used to account for the delay in the reponse of the water table to recharge and that in areas where the water table is deep and there is a thick unsaturated zone, the delay could be of the order of weeks.

The presence of clay-with-flints cover may affect recharge to the underlying Chalk aquifer in a number of different ways. While the main constituent of the deposits is clay based, tending to inhibit recharge, there are lithological variations, involving both silt and sand fractions. These more permeable horizons, together with the contact areas between the clay matrix and the flints, are likely to act as conduits, facilitating groundwater movement through the deposit. In addition, recharge through superficial cracks and rapid marginal recharge via karstic features in the Chalk is possible. A study by Klinck et al. (1998) concluded that a variety of recharge pathways were likely to be associated with clay-with-flints; these are illustrated in Figure 3.6.

Groundwater recharge at the catchment scale has usually been simulated using models based on soil moisture balance techniques, such as the Penman-Grindley (Penman, 1948; Grindley, 1967) or Food and Agriculture Organisation (Food and Agriculture Organisation, 1998) methods. Whilst this has been the commonest approach, other types of model have been used to simulate recharge, for example rainfall run-off models (Moore and Bell, 2002). Generally, soil-moisture balance models have been based on measured daily rainfall data and estimates of potential evaporation from the UK Meteorological Office Rainfall and Evaporation Calculation System (MORECS). MORECS uses the concept of a soil 'field capacity' and only when this is full does recharge occur. In addition to other soil water balance components, MORECS calculates effective precipitation, equivalent to recharge plus run-off, but because it uses a 40 km grid, generally only the potential evaporation values have been used in groundwater recharge modelling studies. During the 1990s, the UK Meteorological Office's Surface Exchange System (MOSES) was developed, which incorporates a more complex description of the soil store and an improved representation of surface run-off and evaporation from the soil than MORECS. MOSES does not use the concept of a field capacity or soil moisture deficit. Whilst MOSES provides an improved process description of the soil water balance, it has generally still been the case that potential evaporation values from MORECS have been used in catchment scale recharge models developed as part of hydrogeological studies.

Values of recharge in the Wessex Basin have been estimated in a number of groundwater modelling studies. For example, a comparison of groundwater models in and around the River Test catchment (Environment Agency, 2004) showed long-term, average annual modelled recharge values varying from around 200 mm a^{-1}, for example in parts of the Bourne catchment) to around 500 mm a^{-1} in the

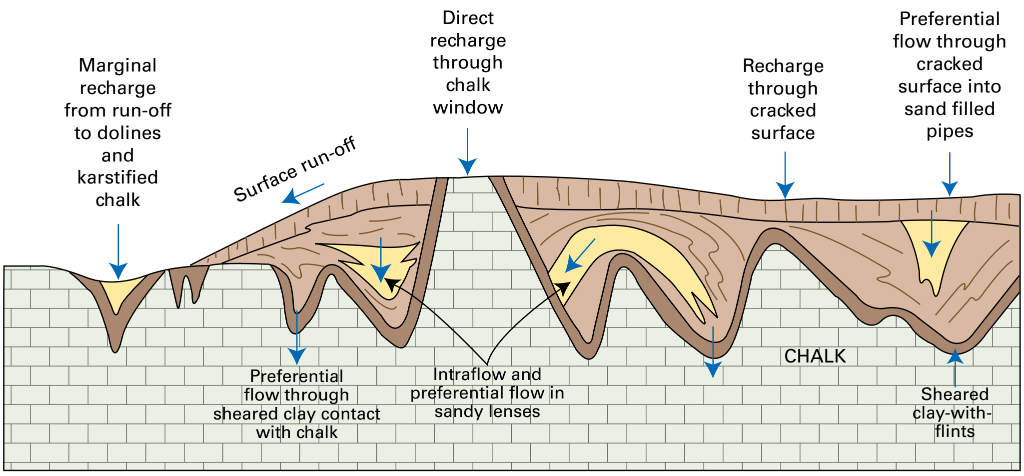


Figure 3.6 Recharge mechanisms associated with clay-with-flints (from Klinck et al., 1998).

south-east of the Itchen catchment. In general, modelled values in the Bourne, Upper Avon and Test catchments were around 250 to 350 mm a^{-1}. In a modelling study of the River Allen, catchment estimates of recharge varied from 340 to 400 mm a^{-1} (Groundwater Development Consultants, 1992).

3.3.2 Groundwater levels in the Wessex Basin Chalk

The Environment Agency regularly monitors groundwater levels in boreholes across the Chalk aquifer of Wessex at a variety of depths depending on the planned use of the data. A subset of these boreholes, termed index wells, which are considered to be representative of the aquifer, are selected to contribute to the National Hydrological Monitoring Programme, which provides information on the state of the nation's water resources on a monthly basis. Many index wells have been used to record water level variations in the aquifer for over 50 years, and the oldest in Wessex began recording in 1894 at Compton House [SU 77 14] near Rowlands Castle. Just outside the Wessex region, in the South Downs, is the Chilgrove House Borehole [SU 83 14], which has the longest record of groundwater levels in Europe (and possibly the world) with a continuous record from 1836 to the present day.

The water level in a well or borehole is a representation of the average vertical hydraulic head in the formations that have been penetrated and are open to the borehole, therefore comparisons of water levels across an area may involve hydraulic heads measured in different formations (or different units within a formation) and at different depths. As a result, the data need to be used with care where vertical head gradients are thought to be significant. However, on a broad regional basis it is considered that chalk borehole water levels may be used to represent general head variations and flow directions.

The water table in the Chalk is usually a subdued reflection of the topography and fluctuates seasonally in response to recharge, discharge and abstraction. Generally, groundwater levels rise throughout the winter, with the highest levels commonly occurring in January and February, and fall over the summer, reaching lows in August or September. Often multiple maximum levels are observed during the winter due to an uneven rainfall distribution, with several prolonged periods of rain resulting in discrete recharge events.

An example of an index well hydrograph for the West Woodyates Manor Borehole [SU 01 19] can be seen in Figure 3.7. This shows the typical form of a chalk hydrograph in the Wessex region, although the mean annual range for this well (25.89 m) is larger than for many of the other index wells in Wessex as it is sited near an interfluve. The maximum annual range for this well (between 1942 and 2000) was 36.20 m with a minimum range of 4.72 m (Marsh and Lees, 2003). The peak in water level can clearly be seen to occur early in the year, with the minimum occurring at the end of the summer. The maximum annual range from an index well in the Wessex Basin Chalk was recorded as 38.10 m (Marsh and Lees, 2003) in a well at Compton House [SU 77 14]. The greatest difference between maximum and minimum water levels tends to occur beneath the high ground, and is typically approximately between 15 and 20 m. In valleys, it tends to be reduced and is more generally only a few metres, although there are exceptions. For example, a borehole at Woodside [SU 33 56], situated near the top of a winterbourne valley, recorded an average annual fluctuation in water level of 14.7 m (Marsh and Lees, 2003). Conversely, a monitoring well at Lower Wield Farm [SU 63 40] sited in an interfluve on the surface water divide, recorded an annual average fluctuation in water level of only 2.40 m (Marsh and Lees, 2003). These seasonal fluctuations mean that piezometric surfaces are only valid for datasets that have been collected simultaneously.

The Wessex and Hampshire and the Isle of Wight hydrogeological maps (Institute of Geological Sciences, 1979a; Institute of Geological Sciences, 1979b) cover the Chalk of the Wessex Basin and were compiled at a scale of 1:100 000 by the Institute of Geological Sciences with Wessex Water Authority and Southern Water Authority respectively. They include contours for the Chalk piezometric surface for September 1975 (Wessex) and October 1973 (Hampshire) — the division occurring roughly along the line of longitude passing through Salisbury. These water level contours are reproduced in Figure 3.8. The contours show that the general direction of regional flow is from the edges of the basin towards the coast, with the contours generally reflecting the topography in a subdued form. Where the Chalk is confined by Palaeogene strata, the Chalk potentiometric surface is not shown, but limited data from boreholes indicate a gradient towards the coast.

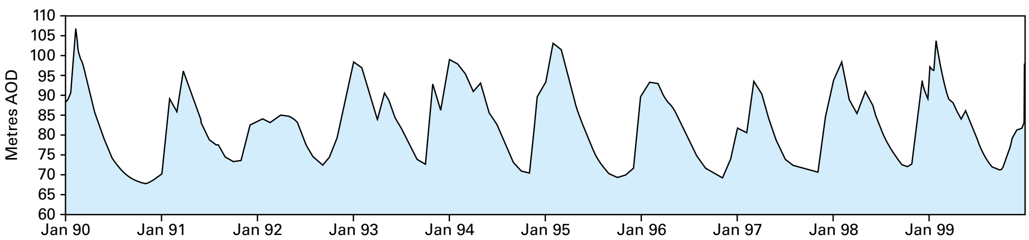
On a regional scale, the contours generally indicate the expected discharge of groundwater to the main river systems (effluent) on their middle reaches, prior to flowing over the Palaeogene deposits. However, in some cases (for example the Piddle and the Bourne) the contours for the upper parts of the catchment are more ambiguous or indicate influent behaviour in the late summer. Groundwater divides are clear between some catchments (for example between the Bourne and Test) but it is less obvious where (and sometimes if) they exist in others (for example between the Frome and Piddle).

Figure 3.9 shows the thickness of the unsaturated zone across the Wessex Basin. This clearly shows the importance of rivers draining groundwater from the aquifer (i.e. thin unsaturated zone) and the fact that many tens of metres of unsaturated zone thicknesses can be found in some interfluve areas.

In south Dorset, annual groundwater level fluctuations are at their greatest in the South Winterbourne catchment, where fluctuations of up to 18 m are observed in the upper reaches of the catchment, with a decrease in the amount of fluctuation downstream. The area around Lulworth also shows marked variations (Alexander, 1981).

As part of their study of the River Itchen for the Environment Agency, Entec (2002) investigated groundwater level data and compared a range of hydrograph characteristics with other factors such as ground level, unsaturated depth and distance to the nearest main surface water course. The

Figure 3.7 West Woodyates hydrograph (Source — BGS National Groundwater Level Archive).



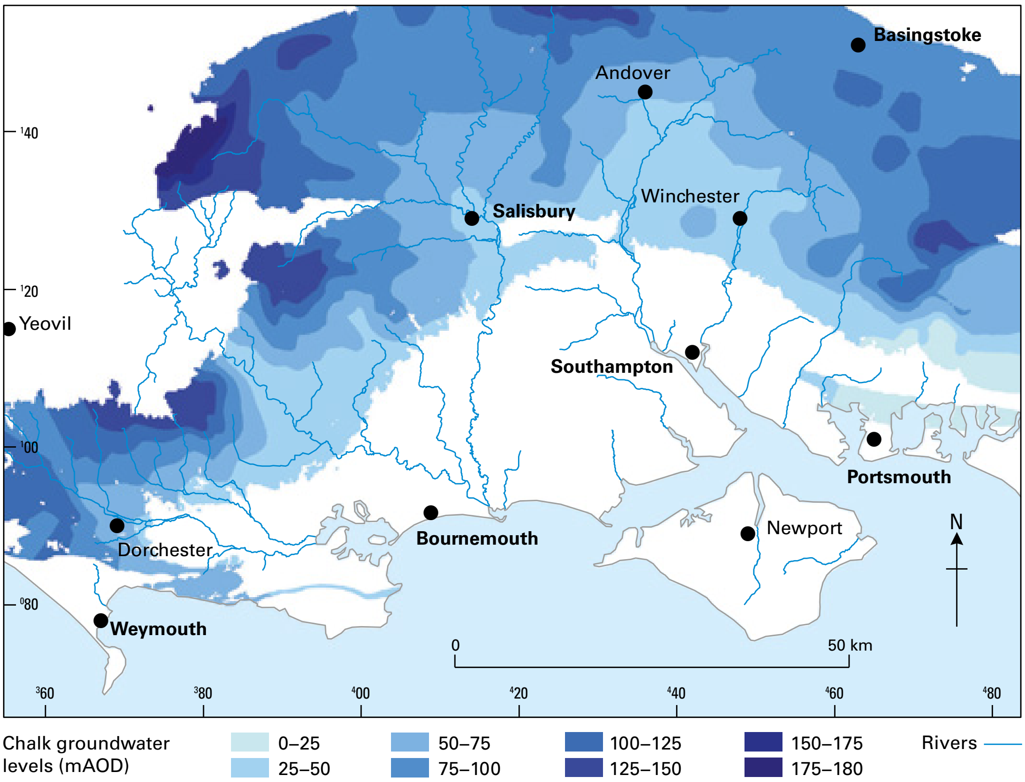


Figure 3.8 Groundwater levels in the Chalk of the Wessex Basin (IGS 1979a, 1979b).
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unsaturated zone thickness was found to vary across the catchment generally between 0 and 60 m but could be as much as 100 m. The Alre subcatchment showed only very limited variation in water levels with ground level and it was inferred that groundwater levels here were controlled by distinct high transmissivity levels in the Chalk.

The study also found a weak correlation between the seasonal amplitude of a groundwater level record and ground level, with slightly greater water level fluctuations where ground levels are higher. This is as would be expected, as in areas of low elevation (valleys) the groundwater levels tend to be controlled by the streams and shows that there is good connectivity between the aquifer and the rivers, which act as drains. Fluctuations in the Candover catchment, however, were almost always less than 5 m. This is consistent with the observation of Rennie (1994) that there is little spatial variation in the degree of fissuring in the catchment. The Dever catchment also shows little annual fluctuation in groundwater levels and this is explained by the role of the River Dever acting as a drain.

A number of individual hydrographs were also analysed and it was observed that generally boreholes near water courses showed relatively flat hydrographs indicating good connectivity with the surface water system. Boreholes in or near synclines tend to show smoother hydrographs than those near anticlines, as observed in the Alre catchment. In addition, generally, summer low water levels do not vary much from year to year, even in drought years. From this it is inferred that water levels reach the base of the active Chalk and then do not tend to drop any further. In summary, analysis of groundwater level amplitudes and responses to recharge show no simple or consistent relationship with factors such as unsaturated zone thickness, nature of the superficial deposits, or distance to major rivers, and suggests that a combination of factors influence water levels.

3.3.2.1 Groundwater flooding

Groundwater flooding, also described as clear water flooding, is a natural phenomenon that occurs when the natural storage capacity of an aquifer is exceeded. It can arise in two main ways. One of the most common forms is associated with river floodplains and occurs when river gravels become fully saturated and groundwater is forced out into the floodplain. The second type of groundwater flooding occurs when the water level in consolidated rock aquifers, such as the Chalk, is so high that the water emerges at the surface as springs and seepages. This second type is the cause of the majority of groundwater flooding events in Wessex associated with the Chalk aquifer, especially in the upper reaches of tributary streams. A significant difference from surface water flooding is that the events last for weeks or months, rather than days, as the groundwater in storage is slowly released.

In Hampshire, more than 100 villages and many roads and fields were flooded for weeks and even months during the winter of 2000/01 (Hampshire Water Partnership, 2003). Similar problems were experienced throughout the Wessex region and have occurred on several occasions in the past. The winterbourne tributary streams of the Test are often areas where Chalk groundwater flooding occurs, due to the source of the watercourse moving in response to groundwater level fluctuations. In the winters of 1993/94 and 1994/95, groundwater levels were exceptionally high and many winterbournes rose much further up their valleys than normal, causing local flooding. In contrast, low winter rainfall in 1991/92 and 1996 caused very low groundwater levels and river flows in the following drought summers (Environment Agency, 1999a). In some villages such as Hambledon, in Hampshire, some form of groundwater flooding is frequently experienced, due to the fluctuations of the water table.

3.3.3 Flow in the saturated zone

3.3.3.1 The unconfined aquifer

The principal groundwater flow mechanism in the saturated zone is along fractures, which are often enlarged by solution, rather than through the Chalk matrix. The hydraulic conductivity of the Chalk matrix is very low (of the order of

Figure 3.9
Unsaturated zone thickness in the Chalk of the Wessex Basin.
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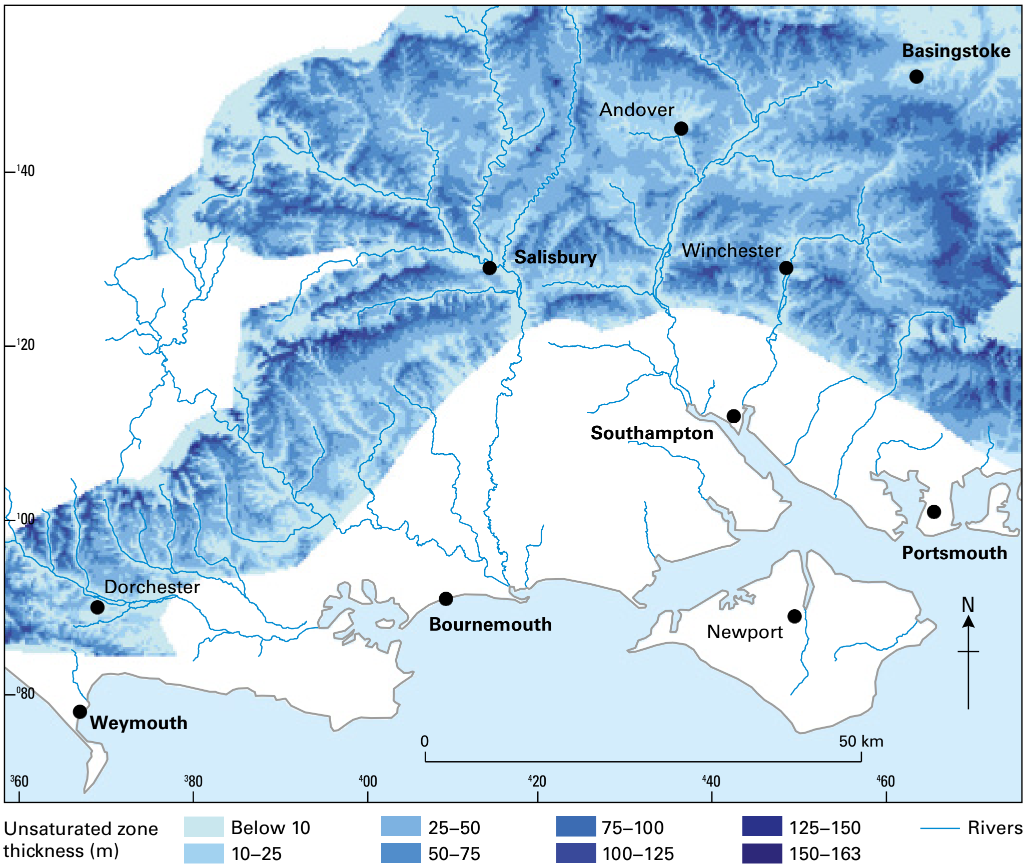

10^{-3} m d^{-1}) and consequently makes a negligible contribution to the overall transmissivity of the aquifer. Subsurface evidence for the location of groundwater flow horizons and their relationship with aquifer lithology is obtained primarily from the interpretation of geophysical borehole logs. Formation and fluid logging of boreholes penetrating the Chalk shows that water normally flows into a borehole at only a few specific points and that these inflows are often associated with certain stratigraphical horizons (which are commonly located at flint, marl and hardground surfaces) at shallow depths. For example Figure 3.10 illustrates water inflows in the Figheldean observation borehole in the River Avon catchment [SU 15 46] where logging was undertaken as part of a low-flow study of the river by the Environment Agency. Electrical resistivity logging showed that the borehole penetrated the Seaford, Lewes Nodular and New Pit Chalk, and fluid logging whilst pumping identified four separate inflows: at 18 m depth (Seaford Chalk); at 31 m (top of Lewes Nodular Chalk); at 50 m (at the top of the Chalk Rock hardgrounds), and at 62 m depth (top New Pit Chalk). The borehole was pumped at 38.5 m^3 h^{-1} and the specific capacity was 8.83 m^3 h^{-1} m^{-1}. Flowmeter logging showed the main inflows were the shallowest, at 18 m and at 31 m depth.

Sometimes the groundwater flow in the Chalk can all be concentrated at one particular horizon. For example Figure 3.11 is a composite plot of geophysical logs recorded by the British Geological Survey in a borehole near Tidworth in the River Bourne catchment. The borehole penetrates the same stratigraphical interval as the Figheldean Borehole, but the pumped-fluid logging revealed that most (>80 per cent) of the inflow was coming from the surface of a hard band having high gamma-ray activity in the Seaford Chalk, thought to be the Stockbridge Rock Member, at 26 to 29 m depth, approximately 50 m above the Chalk Rock horizon. During the pumped logging the discharge rate was 48.5 m^3 h^{-1} and the borehole exhibited a specific capacity of 78.2 m^3 h^{-1} m^{-1}, which was approximately ten times higher than the specific capacity of the Figheldean Borehole, indicating that a well-developed karstic flow feature was probably responsible. A small inflow was also present at 16.6 m depth, a short distance below the casing. In this example, as with Figheldean, the main inflows are from groundwater circulation along fractures associated with particular lithological horizons and junctions between contrasting lithologies, which have probably been enlarged by solution as groundwater flows towards discharge outlets. The groundwater circulating more rapidly along these horizons is cooler than the deeper groundwater circulating more slowly at greater depth.

Specific water inflows to boreholes from only a few solution features is an important characteristic of the Chalk aquifer and is responsible for 'breakaway' features in yield-drawdown plots when seasonal water levels decline or pumping takes water levels to, or below, such contributing horizons. These horizons clearly represent the main drains of the rock mass and are linked to the matrix storage by a finer network of fractures. Optical and acoustic imaging of Chalk boreholes by video-scanning survey is able to show the nature of these solution features and the details of the fracture systems present. Optical imaging and caliper logging also identifies some well-developed fissure horizons present above normal water level in some boreholes. These became locally important in sustaining groundwater flooding that was experienced in some Chalk regions during the exceptionally wet winter of 2000 to 2001. These high-level fissure systems may have developed during periods of higher water table in the Pleistocene and Palaeogene.

In both the River Bourne and River Avon catchments, gamma ray and resistivity logging reveals a strong development of the

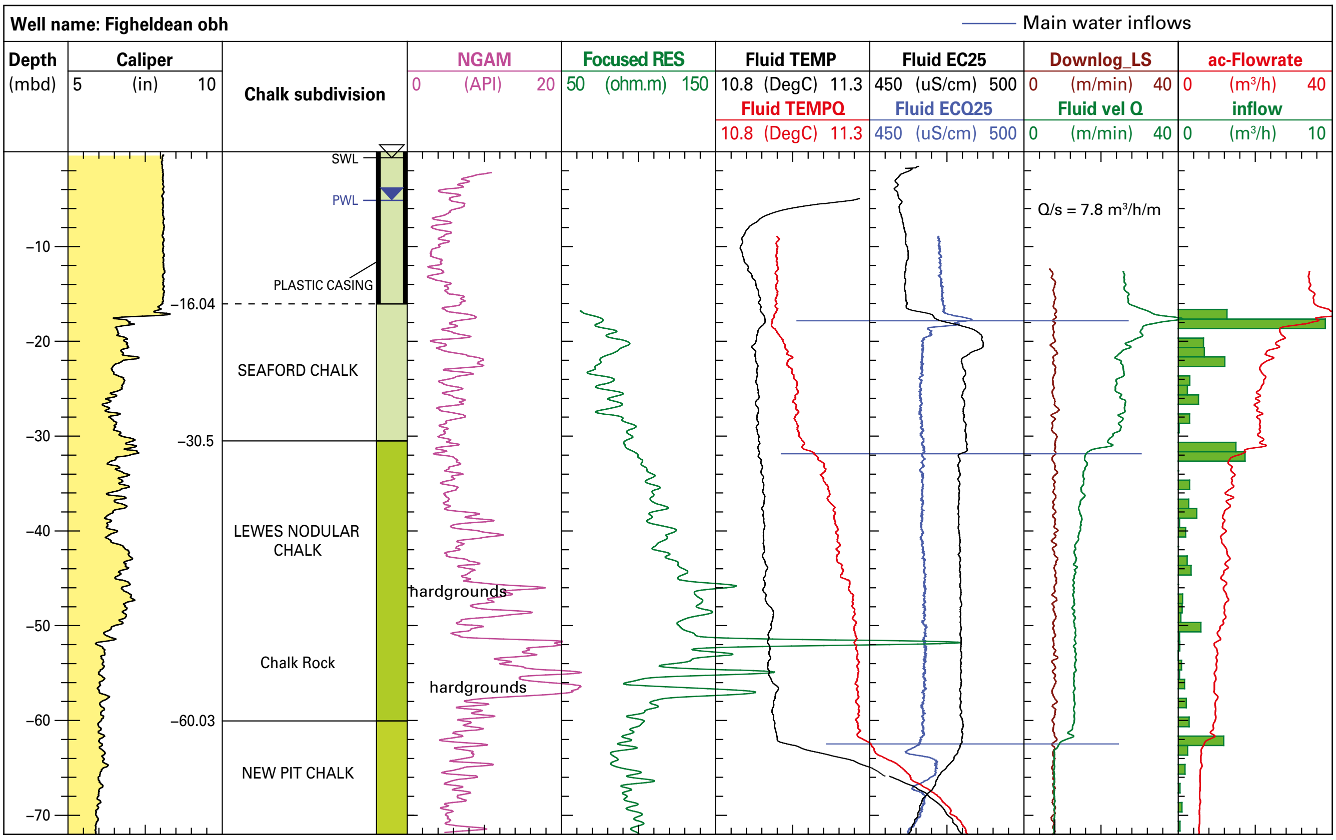

Figure 3.10 Geophysical logs showing water inflows from Seaford, Lewes Nodular and New Pit Chalk, Figheldean Borehole, River Avon catchment (courtesy of Environment Agency).

Chalk Rock hardgrounds near the base of the Lewes Nodular Chalk (formerly marking the base of the Upper Chalk). These hardgrounds are characteristic of shallower water environments of deposition near the margins of the Chalk basins and they represent sea-floor surfaces and areas of shallower water where the sea-bed sediments are condensed and have become indurated. Logging shows at least three distinct zones of higher gamma-ray activity and higher resistivity occupying an interval of 8 to 15 m which are present towards the base of the Lewes Nodular Chalk (see for example Figures 3.10, 3.11 and 3.12). Minerals such as glauconite and francolite, associated with the shallow water and subaerial exposure, are responsible for the enhanced natural gamma-ray activity. Away from the margins of the depositional basin in areas of deeper water sediment, these hardground surfaces become replaced by an expanded nodular Chalk sequence containing thicker, well-developed marl seams. The hardground surfaces are important hydrogeologically because they tend to become the focus for concentrated shallow groundwater flow (as in the Tidworth example) and can have associated high yields. This is probably a result of the lithological contrast and different fracturing styles compared with the adjacent chalk beds.

Geophysical logging by the British Geological Survey in several Chalk boreholes in the Fonthill Bishop area of Wiltshire, on behalf of the South West Region of the Environment Agency, also identified strong development of the Chalk Rock hardgrounds and their importance in groundwater flow. Figure 3.12 illustrates a west–east cross-section through some of the boreholes located close to the interfluve of the Fonthill Brook catchment where the water level is relatively deep (80 to 100 m). The land surface reflects the relative hardness of the Chalk layers as indicated by the induction resistivity profiles (Induction RES). The Chalk Rock horizons are identified by the gamma-ray (NGAM) logs and up to three individual hardground developments are indicated on the diagram.

The static water level (SWL) shown represents the water level measured at the time of logging in late summer and autumn. In July, the water table is at the top of the lowest hardground in Musseldean Copse Borehole but further east, closer to local abstraction, it lies within the underlying New Pit Chalk. In November, the water level in the Willoughby Hedge Borehole further west is at the top of the New Pit Chalk. These observations suggest that local abstraction is fed by flow along the Chalk Rock hardgrounds for at least part of the year and that when the water level drops below the Chalk Rock horizons, increasingly deeper inflows in the New Pit and Holywell Nodular Chalk contribute to the abstraction.

While the locations of flow horizons often appear to be controlled by lithologically distinct stratigraphical horizons such as the Chalk hardgrounds, the hydraulic and chemical influence on their development is such that the flow horizons develop within a few tens of metres of the Chalk surface. Therefore, while flow may follow a particular horizon at shallow depths, in dipping strata, once the layer reaches a certain depth, it will cease to be associated with fractures and flow will be transferred to a different stratigraphical level (although again perhaps associated with certain lithologies) as it moves towards surface discharge points. In the Wessex Basin, groundwater flow is commonly inwards from the edge of the basin towards the coast and is therefore broadly in the direction of dip. Generally, hydraulic gradients are shallower than the dip of the strata and therefore groundwater flow in the shallow solution-enlarged fracture systems will

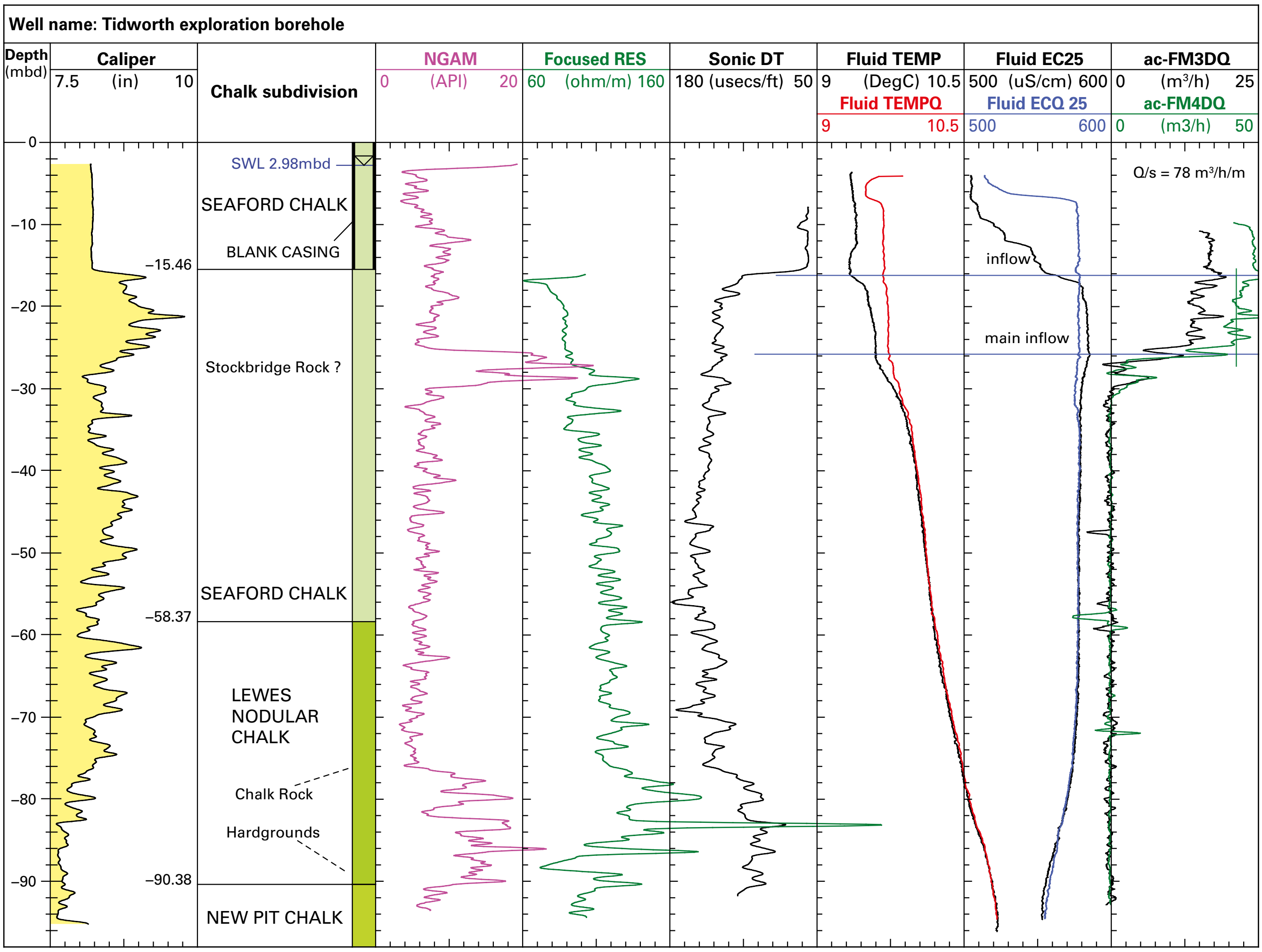

Figure 3.11 Geophysical logs showing concentrated water inflow above a hard band in the Seaford Chalk, North Tidworth Borehole, River Bourne catchment (data kindly provided by Thames Water in 2002).

tend to be transferred from lower to higher stratigraphical horizons as it moves down a catchment.

An example of this is given in Figure 3.13, which shows a section down the River Bourne catchment. The section is aligned approximately north–south and runs from the Aughton Borehole to the Tidworth Borehole via the Leckford Bridge Borehole, all of which are close to the river, hence groundwater is at shallow depths. It is evident that the strata dip down the catchment more steeply than the topographical gradient or the water table and that the dip is steeper in the north. Geophysical logging of the Aughton Borehole indicated flows at horizons in both the basal West Melbury Marly Chalk and the underlying Upper Greensand. Further down the catchment at Leckford Bridge, where the Seaford Chalk crops out, logging indicated flows in the Lewes Nodular Chalk and the lower part of the overlying Seaford Chalk. To the south at Tidworth, where the Lewes Nodular Chalk is deeper, little flow was obtained from this unit, and a hard layer, believed to be the Stockbridge Rock Member in the Seaford Chalk, provided most of the flow. Thus flow is controlled by suitable horizons near to the ground surface.

Figure 3.14 illustrates geophysical logs that were recorded in several of the Candover Scheme exploration boreholes in the eastern part of the Basin in the 1970s (by the Water Research Centre (WRC) and the Instititute of Geological Sciences (IGS) using analogue equipment). The logging data were digitised by the BGS and assembled into a scale cross-section to show the relationship of the Chalk units and their water inflows along a north-east–south-west line from Bradley to Itchen Down Farm in part of the River Itchen catchment. The lithostratigraphical interpretation shows that the boreholes all commence in the Seaford Chalk and penetrate the Lewes Nodular Chalk and the deepest just encounters the New Pit Chalk. The profiles are very similar and it is possible to identify particular named horizons (for example the Seven Sisters Flint band, Belle Tout Marl, Navigation Marl) in each borehole. In the lower part of the Lewes Nodular Chalk, the Lewes Marl, Caburn Marl, Southerham and Glynde Marl can be identified by their prominent low resistivity. These horizons represent the deeper water equivalent of the Chalk Rock hardgrounds seen further west.

The water inflows are interpreted from the fluid log profiles recorded whilst pumping (suffixed ‘Q’) and their positions are depicted by the horizontal blue lines. It is evident that the main inflows are predominantly from the Seaford Chalk and frequently from the same stratigraphical horizon, notably the Seven Sisters Flint band and the Belle Tout beds, which contain some hardgrounds. Figure 3.14 suggests that the inflows at and above the Seven Sisters Flint band probably contribute to the spring flows north-east of Totford. Figure 3.15 shows the geophysical log measurements for the BGS Totford Borehole in the middle of the section in more

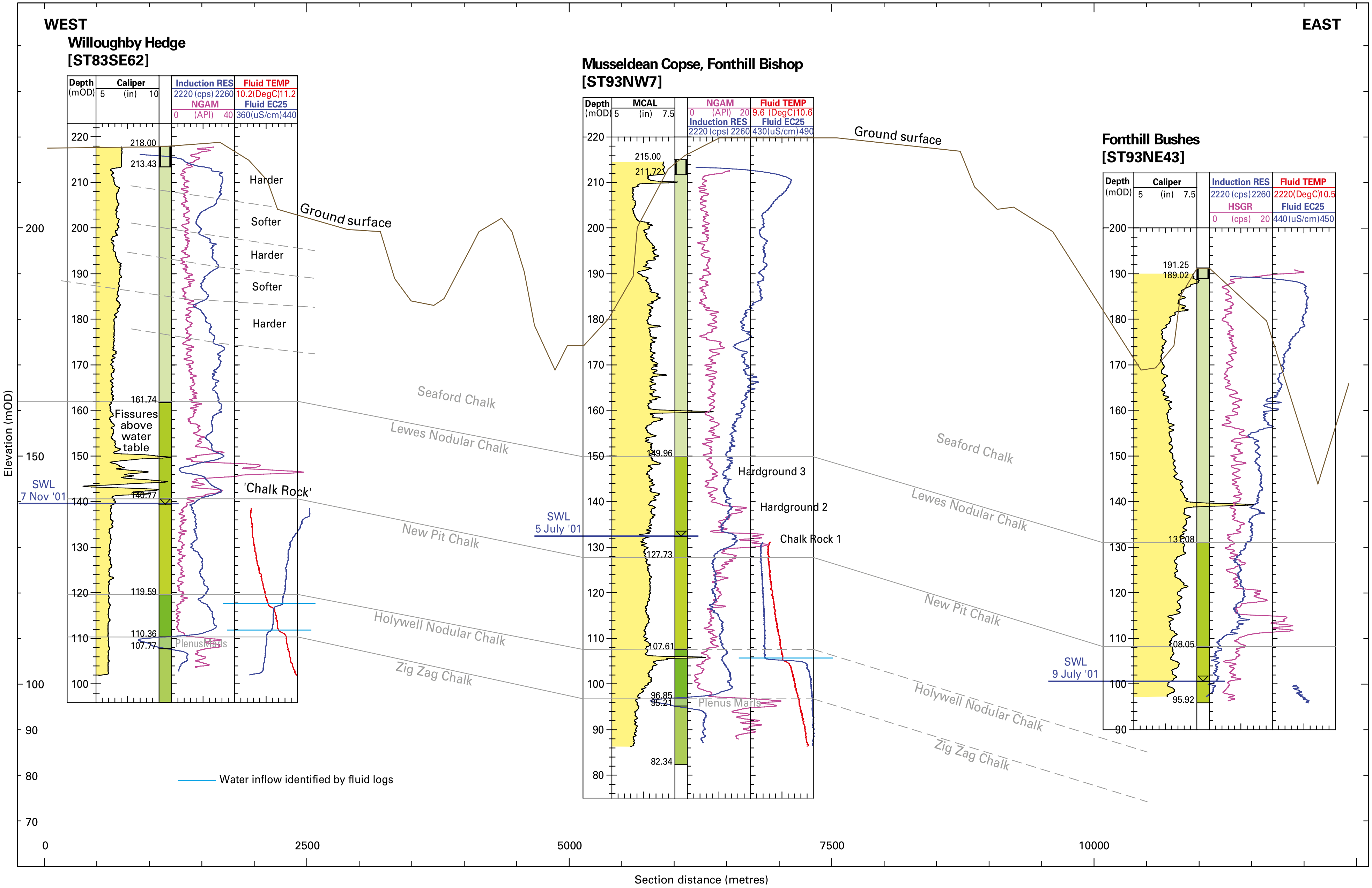

Figure 3.12 West to east cross-section showing the relationship of the Chalk units to topography and the position of the summer water table relative to the Chalk Rock hardgrounds, Fonthill Bishop area, Wiltshire (courtesy of Environment Agency).

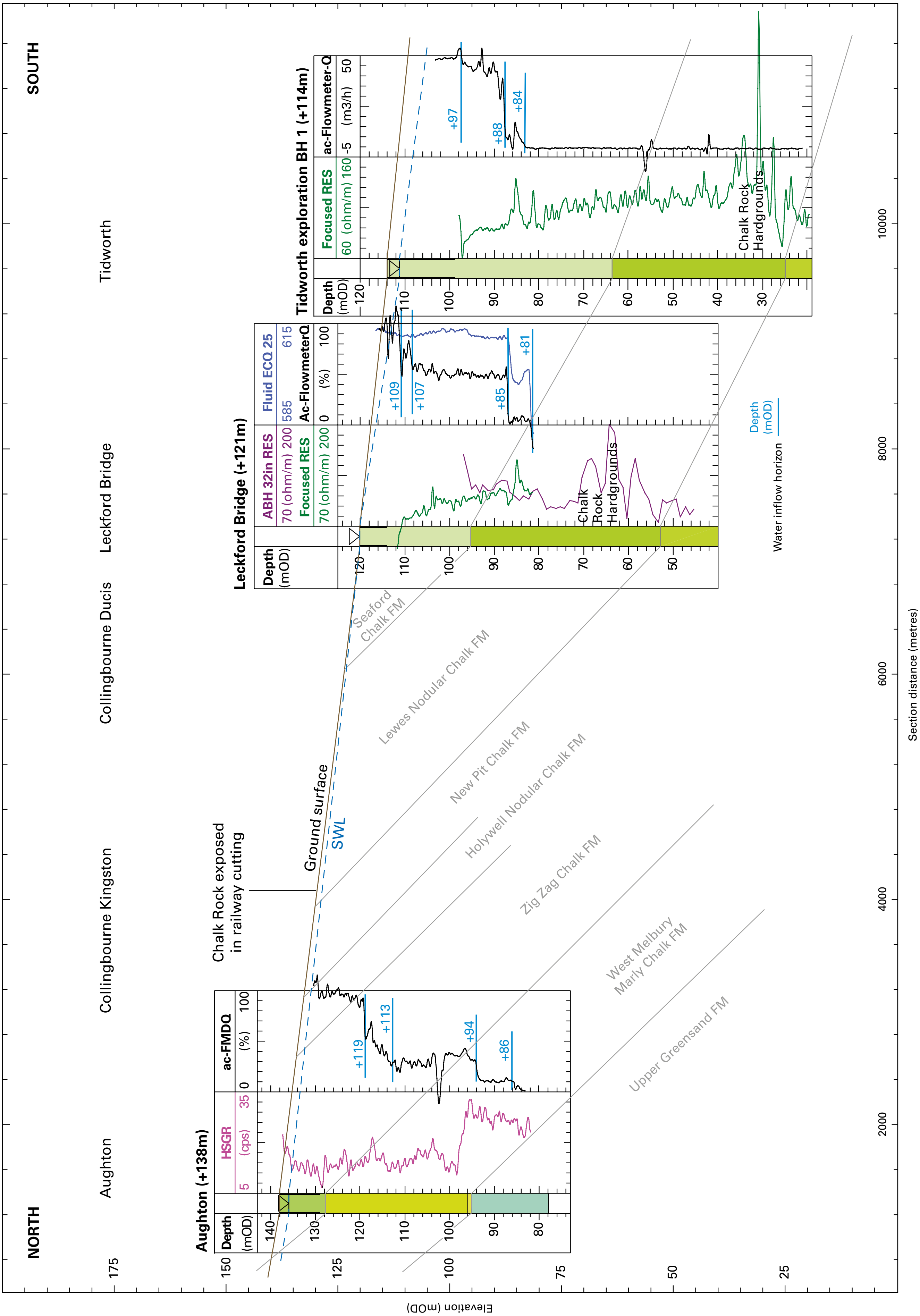

Figure 3.13 Scale cross section N-S showing the relationship of the Chalk units and the water inflow horizons, northern end of River Bourne catchment (courtesy of Environment Agency and Thames Water).

detail. The area-corrected (AC-flow meter) measurement represents the cumulative flow rate to the pump near the top of the borehole and the inflow histogram, processed from the curve (shown in green), depicts the main inflows. The interval packer-test measurements (shown in red) agree well with the flow-meter profile, although the packer testing identified higher permeability within the Lewes Marl–Southerham Marl interval, not seen by the flow meter (perhaps because the flow-meter measurement is head dependent). The flow meter however resolved important inflow through the wellscreen slots near the top of the borehole, which was not selected as a packer-test interval. The matrix hydraulic conductivity measurements made on the cores, shown in black, are uniformly low and emphasise the importance of the solution-enhanced fractures for groundwater flow in the Chalk. The flow meter log reveals that when pumped, the overwhelming bulk of the groundwater is obtained from less than 30 m depth (above about 50 m OD) in the borehole.

Figure 3.16 presents a comparison of caliper logs of selected Candover scheme boreholes plotted as depth below log datum (usually ground level or casing top close to ground level). The logs represent the variation of borehole diameter with depth and the plot reveals that generally there is enlarged diameter above 40 m depth in this area. The diameter enlargements may represent intervals of softer chalk having higher porosity due to weathering and Pleistocene effects, solution enlargement of fractures due to concentrated groundwater flow at certain horizons, or a particular lithology, for example soft sponge beds or marly chalk. They are also influenced by the current and historical range of seasonal water level fluctuation, and particular effects of the drilling, though generally drilling effects are usually minor. The position of water inflows identified by pumped fluid and flow meter logging drawn on the plot show they are all less than 60 m below surface and the majority are at less than 40 m depth, reflecting the hydraulic control on the development of permeability. Their shallow depth is an indication that current recharge inputs can be accommodated by flow within this shallow zone. It may be, in fact, that current recharge could be dissipated within the top few metres only and the deeper flow horizons indicated may have been developed during drought periods or during intervals in the past when base levels and sea level were lower.

3.3.3.2 The confined aquifer

The foregoing discussion indicates that the nature of the groundwater flow system in the Chalk is such that inflows and better borehole yields are usually obtained at shallower depths where there has been a greater natural concentration of groundwater flow to develop the permeability. However, in the Wareham[5] area, where the Palaeogene sediments overlying the Chalk can be more than 100 m thick, fluid logging has identified isolated water inflows at much greater depths (-170 m OD in the Stoborough and Holton Heath boreholes, and at -220 m OD in Wareham Common OBH2). Such deep inflows are not normally encountered in the Chalk aquifer, but the facts that the yield from these deep horizons is negligible (borehole specific capacities are less than 1 $m^3 h^{-1} m^{-1}$), that groundwaters have the chemical and isotopic characteristics of long residence time and that the waters are relatively warm, all suggest that they are part of a slow-moving, poorly developed groundwater flow system. The more rapid groundwater flows in this system originate at the Chalk outcrop and discharge via the sandier layers in the Palaeogene cover.

Where the Chalk aquifer is less deeply confined it is more productive; generally the highest borehole yields in the Wareham area are from the top 50 m of the Chalk in outcrop areas, and from confined Chalk where the Palaeogene cover is less than 70 m thick (Figure 3.17).

The section in Figure 3.17 illustrates the likely transfer of groundwater from the Chalk to the Palaeogene sediments as it moves down flow lines from west to east and from north-west to south-east. The potentiometric surface is above ground level over much of the area and has a gradient which is shallower than the dip of the Chalk. Groundwater is considered to circulate within the sandier layers between more clayey layers in the Palaeogene sequence in lower parts of the basin. In the Arne area east of Wareham, where the Palaeogene sediments are worked for ball clay, the sandy layers have relatively high heads and shallow boreholes are allowed to flow to release the pressure.

Groundwater circulating within the Palaeogene sediments can sometimes be recognised by its effect on fluid temperature logs recorded within the casing of newly drilled boreholes. Figure 3.18 illustrates fluid temperature profiles recorded within relatively long blank casing (approximately 100 m) against Palaeogene deposits overlying the Chalk in the Raglington Farm Borehole at Row Ash [SU 54 13], in the Blackhorse Farm Borehole at Bishops Waltham in Hampshire [SU 56 14], and in a borehole in the Wareham area. In the latter, the two fluid temperature profiles reveal elevated temperature against the casing interval (0 to 100 m) caused by the casing cement. In each of these boreholes, the cooling observed opposite the sandy (low gamma ray) horizons signifies a more rapid circulation of shallow groundwater through the clean, sandier layers, removing the heat generated by the cement.

The borehole construction shown for the Raglington Farm Borehole in Figure 3.18 also illustrates one of the difficulties that can be faced when drilling into the Chalk beneath Palaeogene strata where the top Chalk surface has been deeply eroded and karstified. The casing was initially landed in firm Chalk strata at 126 m depth (see gamma-ray log), only to encounter additional Palaeogene sediment filling conduits in the Chalk land surface below. A dropset casing had to be installed into firm Chalk from 126 to 143 m.

Geophysical logging has demonstrated that in several areas around Wareham the basal Palaeogene sediments are sandy (Figure 3.17). In areas of artesian overflow from the Chalk, artesian pressure can be encountered within sandy basal layers of the Palaeogene sediments, and cause drilling difficulties, before the Chalk is penetrated.

Neither the Raglington Farm nor Blackhorse Farm boreholes had artesian flow, but they had poor yields. Both boreholes were acidised after drilling to improve the yields and residual acid was present when they were logged (see Fluid EC 25 measurements, Figure 3.18) and the quantity of acid remaining was an indication of little or no natural groundwater flow taking place to disperse it. Yields were not improved by the acidisation because there was no existing fracture system present to be developed. At these locations, the fluid temperature logging suggested that the current groundwater flow was taking place mostly within the overlying Palaeogene sediments. In the Blackhorse Farm Borehole, cooling of the borehole fluid between 110 and 120 m depth identifies some groundwater circulation within

[5] A significant number of water exploration boreholes were drilled, tested and geophysically logged in the Dorchester-Wareham area of Dorset as part of the Wessex Water Wareham Groundwater Project in 1992–1995. Subsequently boreholes at Lytchett Minster, north-east of Wareham, were selected for trialling of an aquifer storage and recovery (ASR) scheme and were also geophysically logged.

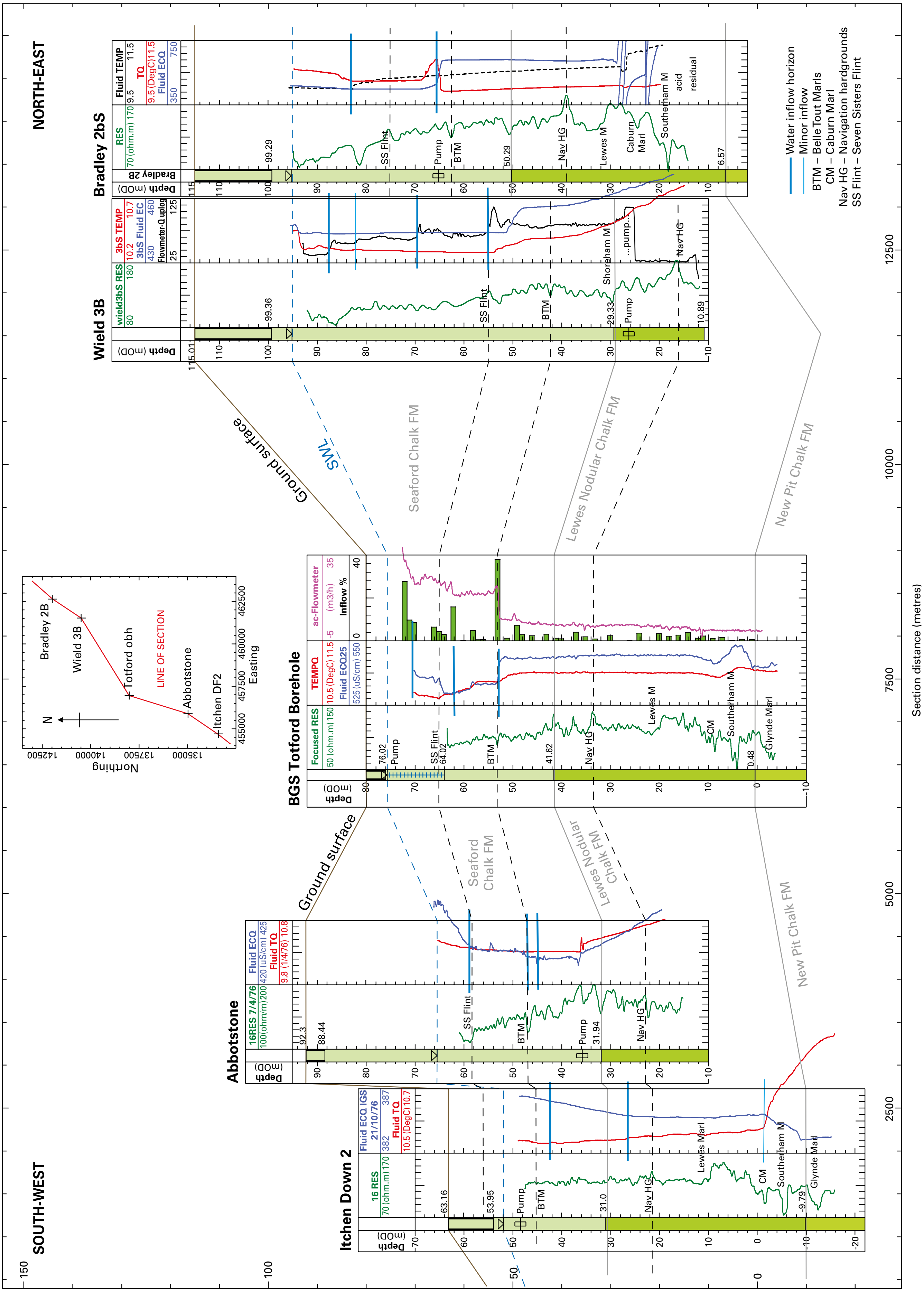

Figure 3.14 *Scale cross-section north-east to south-west using digitised 1970s logging data to correlate Chalk units to show water inflows, Candover Scheme boreholes, Hampshire.*

the top 10 m of the Chalk. Such cooling was not evident however in the Raglington Farm Borehole where the base of the Palaeogene was deeper (139 m).

3.3.3.3 Springs

Many springs issue from the Chalk and may result from the occurrence of marly bands, which impede vertical water flow, and hard, well-fractured rock bands along which there can be considerable lateral flow. Springs determined by lithology are common at the Chalk scarp foot and are often seasonal. Springs may also occur at other levels in the Upper/Middle Chalk (White Chalk), but they are usually small and tend to dry up during the summer and autumn.

Those springs that occur on the dip slope of the Chalk are nearly always in the base of valleys and are of the overflow kind, i.e. where the water table intersects the surface. Identifiable perennial springs often form the perennial head of winterbourne streams, with intermittent springs contributing to winter streamflows upstream. During extreme recharge events, such as occurred in the winter of 2000 to 2001, fissures normally above the winter water table become saturated and flow as springs at high elevations, causing groundwater flooding.

The springs at Bedhampton [SU 707 064] form the largest public supply spring source from the Chalk in the UK. Rapid groundwater flow to the springs has been shown, where a tracer study carried out between a series of stream sinks to the north of the Bere Forest Syncline and the springs 5 km away to the south of the syncline (Atkinson and Smith, 1974) proved a direct connection and indicated turbulent flow through a discrete conduit system. The velocity of groundwater movement was calculated to be 2 km d^{-1}. This conduit system is located in the chalk at the northern margin of the Palaeogene outcrop and it is thought that it has developed due to the increased solution potential of run-off from the nearby or overlying Palaeogene sediments. More than 70 per cent of the tracer dye was recovered from the test, and the majority of it arrived at one spring within a few days. This implies that flow occurred through a discrete set of conduits, rather than a diffuse network.

3.3.4 Surface water – groundwater interaction

3.3.4.1 Complex winterbourne behaviour

Winterbourne behaviour, resulting from annual variations in groundwater levels, is common in streams in the Wessex Basin and is described in Chapter 1. However, across the Wessex Basin there are several rivers and streams where the surface and groundwater interactions appear to be more complex than those implied by the simple winterbourne model. During the dry summer months, a number of Chalk streams and rivers tend to flow in their upper reaches and then cease flowing for a distance along their course before flowing again further downstream; in a few instances, more complicated flow patterns are observed.

Such erratic bourne behaviour has been periodically monitored by the Environment Agency in a number of Chalk streams in the Wessex Basin. In general, this has involved

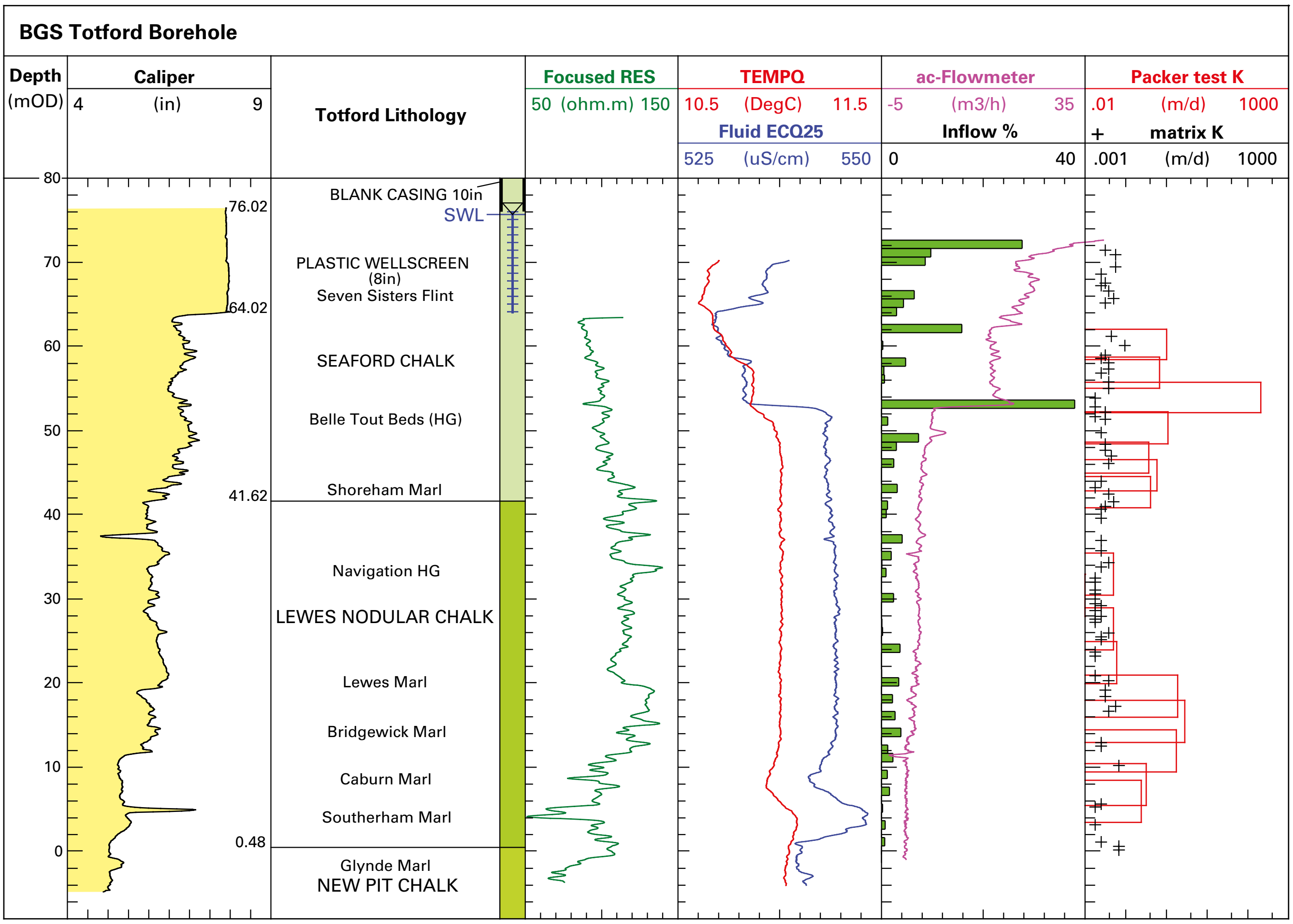

Figure 3.15 Pumped fluid and flowmeter logging and packer test measurements used to identify horizons of fluid movement, Chalk aquifer, BGS Totford Borehole, Hampshire.

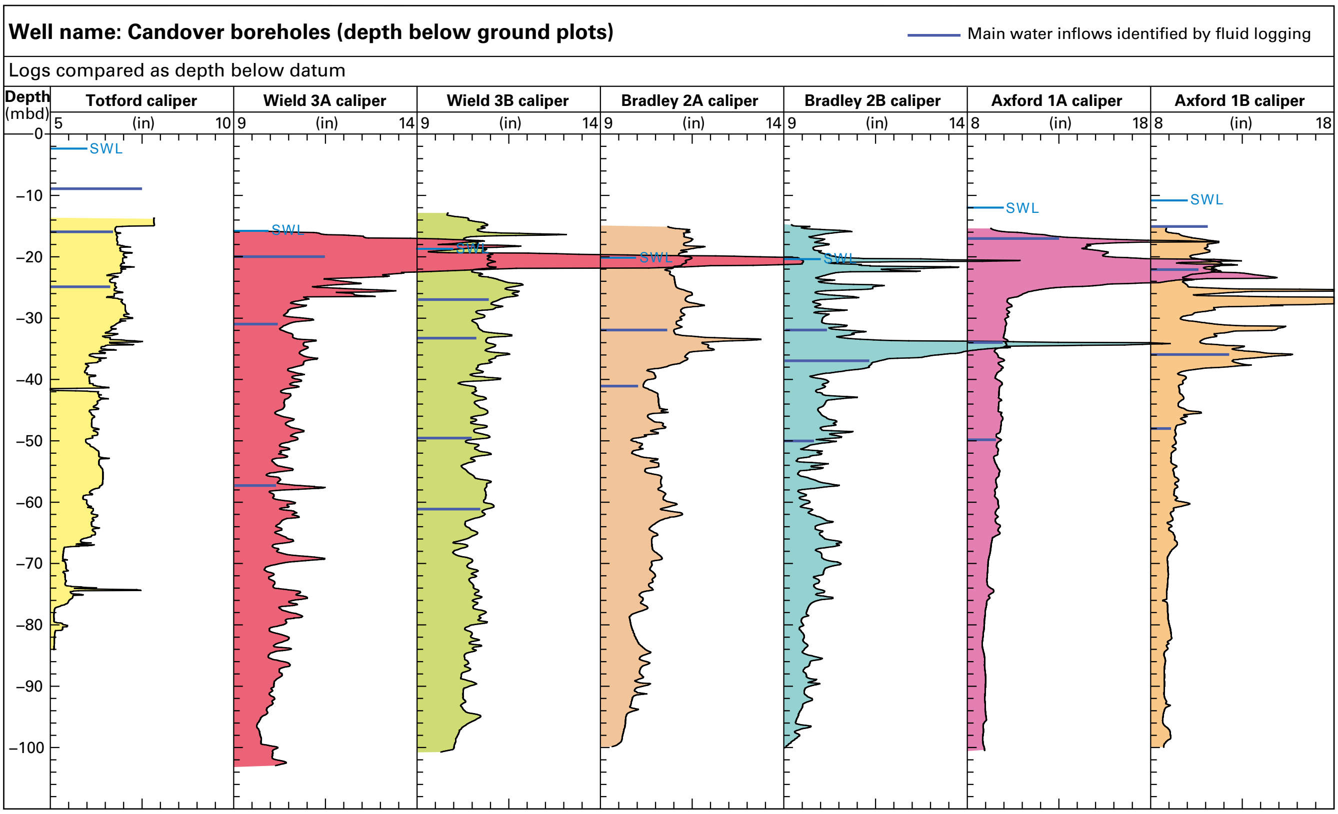

Figure 3.16 Comparisons of caliper logs and main water inflow horizons, depth below surface plot, Candover Scheme boreholes.

noting whether the stream is flowing or not at a number of specified points upstream from a datum near to the perennial head, then repeating the survey at intervals using the same observation points. The results are then plotted to produce a 'bourne signature' for the stream.

The South Winterbourne, a tributary of the River Frome, has been monitored at flow observation points at 1 km intervals along the length of the river, upstream of West Stafford Bridge (Figure 3.19). During the first survey (January 1993) a record was made of whether the river was flowing or not at each observation point and then the survey was repeated at intervals over a period of several years. The results are illustrated in Figure 3.20. For each date on which the survey was undertaken, the corresponding location was shaded if the river was found to be flowing, or left blank if no flow was observed. The chart was then shaded or left blank in intermediate, unobserved periods to produce the smoothed record shown in Figure 3.20.

The figure therefore provides a simple visual indication of the complexity of the flow characteristics of the river. For example, considering the year 1994, the chart shows that in January the river flowed constantly from a point 15 km upstream from the datum point. The head of the river then declined, as would be predicted by the classic winterbourne model until, by mid July, it had reached approximately the 13 km mark. However, between mid July and the end of November, while the head of the river declined very slightly, flow also ceased between around 9 km and 1 km above the datum — a phenomenon not predicted by the conventional bourne flow model. Thus, whereas the conventional winterbourne model would be expected to result in an annual bourne 'signature' with a roughly 'u' or 'v' shaped open form annually — indicating a progressive drying of the stream to its perennial head as a result of falling and then rising water tables — the actual signature of the South Winterbourne was always more complex during the monitored period. This was particularly the case in mid/late summer when a signature of the form no flow/flow/no flow/flow occurred downstream from the maximum river-head position each year.

Figures 3.21 to 3.26 show the winterbourne signatures of a number of other streams and rivers monitored by the Environment Agency in the Wessex Basin (all data plots courtesy of Environment Agency, South West Region).

It can be seen that that the River Till (Figure 3.21) and the Chitterne Brook (Figure 3.22), both tributaries of the Wylye, show the expected winterbourne behaviour for the majority of the period over which they were monitored, with the upstream limit of the rivers gradually moving downstream during the drier summer months. However, in May 1997 the River Till flows over a short distance between the 8 and 9 km observation points before the flows disappears again and re-emerges further downstream. This behaviour is seen again further upstream in Jan/Feb 1998 and in the Chitterne Brook in April 1997.

In the Piddle catchment, however, the Bere Stream (Figure 3.23) shows the opposite behaviour to that expected, producing a signature with an inverted U-shape. Thus it flows all year round in its upper reaches but dries up during the summer months in the downstream section, and the point at which it stops flowing moves progressively upstream from the perennial head.

The Devil's Brook (Figure 3.24) (also a tributary of the Piddle), the South Winterbourne (Figure 3.20) (in the adjacent Frome catchment) and the North Winterbourne (Figure 3.25) (close to the Bere stream, in the Stour catchment) all show a similar behaviour. Flow occurs downstream from the stream head and then dries up over a short section before the flow resumes again further downstream. It should be noted, however,

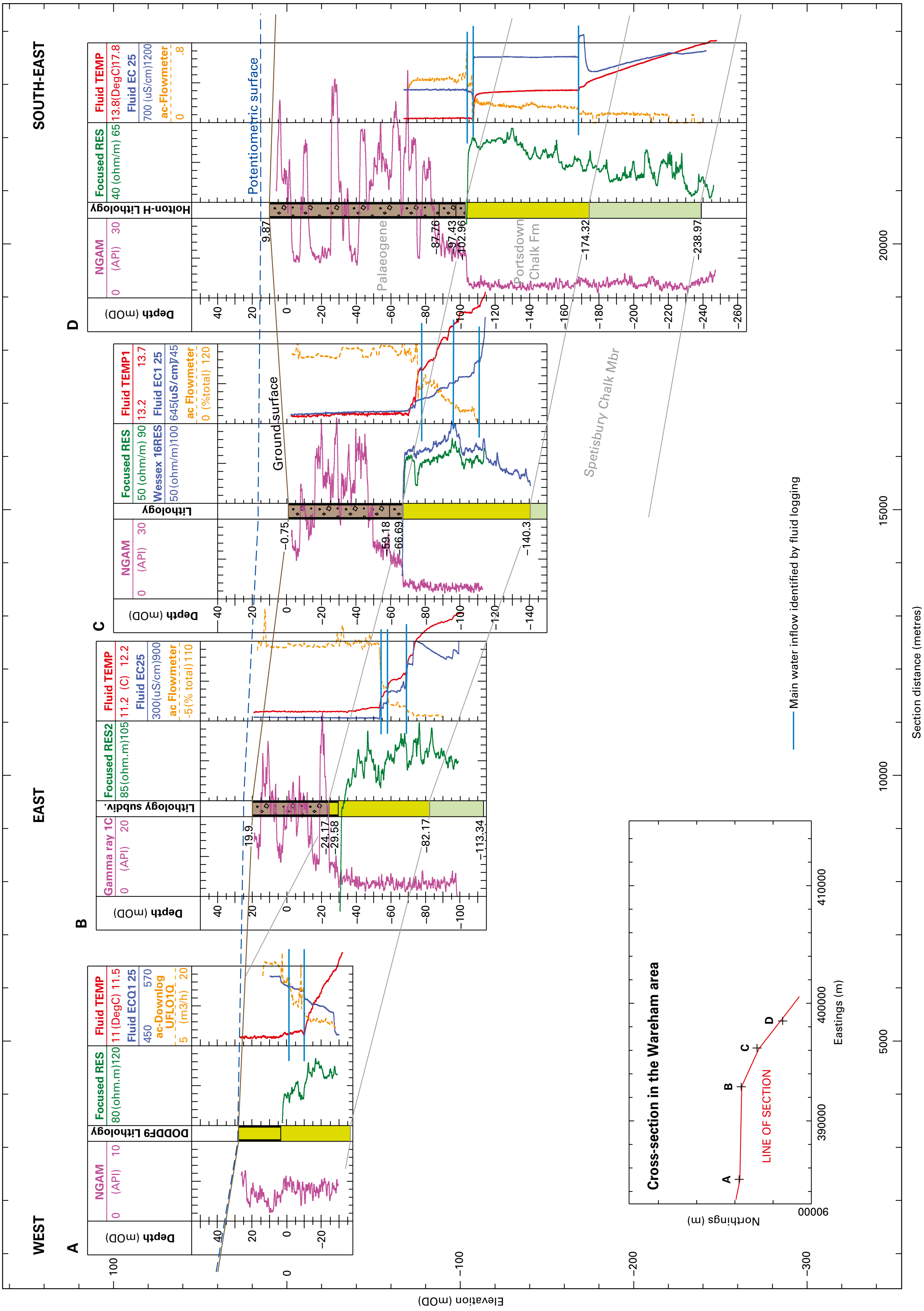

Figure 3.17 Scale cross-section Wareham area, based on geophysical log data showing main water inflow horizons in the Portsdown Chalk.

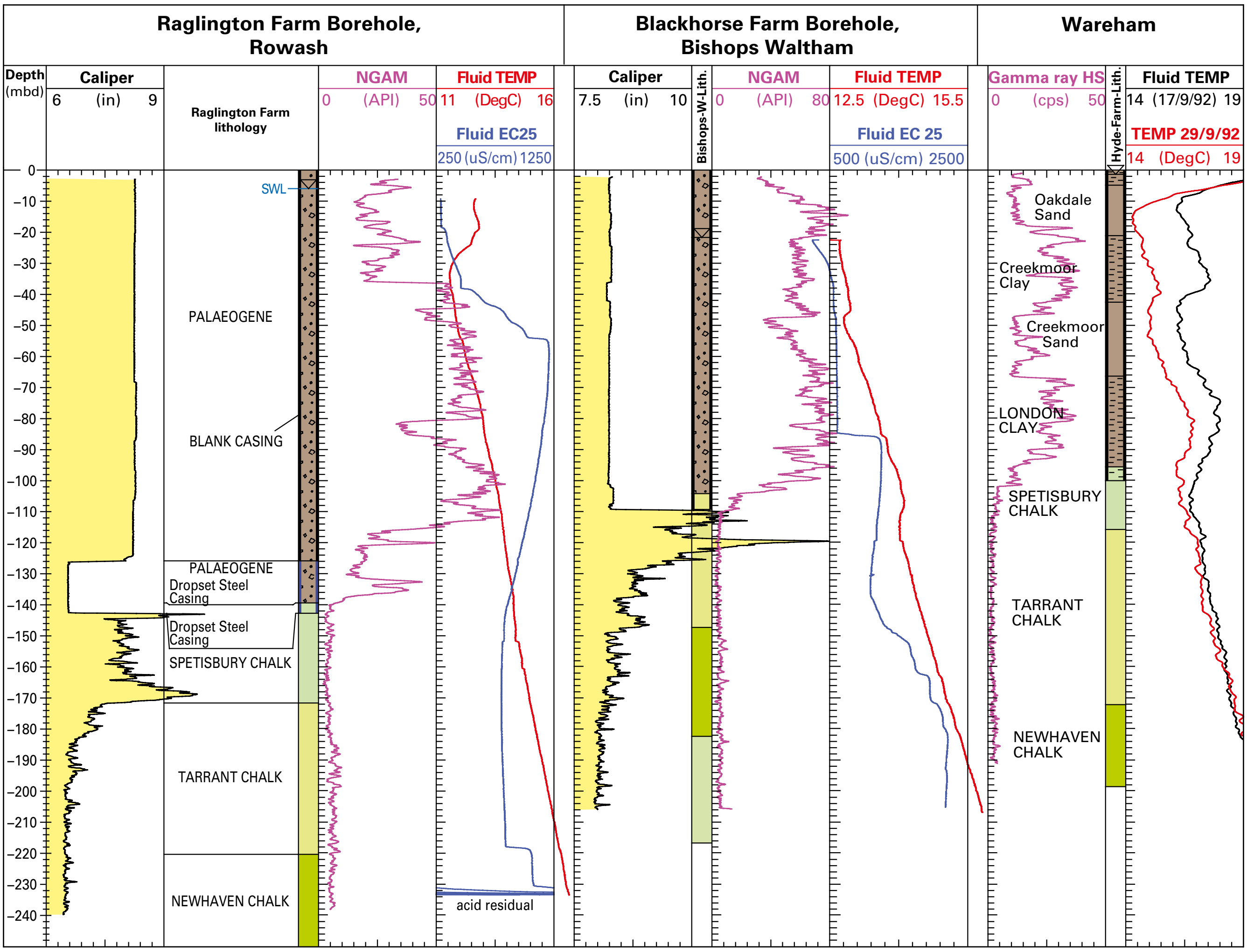

Figure 3.18 Fluid temperature logs of selected Wessex Basin boreholes with thick Palaeogene cover displaying local cooling within casing indicating groundwater movement within sandier layers of the Palaeogene strata.

that the upper reaches of the River Piddle exhibit sections which, while not necessarily drying, are influent (Howden, 2004). This is likely to be the case for other streams, and this simple graphical 'signature' approach can only be regarded as indicating the general nature of the streams — their true complexity can only be revealed by accretion gauging.

The River Bourne (Figure 3.26) was looked at in a detailed study carried out by the Environment Agency that examined low flows in both the River Bourne and the Nine Mile River (Environment Agency, 2001; Environment Agency and Water Management Consultants, 2004). The Bourne appears to dry up along most of its length during the dry months except for a section 24 to 25 km from the datum point (probably associated with discharge from a sewage treatment works) and from 2 km to the datum. However a section around 12 km from the datum was seen to be particularly vulnerable to drying. The Agency also looked at flow accretion profiles and found these to show a similar flow pattern to that recorded at the observation points.

The causes of this behaviour in these rivers and streams appear to be varied. In some cases, a lowering of the water table by local abstractions may result in effluent streams becoming influent over certain reaches. For example, studies carried out on the River Piddle, which also shows a loss of flow in its upper reaches, have concluded that stream-bed leakage is thought to be increased by groundwater abstractions. (Mansell-Moullin, 1986; Wessex Water Authority, 1988; National Rivers Authority, 1992a, 1995a; Halcrow, 1995; Stuart, 2000). A study carried out by Marcus Hodges Environment (1999) on the Upper Piddle found that although reducing the abstraction

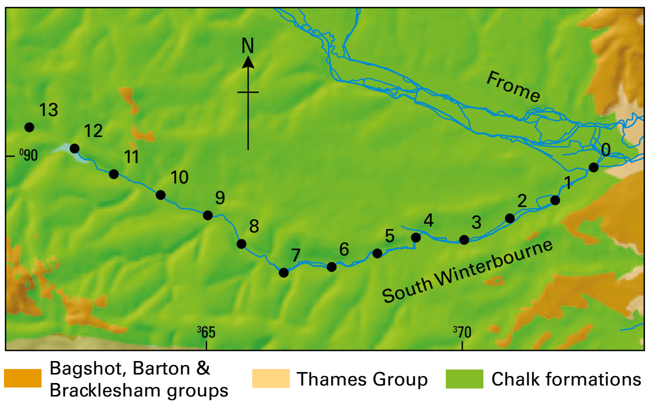

Figure 3.19 South Winterbourne with locations of a number of observation points, showing flow to the 12 km mark (observation points courtesy of Environment Agency).
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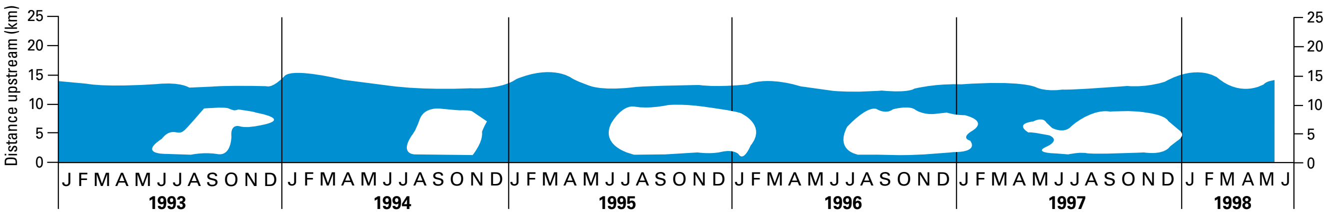

Figure 3.20 South Winterbourne flow signature – Frome catchment (courtesy of Environment Agency).

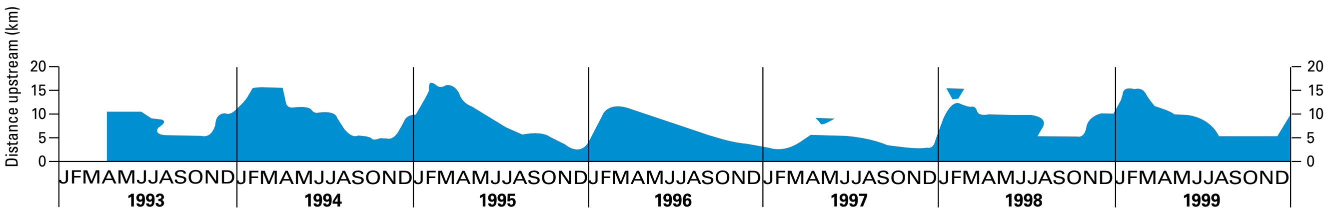

Figure 3.21 River Till flow signature – Wylye (Avon) catchment (courtesy of Environment Agency).

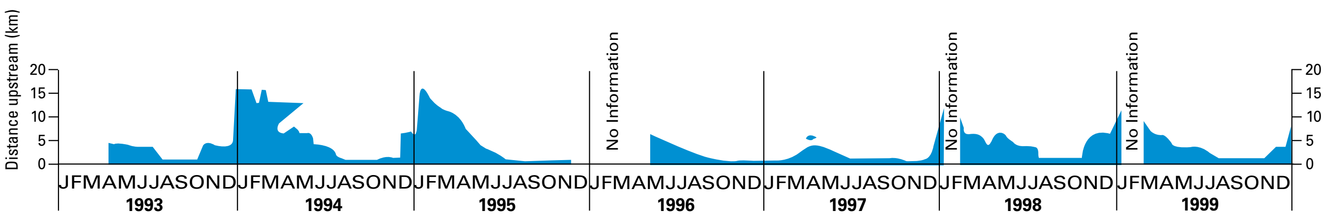

Figure 3.22 Chitterne Brook flow signature – Wylye (Avon) catchment (courtesy of Environment Agency).

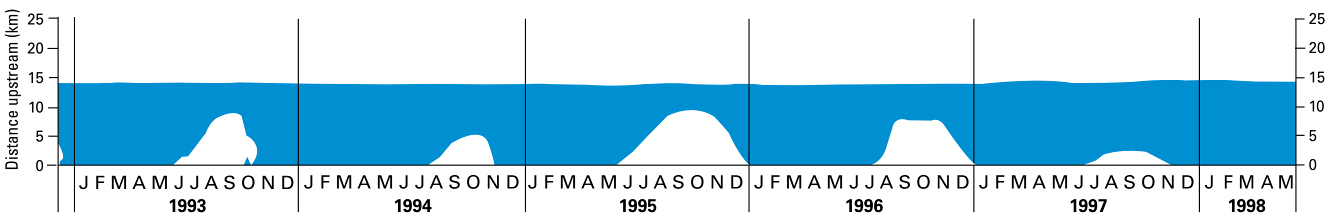

Figure 3.23 Bere Stream flow signature – Piddle catchment (courtesy of Environment Agency).

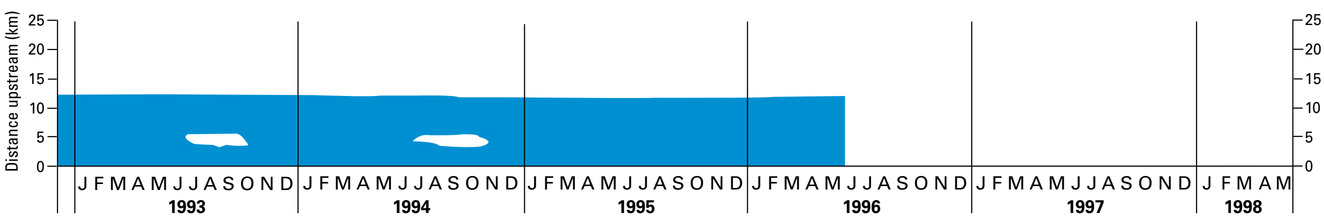

Figure 3.24 Devil's Brook flow signature – Piddle catchment (courtesy of Environment Agency).

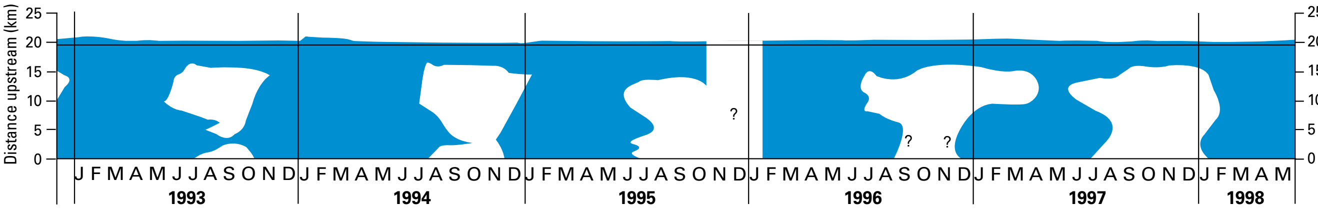

Figure 3.25 North Winterbourne flow signature – Stour catchment (courtesy of Environment Agency).

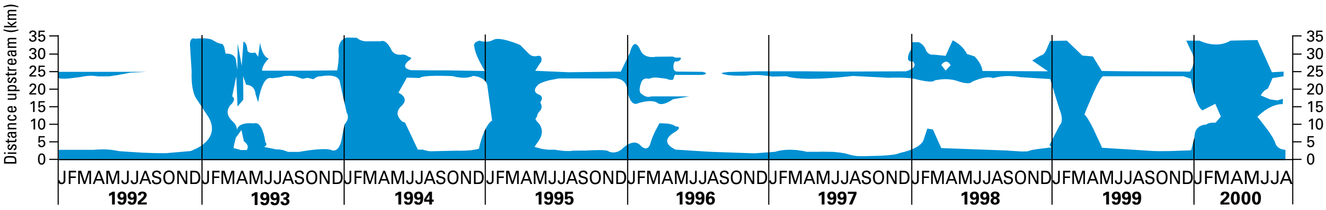

Figure 3.26 River Bourne flow signature – Avon catchment (courtesy of Environment Agency).

rate at the nearby Alton Pancras Borehole [ST 70 01]] resulted in an increase in flow in the Piddle, the additional flow recorded in the river was only 30 per cent of the amount anticipated and that a significant proportion of the water was effectively 'lost'. They concluded that the 'missing' water was being transmitted through the Middle Chalk rather than emerging as flow in the River Piddle. Thus there would appear to be a natural streamflow loss from the Piddle that is exacerbated by abstraction, a conclusion supported by the evidence of mid-stream drying in the Piddle tributaries, described above.

In the River Bourne study (Environment Agency, 2001) historical references (Shore, 1894; Dewar, 1898) were examined and it was concluded that the River Bourne has always been an ephemeral stream and that similar flow characteristics to those seen today were observed in the late 1800s. The relationship between groundwater and surface water behaviour in these streams is therefore complex, with groundwater abstractions involved in some cases, and not in others.

One cause of the complex winterbourne behaviour could be related to the geological setting of the stream. For example, general lithological variations might be a contributory factor. Thus several of the streams illustrated in Figures 3.20 to 3.26 appear prone to drying during the summer after they flow over the Lewes Nodular Chalk/Seaford Chalk boundary and the lower section of the Seaford Chalk. This can be observed in the South Winterbourne, and in the Devil's Brook, the Bere Stream and the North Winterbourne (Figure 3.27). However, the behaviour of other streams does not follow this pattern. The River Till (Figure 3.21) dries up progressively along its length over the Lewes Nodular Chalk and the Seaford Chalk in its upper reaches but flows continuously in the lower reaches over the Lewes Nodular Chalk. The Chitterne Brook (Figure 3.22) dries up continuously along its length, which includes the Seaford Chalk, the New Pit Chalk, the Holywell Nodular Chalk, the Zig Zag Chalk and the West Melbury Chalk. The River Bourne (Figure 3.26) exhibits the complex behaviour mentioned above.

Thus it is apparent that bourne behaviour may not be controlled by Chalk geology at the gross stratigraphical division level, however, detailed studies of particular streams in the Wessex Basin have shown definite correlations between geology (in terms of Chalk lithology and structure) and surface water flows. One such study concerns the Upper Piddle.

3.3.4.2 Case history — the Upper Piddle

The flow characteristics of the River Piddle do not follow the typical winterbourne behaviour discussed in Chapter 1. The hydrogeological processes operating in the Piddle catchment have been the basis of several detailed studies and a number of useful conclusions can be drawn from these with respect to the complex surface–groundwater interactions in chalk streams and rivers.

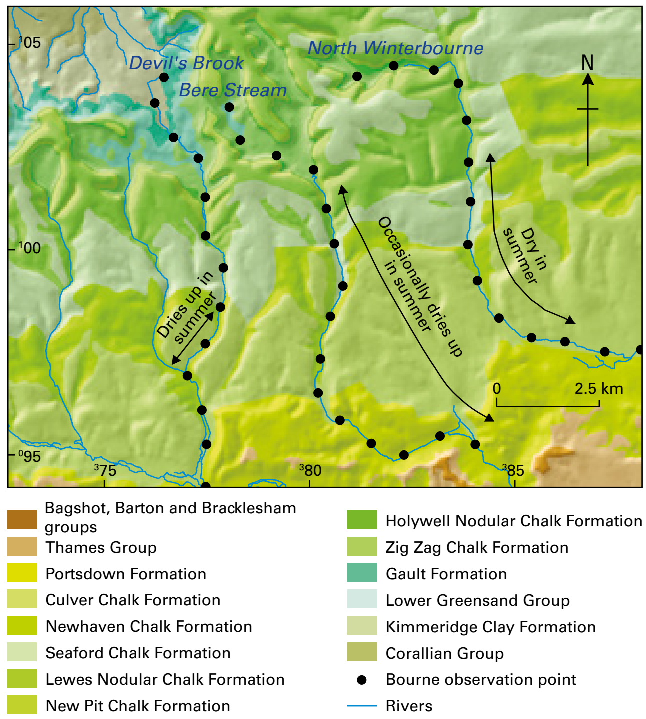

Figure 3.27 Winterbourne behaviour of Devil's Brook, Bere Stream and North Winterbourne in relation to geology.
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Figure 3.28
Geology of the Upper Piddle catchment.
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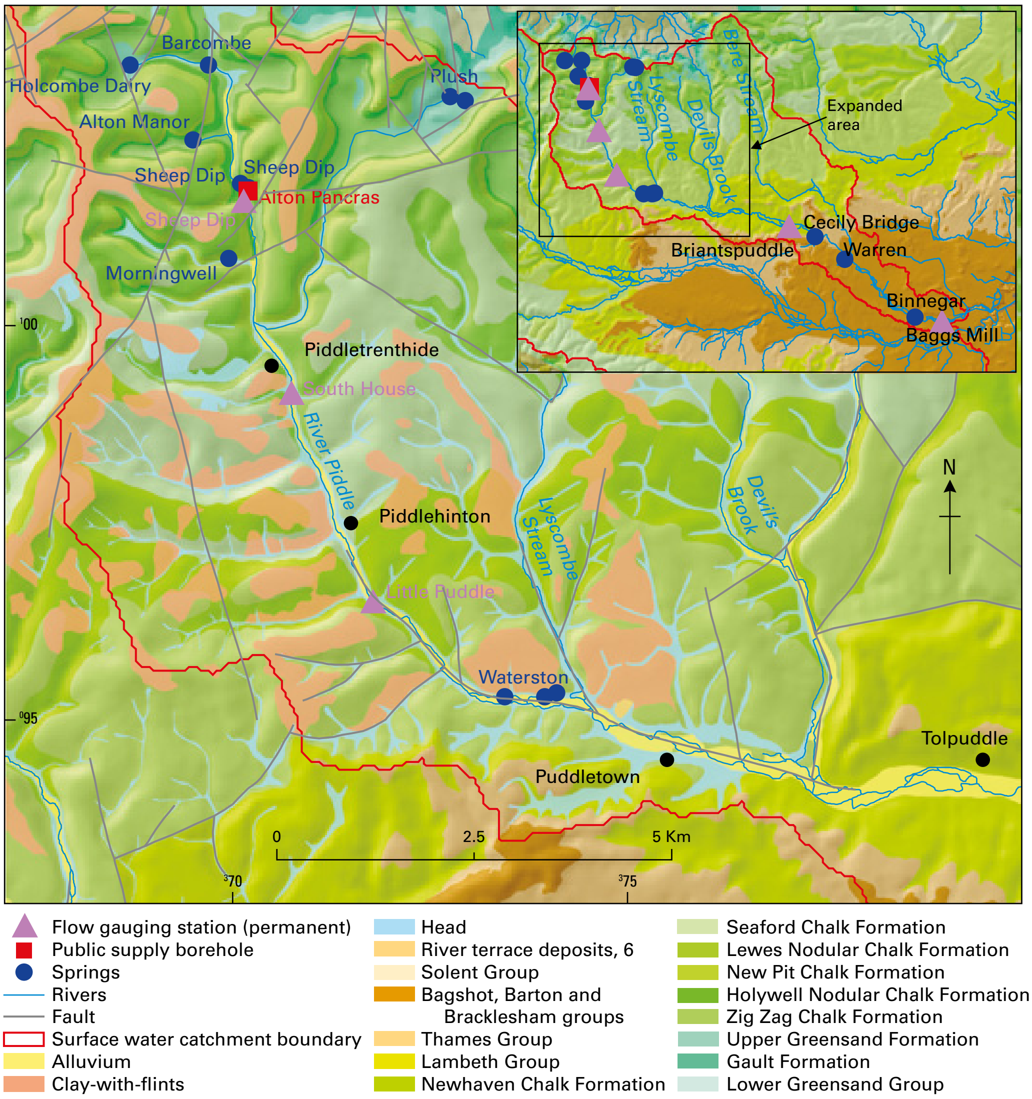


The River Piddle is relatively small and rises at springs in the north Dorset Downs close to the village of Alton Pancras, and flows south-east for approximately 40 km to a common estuary with the River Frome before discharging into the English Channel at Poole Harbour (Figures 3.28; 1.6). Its three main tributaries are the Lyscombe Stream, the Bere Stream and the Devil's Brook.

Groundwater abstraction in the catchment is high, with a total maximum daily licensed quantity of 197 Ml day^{-1} (Howden et al., 2004). The majority of groundwater abstractions (by licensed volume) are for public water supply of which there are four in the catchment and two of these are located adjacent to the River Piddle. Low flows in the river due to abstraction are exacerbated by natural conditions whereby the river becomes perched and leakage occurs (Marcus Hodges Environment, 1999).

The hydrogeology of the Upper Piddle catchment has been the subject of several investigations by the Environment Agency and Wessex Water to determine the potential effects on river flow of groundwater abstraction from a source at Alton Pancras (Figure 3.28). The flow characteristics of the Piddle are complex, with both influent and effluent behaviour seen. Previous studies (Halcrow, 1995; Marcus Hodges Environment, 1999; Howden et al., 2004) have identified the importance of spring sources in supporting streamflow.

The development of a new lithostratigraphical framework for the Chalk (Bristow et al., 1997; Hopson, 2005) has enabled a much more detailed assessment of the influence of lithological and structural controls on groundwater flow to be carried out through the development of a more detailed understanding of the geology. Howden et al. (2004) uses the new interpretation of the Piddle catchment geology (Newell et al., 2002) to investigate surface–groundwater interactions in the river valley and to determine how these effect the distribution of surface water flows in the River Piddle.

Catchment geology

The geology of the Upper Piddle is shown in Figures 1.6 and 3.28. It is predominantly underlain by Chalk, with the river rising just to the south of the Chalk scarp at the junction of the Upper Greensand and Lower Chalk. The Chalk dips to the south by about 2 to 3 degrees and is cut by two sets of faults oriented north-east to south-west and north-west to south-east[6]. Fault throws are typically around 5 to 10 m and with a maximum throw of 25 m.

The dip of the Chalk combined with faulting and erosion has resulted in a complex sequence of outcropping Chalk units along the valley floor and sides. For example, faults cross the Upper Piddle at Sheep Dip and Morningwell (Figure 3.28). The Zig Zag Chalk crops out in the valley floor down to Morningwell, with the Holywell Nodular

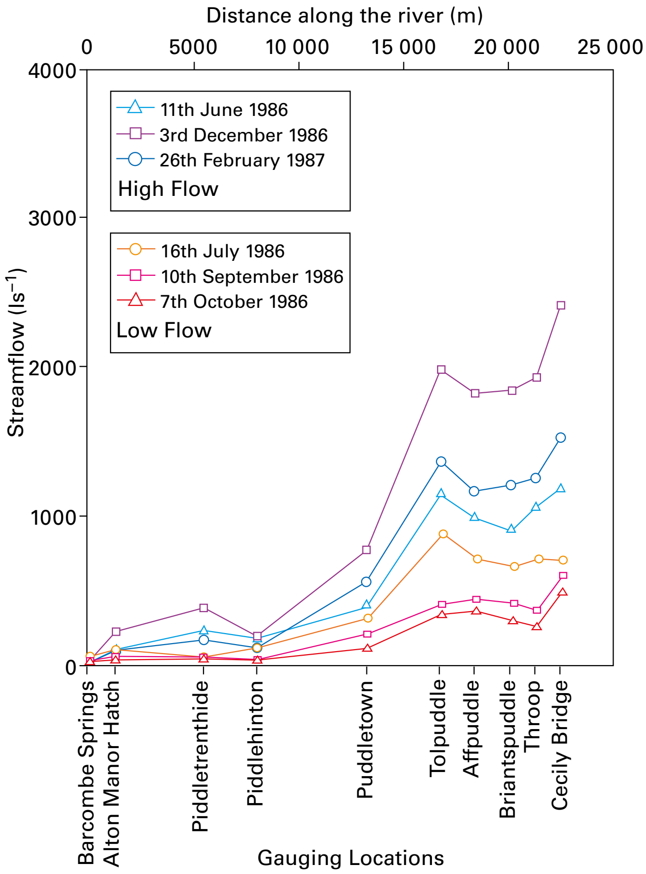


Figure 3.29 Flow accretion profiles for the River Piddle (using flow gaugings by Wessex Water Authority, 1986) after Howden et al., 2004.

Chalk and the New Pit Chalk outcropping along the valley sides. Downstream of the fault at Morningwell, the New Pit Chalk crops out in the valley floor, and further downstream by the Lewes Nodular Chalk. At White Lackington the Seaford Chalk crops out in the valley floor, and further down the catchment outcrops of younger Chalk units are found, i.e. Newhaven and Tarrant Chalk.

Geological controls on surface–groundwater interactions

As part of a study of the Upper Piddle, examination of borehole water level data (Marcus Hodges Environment, 1999) indicated that significant reaches of the river were frequently perched. The study concluded that, while the entire length of the Upper Piddle is usually effluent (gaining) during the winter recharge period (of several weeks in most years), as groundwater levels subsequently decline nearly all the river becomes perched, resulting in influent behaviour and groundwater flow towards the perennial head downstream. For the periods of the year when the river is perched, the sources of river flow are several headwater springs.

Howden et al. (2004) found that the longitudinal streamflow profiles (Figure 3.29) showed a consistent streamflow accretion between Holcombe Dairy (upstream of Barcombe) and Alton Pancras (downstream of Alton Manor), Piddlehinton and Puddletown and between Throop (about 1 km east of Briantspuddle) and Cecily Bridge, with stream-flow depletion occurring between Piddletrenthide and Piddlehinton and also between Tolpuddle and Throop. It was concluded that stream-flow accretion occurs both due to spring flow entering the river channel and at a confluence with a tributary (e.g. the Devil's Brook).

Both studies (Marcus Hodges Environment, 1999; Howden et al., 2004) found a strong correlation between the locations of the springs feeding the Upper Piddle and their geological setting. Table 3.2 summarises their findings and suggests that both lithological and structural controls by faulting play a role in determining the location of springs.

Loss of flow to river-bed leakage is a recognised characteristic of rivers in the Piddle catchment according to the Avon and Dorset River Authority (1970), which records the Piddle as 'going to ground' during the late summer months. The loss of flow in the Upper Piddle is quantifiable using two streamflow gauges on the leakage section: South House and Little Puddle. Data from these flow gauging stations have been used to demonstrate loss of streamflow (Halcrow, 1995; Marcus Hodges Environment, 1999; Stuart, 2000) although no analysis or firm conclusions were drawn from them.

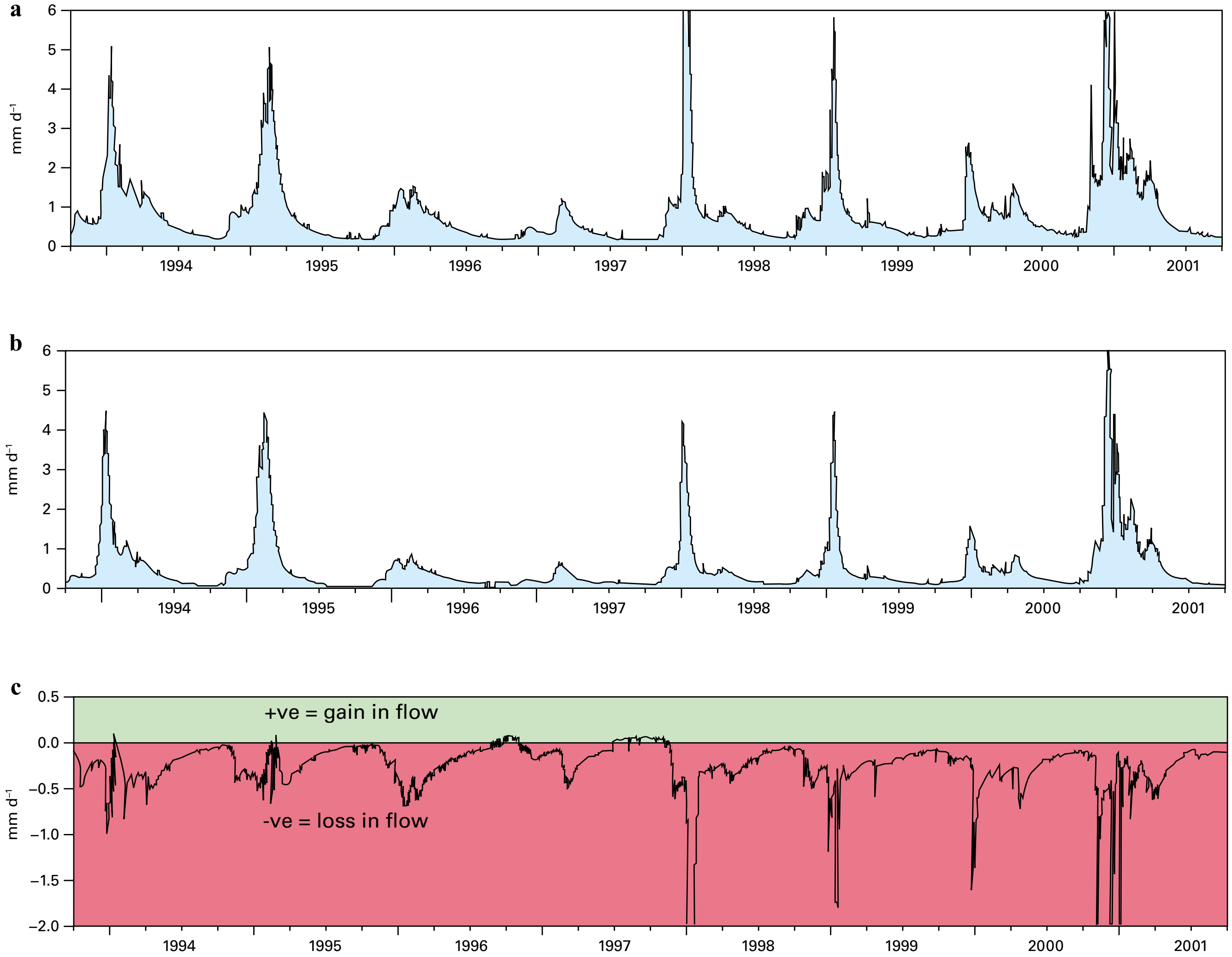
Howden et al. (2004) derived a leakage hydrograph from the difference between the hydrographs from two gauging stations (Little Puddle and South House). If the contributing subcatchment areas to the gauging stations are considered, a flow per unit catchment area can be derived for each station (Figures 3.30a, b), and the flow difference plotted (Figure 3.30c), which enables leakage and leakage variation with flow characteristics to be seen more clearly. Figure 3.30c shows that flow is always greater upstream than downstream, although the difference in flow is typically small. However, during the high flow in 1996 to 1997, stream flow at Little Puddle was depleted by almost 50 per cent compared with South House. Figure 3.30d shows that the leakage characteristic tends to dominate at low flows but that, as flow in Little Puddle increases, it becomes less significant. However, there are a number of exceptions. As there are no springs contributing to stream flow between South House and Little Puddle Howden et al. (2004) consider that it is most likely that groundwater flow carries water under the Little Puddle gauging station and later emerges as springs further down the valley.

Howden et al. (2004) conclude that surface–groundwater interactions in the River Piddle valley corridor take two forms – spring flow and stream leakage – with the river tending to accrete from a series of discrete springs, between which stream-flow depletion may occur. Both these processes are linked to the geology of the river valley and the main hydrogeological controls on the generation of springs can be summarised as shown in Table 3.3. Thus the springs are controlled by lithology, or by a combination of lithology and geological structure, and Howden et al. (2004) point out that it is significant that the lithostratigraphical units supporting significant groundwater flow from springs are limited — i.e. the Melbourn Rock within the Holywell Nodular Chalk or horizons of the Tarrant, Spetisbury and Portsdown Chalks where upper or lower surfaces of flint beds act as a focus for groundwater flow. They also conclude that stream-flow leakage is either due to a lack of contributing spring sources coupled with permeable stream-bed geology or due to the effects of geological structural features along the base of the river valley. However, it is also possible that spring inflows and bypass flow may be possible in gravelly superficial deposits.

[6] These orientations are consistent with fault orientation trends throughout the Chalk of southern England and the Paris Basin (Bevan and Hancock, 1986).

Table 3.2 Hydrogeological controls on springs in the Piddle catchment (adapted from Marcus Hodges Environment, 1999 and Howden et al., 2004).

Location	**Observations**
Holcombe Dairy	Groundwater discharges from a faulted outcrop of Upper Greensand. Summer groundwater levels adjacent to the river are below that of river-bed level.
Barcombe	Flow gauging and water-level monitoring indicate Barcombe to be an area of groundwater discharge to the River Piddle, controlled by a fault that crosses the river at this point in the Zig Zag Chalk. The fault runs north-north-east to south-south-west and throws the Holywell Nodular Chalk against the Zig Zag Chalk. The water source is thought to be the Holywell Nodular Chalk and that confined groundwater in the underlying Upper Greensand may contribute in the winter. Both sources use the fault as a preferential flow path.
Alton Manor	The springs at Alton Manor are situated on the same fault line that crosses the river at Barcombe, however, the greater flow is likely to be attributed to a larger recharge area. The location of the springs may be due to a permeability contrast between the Zig Zag Chalk and the Holywell Nodular Chalk, although other observations in the catchment suggest that the Zig Zag Chalk has moderate to good transmissivity. It is more likely that plastic deformation of the Plenus Marls Member (Holywell Nodular Chalk) and the Zig Zag Chalk along the fault line induces a hydraulic anisotropy and produces a low permeability barrier.
Sheep Dip	This spring appears to be fault controlled, close to the Holywell Nodular Chalk and Zig Zag Chalk boundary.
Morningwell	No 'spring' inflows are observed in the main river where a south-west to north-east trending fault crosses, however, there is a spring at Morningwell in the western-side valley. The spring appears to be fault controlled as water levels in two boreholes up and downstream of a pond filled by the spring can be up to 8 m different. The fault throws the Holywell Nodular Chalk against the Lewes Nodular Chalk and is the same fault that causes both the Alton Manor and Barcombe springs. The role of the fault in the main valley is uncertain although gauging in 1997 either side of the fault suggests a loss of flow between the two stations. There is also a spring at Plush [ST 71 01] on an eastern tributary to the Upper Piddle. This provides flow to the river between Morningwell and South House.
Morningwell to South House reach	Loss of flow along this perched reach ranges from about 2 to 13 l s^{-1}. It appears to be independent of flow, therefore it is presumably controlled by the hydraulic conductivity of the river bed (New Pit Chalk) and the wetted area.
South House to Little Puddle	Loss of flow along this perched reach ranges from about 2 to 13 l s^{-1} and appears to be independent of Chalk units. It is sufficient for groundwater to move south through the aquifer except for a limited period in the winter and when recharge is high.
Waterston	'Perennial' springs emerge at Waterston (former cress beds). Marcus Hodges Environment (1999) concludes that these are associated with the contact between the Chalk and overlying Paleocene deposits to the south that restrict southward groundwater flow. However, Howden et al. (2004) describe the source of the springs as a fault which runs along the river and intersects a fracture in the Tarrant and/or Spetisbury Chalk, which is a preferential groundwater flow path under confined head. In addition, ten artesian boreholes in the vicinity exaggerate the contribution of these springs to streamflow.
Puddletown, Stafford Park, Church Knapp and Athelhampton	There are no geological boundaries or structural features close to these spring sources. Each source issues from the Portsdown Chalk, which has a series of flint and marl bands and it is likely that these bands provide a number of preferential flow pathways which form springs at outcrop.
Cecily Bridge	Springs are located close to the Chalk/Palaeogene boundary. A borehole at Cecily Bridge indicates confined groundwater head in the underlying Chalk. Thus the spring flow is controlled by the magnitude of confined groundwater head, caused by the limited ability of groundwater to flow beneath the Palaeogene deposits.
Warren Heath	Many springs issue on Warren Heath south-west of the river and form channels that flow into the Piddle. The springs are located in the Poole Formation and correspond to boundaries between the Bradstone Sand and Clay members and it is likely they comprise waters from Palaeogene aquifers.
Binnegar	Springs occur where the Oakdale Clay crops out between sand layers of the Poole Formation. Confined groundwater head in the underlying sands creates springs and the permeability contrast at the sand/clay boundary causes springs at the base of the sands overlying the clay aquifer.



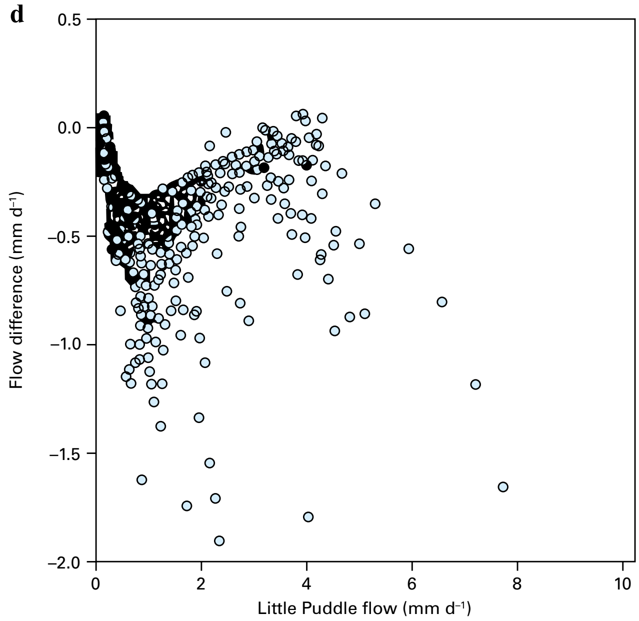


Figure 3.30 a) South House streamflow (normalised by catchment area); b) Little Puddle streamflow (normalised by catchment area); c) Flow difference (normalised) between South House and Little Puddle; d) Flow difference between South House and Little Puddle vs Little Puddle flow (normalised). (after Howden et al., 2004).

Table 3.3 Summary of main hydrogeological controls on springs in the Piddle valley.

Upper Greensand	Confined groundwater head in the Upper Greensand overlain by the Zig Zag Chalk or faulting of an Upper Greensand surface outcrop against less permeable strata
Holywell Nodular Chalk	Gravity drainage at the Holywell Nodular–Zig Zag Chalk boundary or faulting of the Holywell Nodular Chalk against less permeable strata
Portsdown Chalk	The surface outcrop of marl and flint beds
Portsdown Chalk/ West Park Farm boundary	The West Park Farm strata are a confining layer overlying the Portsdown Chalk, creating some artesian springs associated with this confinement
Poole Formation	Interbedded sands and clays of the Poole Formation enable springlines to be formed due to groundwater head in sand layers confined by overlying clays, or drainage from the base of sands overlying clay layers

4 Catchment hydrogeology

4.1 SOUTH DORSET COAST

4.1.1 Geology

South Dorset is dominated by the Abbotsbury–Ridgeway and Purbeck–Isle of Wight fault zones. Interpreted as two *en échelon* fault segments offset by about 4 km in the vicinity of the Poxwell Anticline and Chaldon Pericline, the faults form the boundary between the thinner Jurassic rocks deposited over the South Dorset High and the thicker Jurassic rocks deposited offshore in the Portland–Wight Basin. Both fault zones have suffered repeated episodes of re-activation, both in extension and compression. Miocene compression led to a substantial reversal of movement along the Purbeck Fault, reducing net normal displacements of Permian to lower Cretaceous strata and causing net reverse displacements at higher stratigraphical levels. The Chalk and Cenozoic successions were folded and suffered local reverse faulting, producing a major eastwards-plunging and northwards-verging asymmetrical inversion structure, the northern limb of which represents a zone of steep northerly to vertical (and locally overturned) dips, which form the elevated topography of the Purbeck Hills. The structure is generally referred to as the Purbeck Disturbance, Purbeck–Isle of Wight Disturbance or Purbeck Monocline. Between Lulworth and Worbarrow Bay, it is also referred to as the Lulworth Monocline. Along much of the length of the Purbeck Monocline, the Chalk and Cenozoic boundary, previously interpreted as an unconformable or normally faulted boundary, represents a high-angle reverse fault.

4.1.2 Hydrogeology — Lulworth

An investigation by Wessex Water Authority into the water resources of the Chalk of north Lulworth was conducted in the early 1970s. This work was continued by Alexander (1981). Houston et al. (1986) integrated surface geophysical and downhole logging techniques to try to locate high transmissivity zones within the unconfined Chalk around Lulworth. A resistivity survey was conducted in the South Winterbourne valley to ascertain the depth of the Grey Chalk–Chalk Marl interface (a traditional boundary within the Zig Zag Chalk Formation) and therefore the variations in the effective aquifer thickness (Robins and Lloyd, 1975).

As discussed in Chapter 3, the tectonic hardening of the Chalk has, in general, tended to reduce the intergranular aquifer properties of the Chalk in this area. However, in certain areas, fracture zones, enlarged by solution processes to form groundwater conduits, have significantly enhanced the transmissivity.

An investigation by the Wessex Water Authority into the water resource potential of the Chalk north of Lulworth revealed a complex pattern of groundwater movement (Institute of Geological Sciences, 1979a). The shape of the water table in the unconfined Chalk was found to be unrelated to the surface topography (Figure 4.1), which may be attributable to the intense tectonic disturbance that has affected the Chalk in the area. The study found that, contrary to surface drainage patterns, a high proportion of groundwater

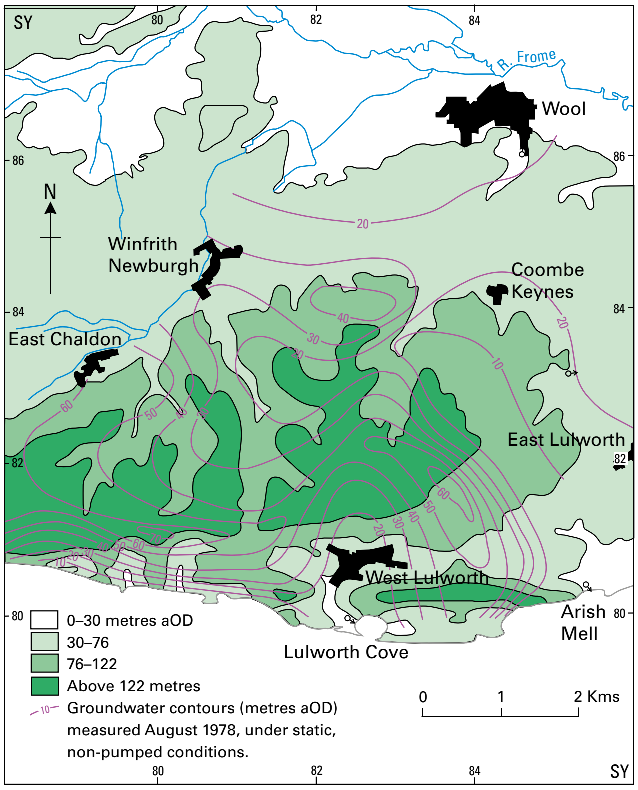


Figure 4.1 Groundwater levels and topography at Lulworth (after Institute of Geological Sciences, 1979a). *contains OS data © Crown copyright and database rights 2017 Ordnance Survey [100021290 EUL]. Use of this data is subject to terms and*

flow is in a seaward direction and appears in the form of spring discharges and seepages direct to the sea, for example those on the coast at Arish Mell [SY 85 80] and West Lulworth [SY 82 80]. Tracer tests and pumping tests have proved local rapid transport towards the Arish Mell springs (Alexander, 1981). A combination of locally low hydraulic gradients, large water level fluctuations in response to recharge and drilling results suggest the existence of a narrow network of discrete solution-enhanced fractures in this area. These high transmissivity solution features probably developed after the sea breached the Chalk aquifer during the Holocene. Groundwater flow was reversed, flowing southward along the fracture zones and discharging at discrete points along the cliff line (Houston et al., 1986).

4.2 FROME AND PIDDLE

4.2.1 Catchment geology

The northern and western boundaries of the Frome and Piddle groundwater catchments are formed by the high Chalk downland, the strata dipping towards the centre of the Wessex Basin. To the far south and south-east the catchment boundaries are formed by structural features in the geology — the Isle of Wight Monocline.

The Frome–Piddle catchment comprises three distinct geological zones (Figure 1.6): the headwaters of the Frome and Piddle cut into Jurassic and Lower Cretaceous strata; the middle reaches flow across Cretaceous chalklands, and the lower reaches traverse the Palaeogene deposits of the Wareham Basin before discharging into Poole Harbour. Jurassic strata are dominated by the thick mudstone formations of the Fuller's Earth, Frome Clay, Oxford Clay and Kimmeridge Clay, separated by intervals of limestone and sandstone. Unconformably overlying these strata are the Lower Greensand, Gault Clay, Upper Greensand and Chalk. Much of this stratigraphy is contained within the narrow outcrop of the primary Chalk escarpment and most of the catchment is underlain by gently inclined dip slopes in Upper Chalk. A second major unconformity separates the Chalk from the Palaeogene, which comprises basal clay-rich strata of the Reading Formation and London Clay overlain by the predominantly sandy Poole Formation (Bracklesham Group). The geological structure is dominated by the eastward-plunging Wareham Syncline, whose axis runs approximately along the Frome valley and is the primary control on the distribution of strata and on the orientation of the drainage system. The syncline is strongly asymmetrical: on the northern margin, Chalk and Palaeogene strata dip gently south-east, but along the southern margin, they are near-vertical or locally overturned along the Purbeck–Isle of White Monocline. This structure forms the elevated topography of the Purbeck Hills, which delineate part of the southern margin of the Frome–Piddle catchment. Within the catchment, laterally extensive north-west to south-east trending faults have been mapped along many of the major river valleys. Superficial deposits cover a substantial area (around 40 per cent) of the catchment and include clay-with-flints, head, river terrace deposits and alluvium with minor amounts of peat and marine or estuarine alluvium near Poole Harbour. Subsidence hollows (dolines) and stream sinkholes are a notable feature along the northern edge of the Wareham Basin between Dorchester in the west, to near Lytchett Minster in the east. Culpepper's Dish is the largest single doline in the area.

4.2.2 Surface water flows

The Frome catchment has several river-flow monitoring sites. Data from those at East Stoke (near to the rivers outflow into Poole Harbour) and at Dorchester (prior to the confluence with the South Winterbourne) are given in Table 4.1.

The high baseflow indices of the River Frome at the two sites indicate a groundwater-dominated Chalk river with a significant increase in flow between Dorchester and East Stoke. Mansell-Moullin (1994) examined annual minimum monthly flow data for the Frome and its tributaries and suggested that, since the low flows at Dorchester are only around 40 per cent of those at East Stoke, the summer groundwater contributions to flow below Dorchester (including those from the tributaries) are important. Aston (1999) pointed out that this extra flow occurs over an area mainly underlain by Palaeogene deposits and shows similar hydrograph characteristics to the Chalk-derived flow at Dorchester. Mansell-Moullin (1994) presents data indicating both gaining and losing sections of the river during low flows in 1970 and suggests a variety of reasons for the pattern including losses by groundwater abstractions, river diversions and river bed leakage, with gains from groundwater discharge, tributary inflows and effluent returns. The variation in flow along the River Frome thus may be complicated, particularly during low flow periods.

The River Piddle drains a smaller area than does the Frome (44 per cent of the Frome catchment area) and mean flows are smaller (Table 4.1). The baseflow index at Baggs Mill of 0.89 is similar to the Frome figure and indicates the significance of Chalk groundwater flows to the river. The River Piddle exhibits complex longitudinal flow behaviour involving upstream gaining reaches, then losing sections followed by further gaining reaches downstream, and this is discussed in Chapter 3 (surface water–groundwater interaction).

4.2.3 Hydrogeology

4.2.3.1 Previous studies

There have been a number of hydrogeological studies carried out on the Rivers Frome and Piddle and these are described briefly below.

In 1985, Wessex Water Authority applied for a 5 per cent increase in the abstraction rate at Alton Pancras pumping station, one of their sources in the Piddle catchment. As a result of public concern about the possible effects of this increase on the river flow, Wessex Water Authority carried out a number of studies to investigate the relationship between increased abstraction quantities and river flow. These studies did not find an adverse link between groundwater abstraction and river flow.

The National Rivers Authority instigated further research as part of the River Piddle Action Plan (National Rivers Authority, 1992a) to examine the problems of low flows in the Piddle catchment. The resultant model, constructed by Halcrow (1995) suggested that the groundwater abstractions did affect flow in the Piddle and its tributaries. A number of remediation alternatives were offered as part of this study, which included augmentation and reductions in the abstraction quantities.

Table 4.1 Gauging station data from selected sites on the rivers Frome and Piddle (source: Marsh and Lees, 2003).

Station name (River name)	Grid reference	Catchment area (km^2)	Period of record	Mean annual rainfall (mm)	Mean flow ($m^3 s^{-1}$)	Q_{10} ($m^3 s^{-1}$)	Q_{95} ($m^3 s^{-1}$)	Base flow index
East Stoke total (Frome)	SY 86 86	414.4	1965–2000	1009	6.41	12.1	2.17	0.85
Dorchester total (Frome)	SY 70 90	206.0	1971–2000	1044	3.07	6.1	0.87	0.83
Baggs Mill (Piddle)	SY 91 87	183.1	1963–2000	977	2.42	4.8	0.78	0.89

The Environment Agency, South West Region commissioned Aspinwall and Company (1997a) to model the catchments of the Rivers Frome and Piddle as part of the determination and implementation of the Groundwater Protection Zones (GPZ) policy. The Chalk was modelled as a steady-state, single-layer system, which was found to be one of the limitations of the model. A multilayered system was probably more realistic. Nevertheless, the model did represent the general pattern of groundwater flow observed across the region. Some sites were, however, found to be sensitive to parameter variations during model calibration. The model used steady-state conditions and it was felt that transient conditions should be modelled to allow verification of the steady-state model. This would have necessitated the capture of detailed seasonal variations in groundwater abstraction and seasonal river baseflow.

Recent British Geological Survey mapping using the revised Chalk stratigraphy has resulted in a detailed geological map of most of the Frome and Piddle basin, (British Geological Survey, 2001). The revised geology of the Chalk is detailed in Chapter 2.

In 1999 a NERC thematic programme, 'Lowland Catchment Research' (LOCAR) was set up to develop the scientific understanding required to implement the EU Water Framework Directive. This was achieved by undertaking detailed, interdisciplinary and integrated hydro-ecological research, the aims of which were to:

- measure and model the processes controlling the transfer of water and pollutants through permeable catchment systems and their associated aquatic habitats, considering various spatial and temporal scales, different land uses and geomorphological settings
- create an integrated model embodying all current and future knowledge to aid in the understanding of the responses of lowland permeable catchment systems to direct and indirect anthropogenic influences.

Three densely instrumented experimental catchments were supported by LOCAR and were selected so that detailed experimental programmes could build on relatively long-term hydrological records of rainfall, river flow and groundwater levels. The Frome and Piddle (as a combined catchment) comprised one of these three catchments, the other two being the Pang–Lambourn in the west Berkshire Downs and the River Tern, a tributary of the River Severn in Shropshire.

4.2.3.2 Hydrogeology

The Chalk forms a major hydrogeological unit in the Frome and Piddle catchments and can be subdivided into an unconfined and confined Chalk aquifer. In the unconfined Chalk, the groundwater head variations recorded in boreholes generally show the expected patterns of high levels during the winter–early spring and low levels during the drier summer months.

As discussed above, the flow regime of the Frome and Piddle catchments is dominated by groundwater baseflow (around 80 to 90 per cent) but flow percentages from direct run-off are increased locally by outcrops of impermeable superficial deposits (e.g. clay-with-flints) (Howden, 2004). Faulting also exerts a control over the surface water drainage pattern; rivers and some streams are aligned, in part, along fault axes. The Upper Greensand, which varies from between approximately 20 and 45 m in thickness (Institute of Geological Sciences, 1979a), may also be considered to be an important aquifer in the catchment, although it only crops out in the valley bottoms and to the west of the Chalk outcrop. There are important Upper Greensand springs such as at Maiden Newton and at the head of the River Cerne (Whitaker and Edwards, 1926). Although the Lower Chalk (Grey Chalk Subgroup) is considered to be an inferior aquifer compared with the Middle and Upper Chalks (White Chalk Subgroup), there is likely to be hydraulic continuity between the Chalk and Upper Greensand.

Cross-catchment groundwater flow between the surface water catchments of the Piddle and Frome has been postulated. For example, a number of groundwater-fed cress farms, which are situated close to the Frome, may have recharge areas that lie partly in the Piddle surface catchment to the north (Environment Agency, 1996). It has been hypothesised that the Frome accepts groundwater from the Piddle catchment via bypass flow along preferential flow horizons, such as fractures, geological faults or possibly dissolution features.

The major hydrogeological characteristics of the Chalk in the Frome and Piddle catchments can be divided into four types (Howden, 2004), which are described below.

1. *Zig Zag Chalk* — acts as an aquitard/aquiclude due to its clayey and marly nature. The basal Glauconitic Marl Member equivalent, or the West Melbury Marly Chalk Formation where it is present, may restrict vertical groundwater movement between the Chalk and the Upper Greensand and promote spring flow at the Chalk –Upper Greensand boundary.
2. *Hardgrounds (e.g. Melbourn Rock, Chalk Rock)* — act as preferential groundwater flow horizons and form springs at outcrop.
3. *Preferential flow horizons* — develop within the top 50 to 60 m and are independent of the stratigraphy. Marl and flint beds create impermeable barriers and promote the development of groundwater flow along their upper and lower surfaces. At outcrop, these flow horizons form springs.
4. *Structural features* — add more complexity at outcrop and, if preferential flow paths are intersected by faults, this may promote spring flow.

The nature of the geological control on springs in the Upper Piddle is discussed in Chapter 3 (surface water–groundwater interaction).

The overlying Palaeogene deposits, although generally considered to be poor or non-aquifers, exert an important influence on the hydrogeological behaviour of the catchment. For example, springs at Broadmayne, to the southeast of Dorchester, and at Tincleton occur where the Chalk is covered by the basal part of the Palaeogene sequence. Springs at Empool Bottom rise through gravels in the Reading Formation and then flow at the contact with overlying clays (Mansell-Moullin, 1994).

The potentiometric surface maps for the Piddle and Frome system show that the groundwater contours tend to follow topographical contours. Areas where the hydraulic gradients are low tend to correspond with areas of Upper/Middle Chalk outcrop. Areas where the hydraulic gradients are steeper tend to correspond with areas of Lower Chalk and Upper Greensand, because of the lower transmissivity of the marl-rich Lower Chalk aquifer.

While there do not appear to have been any comprehensive estimates of the water balance of the Frome catchment, a preliminary estimate made by Paolillo (1969) gave an excess of run-off over recharge of approximately 25 megalitres per day (Ml d^{-1}). Paolillo suggested that this apparent imbalance is probably due to uncertainties in the calculation, but speculated that some groundwater may flow from the adjacent Piddle catchment.

4.2.4 Hydrogeology of the Chalk aquifer at Wareham

Wareham lies at the eastern limit of the Frome and Piddle catchments and in this area of Dorset the Chalk is confined by up to 300 m of Palaeogene clays, sands and gravels (Figure 4.2). This overburden confines the Chalk groundwater and as a result artesian conditions are observed at several boreholes and in some, heads of up to 17 m above ground level have been recorded.

Wessex Water first investigated the Chalk aquifer beneath Wareham from 1991 to 1995 to determine its suitability as a resource for groundwater abstraction. It was found that the quality of the Chalk groundwater in the area was slightly mineralised, and fluoride concentrations of up to 4 mg l^{-1} were recorded, which exceeds the drinking water standard (currently 1.5 mg l^{-1} in England and Wales). The water was dated at between 8000 and 10 000 years old, with no history of abstraction to disturb the aquifer (Eastwood and Stanfield, 2001). In 1994, a six month pumping test was carried out and three boreholes were pumped at an average of 12.5 Ml d^{-1}. The effects of these abstractions were localised, with high drawdowns around each of the boreholes but with no visible adverse environmental impacts on the surface or in the unconfined Chalk (Wessex Water, 1995). Values of transmissivity typically ranged from 200 to 500 m^2 d^{-1} and storage coefficients were of the order of 2 x 10^{-4}. After pumping was stopped, full recovery of groundwater levels took several years. The results from the field data and hydraulic modelling (Wessex Water, 1995; Birmingham University, 1997) indicated that natural recharge to the basin was very limited and that the aquifer was unsuitable for conventional abstraction.

Fluid logging of boreholes as part of the Wareham Groundwater project (Buckley, 1996), indicated that the majority of water-bearing horizons are in the top 50 m of the Chalk aquifer. The potentiometric surface from the edge of the Palaeogene outcrop to the basin centre at Wareham falls only by approximately 10 m, suggesting that the confined Chalk aquifer cannot discharge readily to either the Palaeogene beds or across the Purbeck structure to the south.

In 1996, a feasibility study was carried out to look into the potential of using the scheme for aquifer storage and recovery (ASR) in the vicinity of Wareham. It was found that the Chalk aquifer in this area had the appropriate hydrogeological properties considered suitable for ASR. The principle of ASR and the conclusions of the investigation are discussed in Chapter 6.

4.2.5 Karst in the Frome and Piddle catchments

The area of the Frome and Piddle catchment, on Briantspuddle Heath is noted as hosting the highest density of solution features in the UK (Edmonds, 1983; Waltham et al., 1997). These solution features are particularly prevalent near the feather-edges of the outcrop of Palaeogene strata, e.g. Cul-

Figure 4.2
Geological map of Wareham area.
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pepper's Dish [SY 81 92]. The dolines occur in several large groups, covering a total area of around 16 km^2 and a significant characteristic is their high density, which reaches 157 per km^2 in the largest cluster (Sperling et al., 1977).

The features described by Sperling et al. (1977) are located between the Piddle and the Frome (Figure 3.4). Their origin is uncertain; it may be that these dolines are the surface expressions of fractures that have been enhanced by aggressive water percolation from the Palaeogene cover into the Chalk, resulting in focused dissolution. Another possibility is that these areas provide preferential flow horizons linking the Frome and Piddle catchments together. Similarly, to the east at Bere Regis, a significant proportion of the water use may be derived from the surface catchment of the intermittent North Winterbourne chalk stream. The difficulty in quantifying the transfer of water between adjacent catchments complicates water balance calculations (Environment Agency, 1996).

4.3 STOUR AND ALLEN

4.3.1 Catchment geology

The Stour–Allen catchment includes outcrop geology ranging in age from the Middle Jurassic Fuller's Earth Formation to the Palaeogene Branksome Sand Formation. The regional structural dip is to the south-east such that the headwaters of the Stour cut into Jurassic limestones and mudstones, the middle reaches flow across chalklands, and the lower reaches traverse the Palaeogene deposits of the Hampshire Basin before discharging into Christchurch Harbour (Figure 1.7). In contrast to the other river catchments of Wessex, Jurassic strata underlie a large area of the Stour–Allen basin. They produce a varied topography directly related to the geology with prominent ridges, in part fault controlled, of resistant Jurassic limestones rising above vales formed by the Frome Clay, Oxford Clay and Kimmeridge Clay. The primary escarpment of the Chalk forms an irregular north-west trending ridge and is primarily formed by a narrow outcrop of West Melbury Marly to New Pit Chalk formations resting on a platform of Upper Greensand and Gault. Descending from the primary escarpment is a long, gently inclined slope in Lewes Nodular to Newhaven Chalk formations that underlies much of the catchment. The slope is generally marked by two smaller, heavily dissected subsidiary escarpments capped by the Tarrant and Spetisbury Chalk members of the Culver Chalk Formation (see Bristow et al., 1997, fig. 4). The unconformable contact between the Chalk and the overlying Palaeogene strikes north-east to south-west. The basal part of the Palaeogene succession comprises clay-rich strata of the Reading and London Clay formations. This is overlain by the predominantly sandy succession of the Bracklesham Group. Along the major river courses, much of the Palaeogene is concealed beneath alluvium flanked by gravelly river terrace deposits. The catchment is structurally simple with only minor folding affecting the overall south-east dip of the strata. Surface faults can be divided into two main groups. The first, those with east–west or east-north-east trends, appears to have affected the thickness of Jurassic strata. The second group trends mainly north-north-west, but includes associated north-north-east and north-east trending faults.

4.3.2 Surface water flows

River flows in the upper Stour catchment are flashy, due mainly to the presence of the impervious Jurassic strata in the area, which promote surface run-off rather than recharge. At the Hammoon gauging station (Table 4.2), where flows are measured before the Stour flows over the Chalk, the low baseflow index reflects this high degree of run-off.

The flashy nature of the hydrograph is also shown by the high ratio of Q10 to Q95 flows. Downstream of Hammoon, the Stour is augmented by substantial inflows from tributaries draining the Chalk, for example the River Allen where the high baseflow indices from gauging stations (Table 4.2) indicate the Chalk-fed, groundwater-dominated nature of the river. The North Winterbourne rises near Winterbourne Houghton, tending to go to ground at Winterbourne Stickland. The bed also dries between Winterbourne Kingston and Sturminster Marshall. At Throop, flows are measured near to the outflow from the catchment, but upstream from the confluence with the Moors River. Flows at Throop are substantial compared with those from the Frome and Piddle and the baseflow index reflects the mixture of surface and groundwater sources.

4.3.3 Hydrogeology

There appears to be little hydrogeological interpretation of the Stour catchment. One of the subcatchments, the Allen, has, however, been addressed by several studies.

A water resource study of the River Allen catchment was undertaken by Groundwater Development Consultants for the National Rivers Authority (Groundwater Development Consultants, 1992). This work involved the development of

Table 4.2 Gauging station data from selected sites on the rivers Stour and Allen (source: Marsh and Lees, 2003).

Station name (River name)	Grid reference	Catchment area (km^2)	Period of record	Mean annual rainfall (mm)	Mean annual rainfall (mm)	Q_{10} ($m^3 s^{-1}$)	Q_{95} ($m^3 s^{-1}$)	Base flow index
Throop (Stour)	SZ 11 95	1073.0	1973–2000	881	13.74	31.1	2.61	0.65
Hammoon (Stour)	ST 82 14	523.1	1968–2000	875	7.52	20.6	0.64	0.32
Walford Mill (Allen)	SU 00 00	176.5	1974–2000	879	1.91	4.5	0.30	0.91
Loverley Mill (Allen)	SU 00 08	94.0	1970–2000	906	1.04	2.6	0.17	0.89

an integrated surface water and groundwater numerical model of the Chalk aquifer and river system. The main objectives were to evaluate the effects of groundwater abstraction on catchment hydrology and to examine alternative catchment management strategies. Hydrogeological interpretations suggested by the model included the following:

1. The final calibration of the model produced good simulation of summer low flows and winter peak flows at the two main gauging stations (Loverley Mill in the middle area of the catchment and Walford Mill, to the north of Wimborne Minster). However, it was not possible to simulate observed flow data well for the Allen upstream of the confluence with the Gussage Brook. It was hypothesised that complex aquifer conditions involving low transmissivity barriers and preferential flow directions may be responsible for the poor predictions in this upstream area.
2. The use of low transmissivity zones (less than 200 $m^2 d^{-1}$) in the interfluve areas of the catchment model improved the flow simulation results from those of the previous study (low transmissivity was found at the only interfluve borehole which was tested). Values of transmissivity in the range 1000 to 5000 $m^2 d^{-1}$ were used for the valley areas (i.e. similar to those obtained from valley site pumping tests).
3. The introduction of a permeability change with depth in the upper parts of the catchment improved the simulation of groundwater levels in that area.
4. Analysis of hydrographs for the Allen catchment have illustrated that both groundwater levels and river flows respond rapidly to recharge, implying that the aquifer provides little effective groundwater storage and is highly fissured. During the model calibration procedure, a low unconfined storage coefficient of 0.25 per cent had to be used over most of the catchment.
5. Simulation of the effects that the main abstraction at Stanbridge have on the catchment concluded that, at around half of the licensed abstraction rate of 25 Ml d^{-1}, the pumping station is drawing water from the river rather than from groundwater storage. At larger abstraction rates, increasing quantities of water are taken from groundwater storage, especially during the summer period. This storage is refilled at the expense of river baseflow during winter months.
6. The estimated mean annual recharge varies from 340 mm in the south of the catchment to 400 mm in the north.

Aspinwall and Company (1997b) modelled the catchments of the Rivers Allen and Crane using MODFLOW, as part of the same programme of work that modelled the catchments of the Rivers Frome and Piddle.

Greenaway (1995) studied the hydrogeology of the River Allen catchment and modelled the effect of groundwater abstraction on the surface water flows using MODFLOW. The positions of the groundwater divides and evaluation of the amount of recharge entering the confined Chalk were assessed. The model comprised a three-layer system representing the Palaeogene, the effective Chalk aquifer system and the low permeability Chalk beneath. Results suggested that the regional flow is influenced by the vertical permeability of confining beds and that streams leaving the unconfined part of the aquifer form a focus for groundwater discharge.

The River Allen has also received attention from an ecological perspective by Johnson et al. (1995). Since groundwater was first abstracted in 1946 (at Stanbridge Mill), there has been a significant reduction in salmonid populations, especially over the last few years. A model was constructed to quantify this effect in terms of the reduction on the Q95 value for flow in the River Allen. For the summer months, discharge at the Q95 value was depleted by 55 per cent. The National Rivers Authority, in conjunction with Bournemouth Water plc, used the results to formulate an action plan for the River Allen. These negotiations resulted in a reduction in the current abstraction rates by 50 per cent.

Perkins and Robertson (1980) reported on a series of pumping tests conducted at Shapwick pumping station in the Stour valley. The study concluded that the river and river valley deposits play a major part in the groundwater flow regime and that the Chalk is layered in terms of permeability, with a top zone 15 to 20 m thick being highly permeable and in hydraulic continuity with the river via the river valley deposits.

The total Chalk outcrop for the Stour catchment is estimated at 472 km^2. This, coupled with an estimated annual average infiltration of between 440 and 490 mm, has given a theoretical groundwater resource of 582 $Mm^3 d^{-1}$ (Avon and Dorset River Authority, 1970). By contrast, the theoretical groundwater resource for the combined Frome–Piddle catchment system was estimated to be larger, at 705 $Mm^3 d^{-1}$, despite a smaller outcrop area of 435 km^2. The reason for this is the higher rainfall, and hence recharge, in the upper regions of the Frome–Piddle catchment.

4.4 AVON

4.4.1 Catchment geology

The Avon catchment (Figure 1.8) includes bedrock geological units ranging in age from the Late Jurassic Kimmeridge Clay Formation to the Palaeogene Barton Group. Jurassic strata are restricted to the Vale of Wardour where the eastward flowing River Nadder cuts into Kimmeridge Clay brought to crop by reverse movement on the Mere Fault. The primary escarpment of Chalk has a highly irregular trace in the Avon catchment with abrupt deflections into the fault-controlled vales of Wardour and Pewsey, and the valleys of the rivers Wylye and Ebble. As elsewhere in Wessex, the primary Chalk escarpment is formed from a narrow outcrop of Lower and Middle Chalk capped by an extensive sheet of Upper Chalk which regionally dips to the south-east beneath a cover of Palaeogene sediments. The regional south-easterly dip is punctuated by several broadly west–east trending anticlines and synclines, which include the Palaeogene-cored Alderbury–Mottisfont Syncline and the Dean Hill Anticline. These are developed on linear east–west trending zones of faulted flexures (as with the Vale of Pewsey and the Vale of Wardour), which are related directly to the reversal of underlying basal controlling normal faults (Chadwick, 1986). There are very few mappable faults at surface in the area.

4.4.2 Surface water flows

The River Avon drains the largest catchment area in the Wessex Basin and the flows measured at Knapp Mill near its mouth are the largest recorded in the basin (Table 4.3). The high baseflow index at this site indicates the dominance of Chalk-derived groundwater in the river flow.

The Avon is augmented by a number of important tributaries and selected gauging station data for these are shown in Table 4.3.

Table 4.3 Gauging station data from selected sites on the River Avon and its tributaries (source: Marsh and Lees, 2003).

Station name (river name)	Grid reference	Catchment area (km^2)	Period of record	Mean annual rainfall (mm)	Mean flow (m^3 s^{-1})	Q_{10} (m^3 s^{-1})	Q_{95} (m^3 s^{-1})	Base flow index
Knapp Mill (Avon)	SZ 15 94	1706.0	1975–2000	840	19.66	39.4	6.38	0.90
East Mills (Avon)	SU 15 14	1477.8	1965–2000	835	15.24	28.8	5.50	0.91
Amesbury (Avon)	SU 15 41	323.7	1965–2000	777	3.49	6.7	1.09	0.90
South Newton (Wylye)	SU 08 34	445.4	1967–2000	860	4.09	8.6	1.15	0.90
Norton Bavant (Wylye)	ST 90 42	112.4	1971–2000	950	1.11	2.1	0.45	0.87
Wilton (Nadder)	SU 09 30	220.6	1966–2000	916	2.90	5.8	0.92	0.82
Laverstock (Bourne)	SU 15 30	263.6	1965–2000	790	0.76	1.4	0.19	0.92

The River Wylye exhibits intermittent flows from its source to Kingston Deverill. Here, springs issue at the junction of the Middle and Lower Chalk that only cease flowing in relatively dry years (Halcrow, 1996). From Kingston Deverill, the Wylye flows to the north-east over Lower Chalk to Brixton Deverill and in this section leakage can occur from the river. At Hill Deverill, the Wylye flows over the Upper Greensand aquifer, from which springs contribute a substantial flow to the river. The river continues to flow on Upper Greensand, and to gain flow, to Bishopstrow (to the south-east of Warminster). Beyond Bishopstrow, the river flows again over Lower Chalk and in summer months flow losses to the aquifer can occur, continuing as far downstream as Upton Lovell. Downstream of Upton Lovell, flow accretion generally occurs and the Wylye is joined by the Chitterne Brook and the River Till. The Chitterne Brook dries seasonally just above the Wylye confluence. The River Till flows continuously from a major spring located at the junction between the Upper and Middle Chalk (between the Lewes Nodular and New Pit Chalk formations), a short distance upstream from Berwick St James (Halcrow, 1996).

Flow data for the Wylye at South Newton, before its confluence with the Nadder, and upstream at Norton Bavant, indicate the substantial gain in flow between the two stations and the very high contribution of baseflow to the total flow, typical of Chalk catchments.

Flow data for the Nadder, from a gauging station at Wilton (Table 4.3), indicates that, while principally spring fed, the river also produces a relatively large flood flow, as a result of the varied geology of its catchment area. Such effects are noticeable on the Avon downstream of Salisbury (Avon and Dorset River Authority, 1970).

Flow data from the Laverstock gauging station on the lower reaches of the Bourne are shown in Table 4.3. The general characteristics of flow data are typical of a Chalk catchment. However, the nature of the flow in the Bourne is unusual above its perennial head at Idmiston: while flow commonly occurs in the upper reaches of the river for several kilometres downstream, as far as Collingbourne Ducis/Collingbourne Kingston, the river often dries in its central section down to the Idmiston perennial springs (Environment Agency, 2001). The Nine Mile River is a winterbourne for much of its length.

4.4.3 Hydrogeology — Upper Avon

A groundwater modelling study of the Upper Hampshire Avon catchment (encompassing the catchments of tributaries down to the River Ebble) was undertaken by Halcrow for the National Rivers Authority (Halcrow, 1992). The conceptual model for the Hampshire Avon was later updated by the Environment Agency and stakeholders between 1999 and 2006. A new model was developed for the Bourne and Nine Mile Rivers in 2004 and the whole of the Hampshire Avon catchment in 2005/06. The purposes of these modelling studies were to quantify the impact of abstraction on local groundwater resources and to provide a framework for use in the management of the groundwater resources of the catchment. The understanding of the catchment hydrogeology was significantly improved following the remapping of the geology by the British Geological Survey and the interpretation of this and other information by the Agency. The main findings from this work are summarised below.

The aquifer properties distribution for the model was estimated from pumping tests, packer tests and well yields and inferred from hydrogeological maps. The distribution was further refined during calibration. The transmissivity distribution is thought to be largely controlled by the Chalk lithology and structure. Hard bands near to the surface that crop out down the catchment have been shown to significantly control surface and groundwater movement. These hard bands are often associated with the location of major springs, and sometimes the perennial head, and their upstream outcrop may coincide with a location where a stream or river loses water. Anticlinal structures may control groundwater movement, diverting groundwater across a surface water catchment.

Further enhancement of transmissivity has occurred in the major valley areas through solution weathering. Transmissivities were found to vary from 100 to 250 m^2 d^{-1} in the West Melbury Marly Chalk and Zig Zag Chalk to 1000 to 3000 m^2 d^{-1} in part of the Seaford Chalk (where significant hard rock bands occur below the water table). Transmissivities are thought to increase in major valleys by approximately 50 per cent (Environment Agency and Water Management Consultants, 2004).

The storage coefficient varied from 0.005 in the Lower Chalk, 0.02 in the Middle and Upper Chalk, and 0.05 in the Upper Greensand. The model gave a good representation of water levels and surface flows and was used in simulation runs to help understand the relationship between pumping and stream flows. Typically the abstractions were found to have the greatest volumetric impact during wetter months, when chalk storage was replenished — November to April.

However, the greatest impact as a percentage of river flow occurred during summer months — May to September. Flows in some river reaches were found to increase as a result of abstractions artificially extending the catchment area and the subsequent discharge of water.

4.4.4 Hydrogeology — Wylye

In the 1990s the National Rivers Authority commissioned Halcrow to undertake a groundwater modelling study of the Wylye catchment in order to evaluate the effects of abstraction and to help with selection of appropriate flow-alleviation schemes. The conceptual and numerical models were updated and renewed by the Environment Agency and Wessex Water in 2004 to 2006. During model calibration the following features of hydrogeological significance were found by Halcrow (1996):

1. Modelled transmissivities varied from less than 500 $m^2 d^{-1}$ over interfluves to between 4000 and 10 000 $m^2 d^{-1}$ in the river valleys, with a general increase from the Upper Wylye to the middle and lower reaches of the Wylye. High values were also used along the River Till.
2. Modelled storage coefficients varied from less than 0.003, characterising interfluve areas, to up to 0.03 for the Chalk in valleys and up to 0.1 characterising the Upper Greensand.
3. Model-generated stream-flow hydrographs generally compared well with field data. However, there was some overestimation of peak and low flows at the South Newton gauging station. This was considered to have been caused either by movement of groundwater divides (for example occasionally resulting in groundwater flow from the River Till catchment to the Avon) or groundwater flow out of the Wylye catchment beneath the river bed and therefore not recorded by the river gauge.
4. The model simulated the observed groundwater head distribution and behaviour at most locations, including the reduction of the potentiometric surface below the river bed in influent sections of the Upper Wylye, the dampened response and prolonged hydrograph recessions in the Upper Greensand outcrop and the dampened response of Chalk water levels near to the perennial sections of the river.

As part of the Upper Wylye investigation, Avon and Dorset River Authority et al. (1973) utilised geophysical logging techniques at three locations: Brixten Deverill, Heytesbury and Chitterne. At Chitterne, a borehole that penetrates the greater part of the Chalk was tested. The results of this survey were used to determine the major flow horizons within the Chalk: 90 per cent of the flow was found to enter the borehole from the top 47 m of the Chalk.

4.4.5 Hydrogeology — Bourne

The Environment Agency carried out a detailed investigation of the River Bourne and Nine Mile River catchments (Environment Agency, 2001, Environment Agency and Water Management Consultants, 2004). The work was undertaken in response to Habitats Directive and UK Biodiversity Action Plan requirements and to assess the impacts of abstraction on the river. The aim of the study was to collect and analyse data for the two catchments in order to develop a detailed conceptual, and then numerical, model of the hydrogeology.

The Bourne and Nine Mile Rivers flow in a south-westerly direction from their sources, to the east of Salisbury Plain, to their confluences with the River Avon (Figure 1.8). The total surface catchment area of the rivers is approximately 204 km^2 and the catchments are underlain by Chalk. Both rivers are substantially groundwater fed and both exhibit winterbourne behaviour. Figure 3.26 shows the winterbourne signature of the Bourne and it is evident that the flow system is complex. The perennial head of the river is at Idmiston (Figure 4.3) where substantial springs occur; upstream of this point flow is often limited south of Collingbourne Ducis, with Cholderton experiencing the greatest proportion of dry periods, whereas further north the river often flows in its upper reaches. It is evident from historical literature that the complex flow behaviour of the river is natural and predates current abstractions.

The potentiometry of the Bourne catchment is greatly affected by its location between the major rivers Avon and Test, both of which are at significantly lower elevations (around 40 m) than the Bourne (Environment Agency and Water Management Consultants, 2004). The result of this, and further hydrogeological behaviour outlined below, is that the Bourne groundwater catchment is significantly smaller

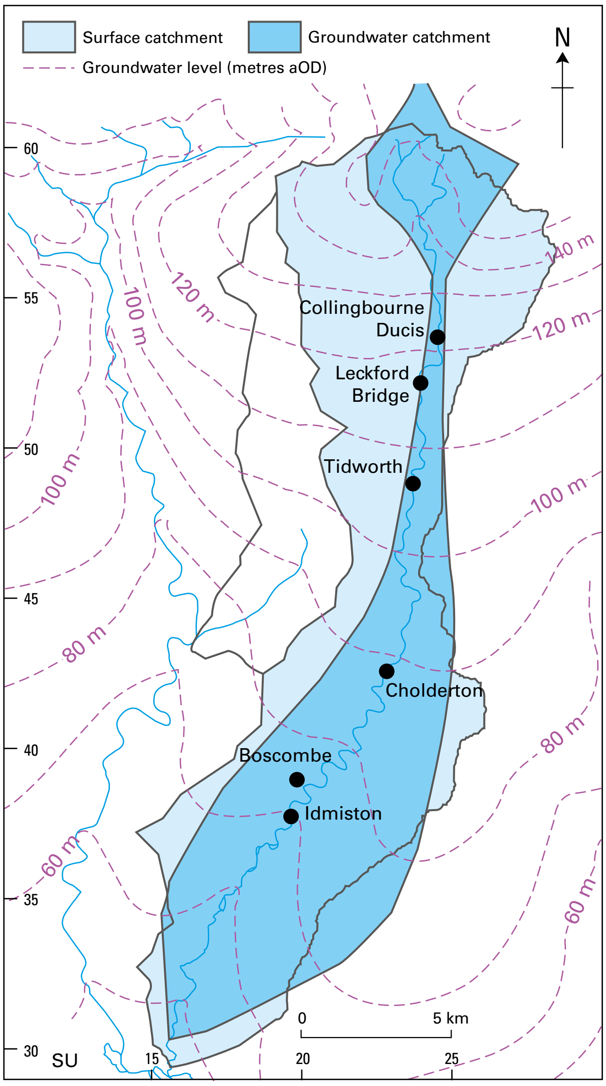

Figure 4.3 River Bourne location map, and groundwater contours for 27 January 1994 (adapted from Environment Agency and Water Management Consultants, 2004).

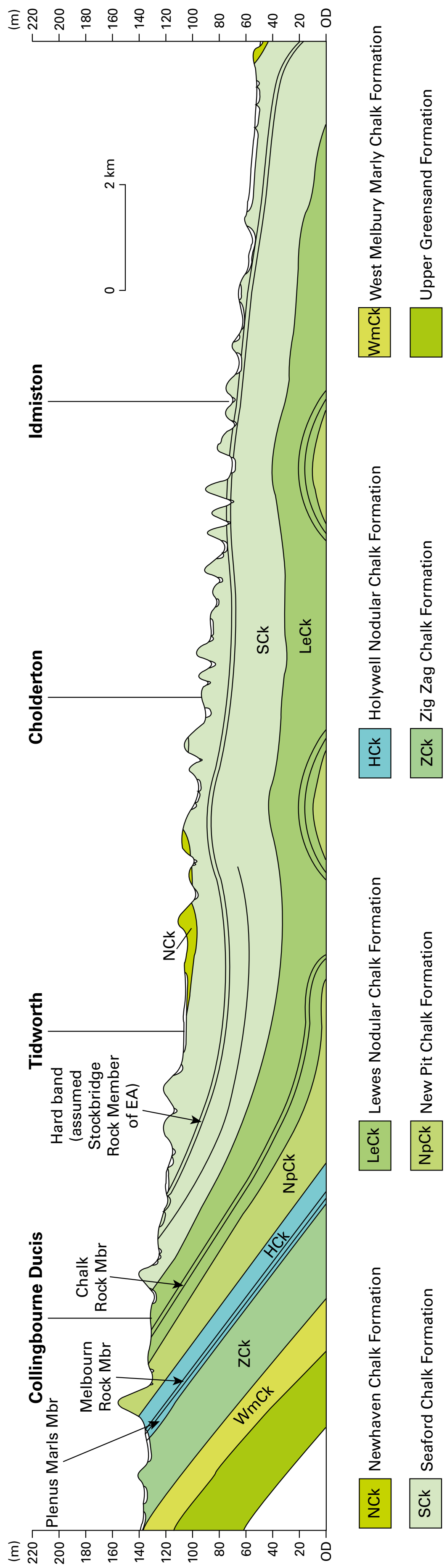

Figure 4.4 Sketch of geological cross-section of River Bourne showing the general relationship of the units within the Chalk Group (adapted from Environment Agency and Water Management Consultants, 2004).

than the surface water catchment. The majority of recharge in the upper reaches of the catchment diverges towards the Avon and Test rivers and their tributaries, rather than towards the Bourne river. In addition, the groundwater catchment boundaries vary significantly seasonally. When groundwater levels are at their highest, the river gains along its whole length, groundwater flows converge on the river and the catchment area is at its largest, although even under these conditions the groundwater catchment is significantly narrower in its central section than in its headwater or downstream sections, as illustrated in Figure 4.3. When groundwater levels are low, the river only gains from the perennial springs at Idmiston, the groundwater catchment tends to become narrower and moves to the west, suggesting that under these conditions groundwater in much of the upper Bourne catchment flows towards the Test and its tributaries (Environment Agency and Water Management Consultants, 2004). Commonly, in wet months, intermediate and complex conditions occur, with the river gaining in the north and south, while losing, and acting as a groundwater divide, in its central section. This distinction between groundwaters in the upper part of the catchment and those in the lower part is supported by hydrochemical evidence (Chapter 5).

The Bourne rises to the north of the northward-facing primary Chalk scarp, which separates the Upper Greensand lowlands of the Vale of Pewsey anticline from the gently undulating southerly dipping Chalk downland to the south. A much dissected secondary Chalk escarpment is represented by the ranges of hills bounding the Bourne catchment. At the head of the catchment, the Chalk dips steeply to the south-east and units from the West Melbury Marly Chalk to the Lewes Nodular Chalk outcrop successively downstream (Figure 4.4). In the centre of the catchment, from Leckford Bridge–Tidworth to south of Idmiston, the dip of the Chalk decreases and the Seaford Chalk outcrops. Further south the dip steepens to the south-east again. A number of small anticlines with approximately east–west trends occur; they are seen in the flatter section of the Chalk, for example near Cholderton and Boscombe.

Contributing to the Bourne and Nine Mile River study, the Chalk was remapped by the British Geological Survey (Farrant et al., 2000) using the new Chalk stratigraphical nomenclature. This work enabled the links between catchment geology, hydrology and hydrogeology to be investigated. One result of this was the description of the Chalk aquifer units in terms of their geological and hydrogeological characteristics. These are summarised in Table 4.4.

In addition to the general hydrogeological characteristics of the identified Chalk stratigraphic units, certain features of the geology were identified as being particularly important in terms of groundwater and surface water flow in the catchment. For example, the spatial distribution of hard rock bands, such as that at 28 to 36 m above the base of the Seaford Chalk at Tidworth (potentially the base of the Stockbridge Rock and described as 'assumed Stockbridge Rock'), the Chalk Rock, the Melbourn Rock and of softer marls such as the Plenus Marl, were considered to have an important influence both on groundwater movement and on groundwater–surface water interaction.

In the upper Bourne catchment, the low-permeability Plenus Marls, which dip more steeply than the surface topography,

Table 4.4 Summary of the principal geological and hydrogeological characteristics of the Chalk Group formations present in the Bourne and Nine Mile River catchments (adapted from Farrant et al., 2001, Environment Agency, 2001).

Subgroup	Formation	Geological characteristics	Hydrogeological characteristics
White Chalk Subgroup	Portsdown Chalk	Only a few outcrops in the extreme south of the study area. The formation consists of white flinty chalk with common marl seams	No observations: this formation is poorly represented in the study area
	Culver Chalk	Massively bedded, soft, white chalk without marl seams but well-developed nodular and semi-tabular flints. Regular orthogonal joints	Solution features may occur above sheet flints and along faults and master joints
	Newhaven Chalk	Lithologically similar to the Seaford Chalk. Soft to medium hard, smooth, white chalk with numerous marl seams and flint bands. Flint bands not as numerous as in the Seaford Chalk. Well-developed conjugate joint sets, dissipated along marl seams	Dissolution may occur along thicker marl seams where groundwater is forced to flow horizontally
	Seaford Chalk	Smooth, white chalk with abundant nodular and semi-tabular flints. Stockbridge Rock Member is a very hard, porcellaneous chalk. Massively bedded chalk with regular orthogonal joints	Solution features may occur above sheet flints and along faults and master joints. Hard rock bands 28 to 36 m above the base of the Seaford Chalk (identified by geophysical logging) provide main inflow horizons to boreholes that intersect this horizon i.e. Tidworth Borehole. Extrapolation of this hard rock band north to Leckford Bridge coincides with the location of major losing reach of river, and to the south, the main spring flows at Idmiston
	Lewes Nodular Chalk	Hard to very hard, nodular chalk. Formation includes the Chalk Rock Member, joint sets open and steeply inclined	Joints often solution enlarged, some solution cavities along the top of sheet flints. The Chalk Rock, ~ 12 m above the base of the formation, provides the main inflow horizon at a number of boreholes
	New Pit Chalk	Smooth, firm, white chalk, massively bedded with marl seams. Well-developed conjugate joints, dissipate along marl seams	Dissolution may occur associated with tops of thicker marl seams where ground-water is forced to flow horizontally
	Holywell Nodular Chalk	Hard, nodular chalk. Plenus Marls consist of alternating blocky, white chalk and grey, silty marls. The Melbourn Rock is a very hard, nodular chalk up to 3 m thick	Perched water tables occur above the clay-rich Plenus Marls Member and flowing horizons recorded in the hard nodular Melbourn Rock and overlying nodular shelly unit. Plenus Marls may confine waters below and may back up groundwater flow down dip. Spring line may occur at these locations, followed by river leakage into the Melbourn Rock. Melbourn Rock may provide spring lines in winter period when recharge exceeds capacity of this relatively high transmissive horizon
Grey Chalk Subgroup	Zig Zag Chalk	Medium hard, pale grey, blocky chalk. Lower part with higher marl content	May form spring line at base of formation immediately above relatively low permeability West Melbury Chalk. Vertical jointing within the limestone bands feed water to the marl bands that may act to prevent further vertical infiltration and may back up water down dip. Limestone horizons may carry greater volumes of water and provide reaches of effluent river flow where a further outflow location down gradient is present
	West Mel-bury Marly Chalk	Bedded, grey, marly chalk with thin limestones. Base marked by marl that may be transitional with the Upper Greensand	Forms an aquitard between Upper Greensand and overlying Zig Zag Chalk due to high clay content. Vertical jointing within the limestone bands feeds water to the marl bands that may act to prevent further vertical infiltration. Dip of the chalk to the south-east may back up recharge from Upper Greensand and produce spring lines. Relatively low rate of recharge through this formation

were considered to form a barrier to southerly groundwater movement, causing springs to occur up gradient and promoting river flow. Further south, the outcrop of hard rock bands such as the Melbourn Rock, Chalk Rock and hard rock bands in the Seaford Chalk are associated with more influent (losing) behaviour of the river. In the centre of the Bourne catchment, the assumed Stockbridge Rock and deeper hardgrounds are found at increasing depth, with the assumed Stockbridge Rock rising to crop out again at Idmiston. This coincides with the occurrence of the springs forming the perennial head of the Bourne. Geological modelling shows that this horizon also crops out at the locations of the perennial heads of the River Anton and Wallop Brook in the Test catchment. On this basis and on the potentiometric evidence, the Environment Agency study postulated that large volumes of water are transmitted within the hardgrounds (particularly the assumed Stockbridge Rock) from the upper parts of the Bourne catchment to the south-west to the Avon, south to the Bourne at Idmiston and south-east to the River Test tributaries. Evidence from borehole logging of the importance of these Chalk hardgrounds in controlling groundwater flow at moderate depths was discussed earlier in this report — for example, see Figure 3.13. Later numerical modelling confirmed that this conceptual understanding is likely to be correct.

In addition to the postulated lithological controls on groundwater flows in the Bourne catchment, the study also concluded that the synclinal and anticlinal structural features played a part, so that, for example, the groundwater potentiometric surface is affected not only by the relative topography of the Bourne and its neighbouring river valleys, but also by the nature and geometry of the anticlinal and synclinal structures running across the valley and the depth to different rock units.

In addition, it was noted that trends in drainage directions are influenced by dominant fracture set orientations as well as topographical trends and regional geological dip. Many river reaches in the study area run parallel to the dominant north-west to south-east and east-north-east to west-south-west or subordinate north to south and east to west fracture trends.

A distributed, time-variant numerical model of the Bourne and Nine Mile river catchments was developed during the Environment Agency study in order to explore the impacts of abstractions on groundwater flows to the rivers and on head distributions. It was found that the model was most accurate when the saturated aquifer thickness was 70 m and when vertical hydraulic conductivity was half the horizontal value. The highest transmissivities used were along the middle section of the river valley, where values for the Seaford Chalk of between 1000 $m^2 d^{-1}$ and 3000 $m^2 d^{-1}$, depending on groundwater level, were used.

4.5 TEST AND ITCHEN

4.5.1 Catchment geology

The Test is a chalkland catchment (Figure 1.9) located on a broad, highly asymmetrical anticlinal structure (Figures 2.1 and 2.2). To the north, the Chalk dips steeply below the Palaeogene of the London Basin. The Upper Greensand is brought to crop in the core of the anticline at Kingsclere. To the south, the Chalk dips at a low angle beneath the Palaeogene cover of the Hampshire Basin. Superimposed on this long, southward-dipping limb are smaller, west–east trending, lower-amplitude synclines and anticlines including the Winchester–Kings Somborne Syncline, the Stockbridge Anticline and the Micheldever Syncline. In the south-west of the catchment, the River Dun drains axially along the west–east trending Alderbury–Mottisfont Syncline, which contains a core of Palaeogene strata.

The Itchen catchment (Figure 1.10) includes solid geological units ranging in age from the Cretaceous Lower Chalk to the Palaeogene Bracklesham Group. The catchment lies on the broad chalk plain at the western end of the Weald Anticline. As with the Test catchment to the north and west, the Chalk dips below the Palaeogene of the London Basin. Likewise to the south, the southerly dip of the Chalk takes it below the Palaeogene of the Hampshire Basin. Superimposed on this regional structure are smaller west–east trending, lower amplitude synclines and anticlines including the Winchester Anticline, the Stockbridge Anticline and the Micheldever Syncline. In general, these structures have steeper dips on their northern limbs, probably reflecting the reactivation of deep-seated, Jurassic fault blocks. The Winchester Anticline brings Lower and Middle Chalk to the surface in a catchment that is predominantly Upper Chalk.

The Chalk in the northern and eastern parts of the catchments is covered by extensive amounts of clay-with-flints, particularly the area to the east and north-east of Alresford. To the west of Alresford, these deposits are less extensive and are present as coverings to interfluves. To the south, around the market town of Romsey, Palaeogene gravels, sands and clays occur.

There is evidence that a number of processes may have significantly modified the rock mass properties of the Chalk following lithification. During the Miocene Alpine orogeny, gentle folds were formed, which generally trend east–west. In the earliest Tertiary, uplift of the Chalk caused some erosion prior to the deposition of the Reading Formation. The main period of subaerial erosion, however, affecting both the Chalk and Palaeogene deposits, occurred in the Quaternary following the main uplift at the end of the Palaeogene. It is inferred (Entec, 2002) that the bulk Chalk fabric was modified during the Lower and Middle Pleistocene due to the development of a 'partly evolved' groundwater system that was in place prior to the Devensian glacial period. During the Devensian, periglacial action further modified the rock mass properties of the valleys where dissolution probably took place in unfrozen taliks.

During the late Cenozoic and Quaternary, erosion is thought to have been controlled at least in part by structural style, with some initial valley development occurring along the axes of synclines such as those trending east–west through the River Alre. Headward erosion from the south caused river capture of east–west-trending rivers. Stress release associated with erosion of river valleys is thought to have caused the development and enlargement of fractures in the valleys and allowed groundwater movement, particularly along bedding planes. It is assumed that most of this fracture development in the valleys took place during the Devensian and the presence of dolines in the Chalk close to the edge of the Reading Formation is interpreted as being associated with this phase of fracture development (Entec, 2002).

The Reading Formation shows a large degree of variation in these catchments. In general, the Reading Formation is sandier in the west with only localised sandy deposits in other areas. The predominance of clay deposits in the east means that the unit is not effectively connected to the Chalk. In the west, sand units are in hydraulic continuity with the Chalk.

There is some debate about the degree of connectivity between the Chalk and Upper Greensand. It appears that they may be in continuity to the west of the River Test but pumping test data shows that they do not appear to be linked in the Itchen catchment.

4.5.2 Relationship between geology and hydrogeology

A hydrogeological study of the River Itchen for the Environment Agency (Entec, 2002), was undertaken as part of a broader study to determine a sustainable management strategy for the river Itchen. This involved a data collation exercise, a review of existing models for the Bourne and Nine Mile River, the River Kennet and the River Itchen, and the preparation of a conceptual model of the catchment, leading to a numerical model. This model was subsequently extended to include the River Test and the new Test and Itchen model replaced the previous Itchen model (Entec, 2005).

The model used the following boundaries. Groundwater flow appears to be bounded to the south with little or no flow southward into the undeveloped confined Chalk. To the north, the Kingsclere Anticline is a flow barrier, although there may be some flow northwards into the Thames Basin east of Kingsclere. The groundwater divide north of the Candover and Dever catchments is relatively well defined by the lower-transmissivity Chalk associated with the Ellisfield, Lasham and Medstead groundwater mounds. To the west and south-east, the Upper Chalk drains to the River Avon and River Meon respectively.

Based on the work of Headworth (1978) on fissure inflow zones to artesian boreholes in the Alre catchment, that of Rennie (1994) who reviewed fracture zone elevations in part of the Candover catchment, and the new British Geological Survey mapping, it has been suggested that important fissure zones associated with tabular flinty bands and possibly in the Seaford Chalk occur everywhere at a fixed stratigraphical elevation postulated to occur generally between 60 and 80 m above the base of the Upper Chalk (Entec, 2002). The fissure zones are assumed to affect aquifer transmissivity and groundwater flow significantly across substantial parts of the catchment; however, in addition, a number of other factors are considered important (Entec, 2002).

- The presence or absence of marls – the Lower and Middle Chalk Formations are generally marlier than the Upper Chalk and are less transmissive.
- The development of more localised solution enhanced fracture zones in the Upper Chalk above and below the main zone.
- The nature of cover – thick, low permeability cover reduces recharge, the underlying Chalk remains undeveloped, and transmissivity remains relatively low.
- Periglacial influences – periglacial processes enhance flow and transmissivity in present-day dry, ephemeral and perennial river valleys, compared to interfluves.
- Postglacial and recent groundwater flow – this enhances any fracture development and leads to higher transmissivities around present-day rivers.

Comparison of aquifer properties data, published in the Aquifer Properties Manual (Allen et al., 1997), with the geographical location of axes of major folds in the study area showed that there appear to be some systematic relationships, as discussed in Chapter 3. In general, transmissivities are higher along the synclinal axes than anticlinal axes and storage coefficients are higher near water courses. These observations are consistent with those of Giles and Lowings (1990) who identified five groundwater mounds (at Ellisfield, Lasham, Medstead, Froxfield and Preshaw: see Figure 3.2) that form groundwater catchment divides — all but one related to anticlinal structures in the Chalk.

The potential for developing secondary hydraulic connectivity increases from Lower to Middle to Upper Chalk with brittle 'hardbands' locally enhancing fracturing, but the potential for fracture development reduces with depth below ground level. Consequently, the presence of Upper Chalk and/or hardgrounds in valleys may be important in enhancing flow to abstraction wells (Entec, 2002).

The effect of the postulated stratigraphically related fissure zones on groundwater flows will be strongly influenced by regional structure. In both the Test and Itchen catchments, it appears that synclinal axes combined with fissure zones can concentrate flow in certain river valleys, notably the River Alre and River Anton.

It is envisaged that storage is influenced by similar factors to transmissivity and will show variations across the catchment. It is thought that the lowest unconfined specific yield values of around 0.5 per cent are found on the interfluves, beneath clay-with-flints cover and for the Middle and Lower Chalk (Entec, 2005). Most of the remaining areas are assumed to have unconfined specific yields of the order of 1 per cent and may be locally increased up to about 10 per cent close to rivers and in valley floors where saturated permeable drift deposits are in good continuity with the underlying Chalk.

4.5.3 Surface water flows

Neither the Test nor the Itchen are truly natural rivers in their current form. Along most of their lengths, the rivers are split into two or more channels with sluices to regulate flows. The surface catchment of the River Test is some three times larger than that of the River Itchen (1260 km^2 compared with 400 km^2). Of the 400 km^2 of River Itchen, 360 km^2 drains Chalk.

Gauging data for selected stations on the Test and its tributaries are shown in Table 4.5. They clearly show the high baseflows contributed by the Chalk tributaries such as the Dever, Anton and Wallop Brook (all with baseflow indices of approximately 0.96), whereas the groundwater contribution to surface flows in a river such as the Blackwater that drains Palaeogene deposits is less significant (baseflow index of 0.51).

The three tributaries which feed the Upper Itchen (the Candover, Cheriton and Alre) are all substantially derived from the Chalk as shown by their high baseflow indices (Table 4.6); of the three, the Alre is volumetrically the most significant, with much of its flow from artesian boreholes and springs, which supply watercress beds. It has been suggested (Entec, 2005) that the groundwater catchment of the Alre is significantly larger than the surface water catchment.

As the Itchen initially flows west, its flow increases substantially until it reaches 4.22 $m^3 s^{-1}$ on average at Easton (Table 4.6). As the river turns south further increases in flow are seen, which are mainly from groundwaters (as shown for example by the very high baseflow index at Highbridge) but including, further south, a modest increment from the surface water draining Monks Brook. Near to its mouth, gauged flows average 5.40 $m^3 s^{-1}$ (Table 4.6), which is around half the flow of the River Test, and about a quarter of that of the Avon. This is somewhat larger than that expected given the surface catchment area, but this is an underestimate of the groundwater catchment area.

4.5.4 Groundwater flooding

A characteristic of the Test and Itchen catchments is groundwater flooding following high winter rainfall. There was extensive groundwater flooding in both catchments in the winter of 1994–95, 2000–01 and 2002–03. Chalk stream heads migrated kilometres upstream of their usual positions and flooding affected roads, houses and businesses over a period of several weeks.

4.5.5 Hydrogeology — Test

Historically, there appears to have been relatively little hydrogeological work performed solely within the Test catchment. Headworth (1972) for example calculated a specific yield (of about 0.033) for the catchment using recession curves from boreholes and river hydrographs.

Table 4.5 Gauging station data from selected sites on the River Test and tributaries (source: Marsh and Lees, 2003).

Station name (river name)	Grid reference	Catchment area (km^2)	Period of record	Mean annual rainfall (mm)	Mean flow ($m^3 s^{-1}$)	Q_{10} ($m^3 s^{-1}$)	Q_{95} ($m^3 s^{-1}$)	Base flow index
Weston Colley (Dever)	SU 49 39	52.7	1979–1995	774	0.10	0.2	0.03	0.96
Fullerton (Anton)	SU 37 39	185.0	1975–1999	782	1.82	2.7	0.95	0.96
Broughton (Wallop Brook)	SU 31 33	53.6	1955–1999	803	0.35	0.8	0.02	0.94
Ower (Blackwater)	SU 32 17	104.7	1976–1999	865	0.85	2.1	0.15	0.51
Chilbolton (Test)	SU 38 39	453.0	1989–2000	836	5.45	8.4	2.89	0.97
Broadlands (Test)	SU 35 18	1040	1957–2000	819	11.01	16.7	5.76	0.94

Table 4.6 Gauging station data from selected sites on the River Itchen and its tributaries (source: Marsh and Lees, 2003).

Station name (river name)	Grid reference	Catchment area (km^2)	Period of record	Mean annual rainfall (mm)	Mean flow ($m^3 s^{-1}$)	Q_{10} ($m^3 s^{-1}$)	Q_{95} ($m^3 s^{-1}$)	Base flow index
Alresford (Alre)	SU 57 32	57.0	1970–1999	873	1.55	2.1	1.03	0.98
Sewards Bridge (Cheriton)	SU 57 32	75.1	1970–2000	909	0.64	1.0	0.27	0.97
Borough Bridge (Candover)	SU 56 32	71.2	1970–1999	825	0.52	0.8	0.27	0.96
Stoneham Lane (Monks Brook)	SU 44 17	43.3	1987–2000	823	0.23	0.6	0.02	0.41
Easton (Itchen)	SU 51 32	236.8	1975–2000	871	4.22	6.0	2.66	0.98
Highbridge (Itchen)	SU 46 21	360	1958–2000	855	5.30	7.8	2.92	0.96
Riverside Park (Itchen)	SU 44 15	415	1982–1999	837	5.40	8.8	2.83	0.92

More recently, however, the modelling study undertaken for the Environment Agency (Entec, 2005) examined in detail the available information for the River Test.

Previous modelling on the Bourne Rivulet and Wallop Brook by Mott MacDonald made use of stepped contrasts in hydraulic conductivity with depth to simulate seasonal flow profiles and groundwater level responses. The model also simulated low transmissivity in an anticlinal axis in the Wallop Brook catchment. For this catchment, observations, both from groundwater hydrographs and the calibration exercise, indicated that a two-layered model was required for the area. The upper layer had a high hydraulic conductivity and thinned from the river towards the interfluves. The lower layer was given a low hydraulic conductivity.

Large cress beds in the Test catchment affect the natural flow regime of several Chalk tributaries. The cress beds make use of both artesian and pumped boreholes. Abstraction can cause flows upstream of the beds to be depleted whilst flows downstream are augmented by the cress-bed discharges.

Pumping tests have been carried out at several of the major public water supply sources and give a range of transmissivity and storage values. As many of these abstractions are in valleys, the aquifer parameters do not represent the full range of Chalk aquifer characteristics.

Analysis of flow data for the River Test shows that the catchments with the biggest flows for their catchment areas are the Upper Test to Chilbolton, the Pilhill Brook and the River Anton and River Dun. The catchment to Chilbolton follows a syncline, which may be effective in draining the area. The Anton and Pilhill Brook appear to have very high flows considering their surface catchment areas and it has been inferred (Entec, 2005) that the groundwater catchment is far larger than the surface water catchment.

The Stockbridge Rock Member may influence flows in the Anton, Pilhill Brook and the Test around Chilbolton and Kings Somborne. In these locations there is generally strong flow accretion which may be related to this hardground. The rock unit also crops out under the River Bourne and it has been suggested (Entec, 2005) that it may act as a drain, moving water eastwards towards the Anton and Pilhill Brook.

4.5.5.1 Water balance

A water balance was carried out over the period 1991 to 1995 with a monthly time step and with results aggregated to annual average and long-term average figures (Entec, 2005). The result is shown in Table 4.7 and indicates that a modest percentage (<4 per cent) of the available resource in the Test catchment is committed to abstraction.

4.5.6 Hydrogeology — Itchen

In contrast to the Test, the Itchen catchment has been relatively well studied. Headworth (1972) estimated the specific yield of the Chalk in the catchment as about 0.034 using recession curves from boreholes and river hydrographs. Later, a scheme designed to augment the flow of the River Itchen during drought years enabled the nature of the aquifer to be studied in greater detail. Initially, the behaviour of artesian boreholes located at watercress farms (most of which were near Alresford, to the south of the Candover valley with some in the River Dever catchment) was investigated (Headworth, 1978). This work concluded that the boreholes penetrated Chalk with very high transmissivity in which upward leakage occurred through less permeable layers and that groundwater flow was concentrated into a relatively narrow zone of little more than 30 m thickness.

In the Candover valley, six production boreholes were drilled near the heads of various dry valleys. These were then tested by pumping them individually, and as a group. A mathematical model was subsequently constructed for the catchment (Southern Water Authority, 1979; Keating, 1978; Headworth et al., 1982; Keating, 1982). However, the model did not give a good representation of the water levels or stream flows, so a lumped parameter model was developed. The aquifer was assumed to have two layers: a shallow layer with a transmissivity of 10 000 $m^2 d^{-1}$ and a storage coefficient of 0.05, and a deeper layer with transmissivity of 1000 $m^2 d^{-1}$ and a storage coefficient of 0.01. The model gave good representations of the winterbourne and groundwater hydrographs.

In parallel with the river augmentation project, the BGS carried out permeability tests using a variety of different techniques (Price et al., 1977; Price et al., 1993). Three boreholes were studied in the Candover catchment using packer tests, rock-core analysis and geophysical logs.

As an extension of the river augmentation scheme, another tributary catchment of the Itchen, the Alre, was investigated. A number of pilot boreholes were drilled and four production boreholes completed. As with the Candover scheme the boreholes were tested together and individually (Southern Water Authority, 1984; Giles and Lowings, 1990; Southern Science, 1991). Subsequently, a groundwater model of the Alre and Cheriton catchments was developed (Irving, 1993). Although requiring refinement, the model gave a good representation of groundwater levels and stream flow.

Table 4.7 Water balance calculation for the Test catchment (1991 to 1995) (data from Entec, 2005).

	River Test to Kimbridge
Area (km^2)	957
Total available water (Ml d^{-1})	1073
Recharge (Ml d^{-1})	999 (381mm a^{-1})
Discharges (Ml d^{-1})	27
Abstractions (Ml d^{-1})	40
River flow (Ml d^{-1})	960
Baseflow (Ml d^{-1})	912
Imbalance (Ml d^{-1})	97

Rennie (1994) reviewed fracture-zone elevations in boreholes on a section along the Candover catchment. This work suggested that zones of preferentially enlarged fractures can be extrapolated between Totford, Axford and Wield, approximately parallel with the falling elevation of the river bed. TV logs of boreholes at Totford and Axford show that some of these zones are associated with tabular flint bands (see also the discussion based on borehole geophysical work in the Candover catchment in Chapter 3).

Allen et al. (1997) summarised the results of a number of modelling projects conducted in the Hampshire region. Several pieces of evidence, including the collected data, were examined to give an indication of the lateral variation of aquifer properties in the Hampshire area. It was thought that transmissivity values of 1000 $m^2 d^{-1}$ are common in the valleys, and that both transmissivity and storage coefficient decrease up the interfluves. A layered aquifer with an extensive high transmissivity zone is thought to exist in the Candover catchment, with typical transmissivity values of 1000 to 3000 $m^2 d^{-1}$ and storage coefficient values of 0.01 to 0.03. The neighbouring Alre catchment is thought to have a discrete set of large diameter conduits, which, if intersected, will give extremely high transmissivity values (>5000 $m^2 d^{-1}$). However, if a borehole does not intersect the system, the yield is very low. Estimates of storage coefficient from pumping tests in the Alre are lower than those calculated from modelling or river hydrographs. Along the axes of anticlines, aquifer properties are considered to be less well developed. Often anticlinal axes are associated with groundwater mounds that have a low transmissivity, possibly less than 100 $m^2 d^{-1}$.

In the upper Itchen catchment, the east–west folding can strongly affect the relationship between fissured zones and the surface and therefore the ease with which water can enter and leave the groundwater system. For example, the Alre follows the course of a syncline that dies out around the confluence with the Itchen as anticlinal axes to the north and south converge. It has been suggested (Entec, 2002) that this structural configuration, in conjunction with the general regional structure, assists both recharge and discharge processes in the aquifer. Recharge is helped by the cropping out of the main fracture zone in the upper parts of the Alre and Itchen catchments (locally enhanced by run-off from clay-with-flints cover) and by enlargement of the groundwater catchment due to an anticlinal structure. Discharge is aided because the structural setting — principally the convergence of the anticlines and the dying out of the Alre syncline — causes outcrops of the structurally controlled fracture zone to occur in the bed of the River Itchen, downstream of the Alre. This causes significant baseflow accretion in this section of the river during summer months. The high flows of the Alre itself are in fact somewhat artificial as they are supported by discharge from artesian boreholes. These boreholes penetrate the high-transmissivity fracture zone which lies below a low-permeability Chalk layer. In the absence of the boreholes most of the groundwater flow would continue down-gradient, to appear in the Itchen further downstream, probably where the fracture zone meets the Itchen river bed (Entec, 2002). The very high transmissivity values found in the Alre catchment are assumed to be associated with this zone.

In the Candover catchment, groundwater flow appears to be concentrated in a series of individual horizons in the Chalk (Headworth, et al., 1982; Rennie, 1994). This is illustrated by the stepped nature of flow hydrographs which is taken to indicate the drying of fracture horizons which supply water to the river as groundwater levels fall.

Entec (2002) suggest that comparison of the elevations of groundwater flow horizons between the Candover and the Alre imply that the two are related. The Cheriton accretes at a fairly constant rate down its length. Flow is baseflow dominated and the river responds quickly to recharge. Geophysical evidence suggests that fracturing in the aquifer is not related to the same stratigraphical horizons as that seen in the Candover and the Alre (Entec, 2002).

The Alre catchment is significantly more productive than those of the Candover and Cheriton rivers and it appears from potentiometric data that the Alre groundwater catchment is substantially larger than the surface catchment.

The Candover and Cheriton rivers generally respond to recharge more rapidly than the Alre and are more seasonably variable. This is attributed to the fact that the Alre is augmented by artesian flows. Higher flows in the Cheriton than the Candover occur at times of high groundwater water levels, because the former drains a larger block of aquifer, despite having a similar surface catchment size.

4.5.6.1 Water balance

A water balance was carried out over the period 1991 to 1995 with a monthly time step and with results aggregated to annual average and long-term average figures (Entec 2005). The results in Table 4.8 indicate that a much higher percentage (about 20 per cent) of available groundwater is abstracted compared with the Test catchment (<4 per cent).

4.6 EAST HAMPSHIRE

4.6.1 Catchment geology

The geology of East Hampshire is dominated by the asymmetrical syncline of the Hampshire Basin (see Figures 1.11 and 2.2). Mainland East Hampshire lies on the northern limb of the syncline, which in general dips at a relatively low angle to the south. This limb carries two major subsidiary anticlinal structures, the Warnford Dome in the north, which brings Lower Chalk to crop in the head waters of the River Meon, and the Portsdown Anticline, which brings a west–east-trending ridge of Upper Chalk (Portsdown Chalk Formation and the Spetisbury Chalk Member of the Culver Chalk Formation) to surface within the area of Palaeogene cover north of Portsmouth. Well-defined, strike-orientated, near-vertical, narrow fracture zones are a feature of the chalk members exposed on the Portsdown structure. The zones are narrow, usually between 0.5 and 1 m wide, with parallel faces (Hopson, 2000). Between the Portsdown Anticline and the main outcrop of the Chalk Group to the north is the Bere Forest Syncline, where the sequence of Palaeogene strata is preserved (in places exceeding 100 m in thickness). The Bere Forest Syncline continues to the east of Portsdown where it is termed the Chichester Syncline.

Drift deposits occur overlying both the Chalk and Palaeogene rocks. Head and alluvium are found mainly in the north–south dry valleys on the Chalk with terrace gravels in the Meon valley. Clay-with-flints is commonly located on hilltops above the valleys. In the area of the Bere Syncline, head is common overlying the London Clay. To the south of Portsdown, the Palaeogene and Chalk has an extensive cover of river terrace, raised marine and tidal flat deposits with aeolian sands and silts.

4.6.2 Surface water flows

In the East Hampshire area, many streams rise from springs at the southern margin of the Chalk, where it is overlain by Palaeogene sands and clays. The Hamble has a number of tributaries which originate at this Chalk/Palaeogene springline. These springs are unreliable in summer months, leading to low stream flows (Environment Agency, 1999c). Most of the Hamble's flow is derived from a relatively dense network of minor streams, which drain a wide area of superficial deposits, leading to a lower baseflow index than would be expected for a purely chalk-fed river (Table 4.9).

The River Meon is sometimes intermittent upstream of Warnford, where it is augmented by large springs and discharges from cress beds. Where it is gauged at Mislingford, the Meon exhibits the characteristics of a typical Chalk river, with a high baseflow index (Table 4.9). Where the river flows over the Palaeogene deposits, its response to rainfall is more flashy. Further south, at Funtley, the Meon again flows over the Chalk where minor (previously major) springs occur (Environment Agency, 1999c) after which it again crosses Palaeogene deposits.

4.6.3 Hydrogeology

The Chalk is the main aquifer in East Hampshire. Test pumping shows that the underlying Upper Greensand is often not considered to be in hydraulic continuity with the Chalk, and its depth over the most of the area precludes its use as an aquifer, although usable water supplies can be obtained where it occurs at shallower depths. Water supplies can also be obtained from the arenaceous units of the overlying Palaeogene strata, although these vary considerably in both quantity and quality.

In the east, there is rapid and substantial movement of groundwater from the north under the Palaeogene deposits of the Chichester–Bere Forest Syncline to major springs at Havant and Bedhampton. To the west, the Chalk under the Bere Forest Syncline appears to have poor aquifer properties and limited resource potential, presumably as a result of the thickness of overburden.

The hydrogeology of the Portsdown Anticline (for example, its effect on the Bedhampton springs) is becoming better understood. Groundwater appears to flow off the anticline in a generally radial pattern, supplying springs along the north coast of Portsmouth Harbour and springs feeding the River Wallington.

The Palaeogene cover has an important bearing on the Chalk aquifer properties in this area because it inhibits direct recharge to the underlying Chalk aquifer; in particular, the

Table 4.8 Water balance calculation for the Itchen catchment 1991 to 1995 (data from Entec, 2005).

	Itchen to Allbrook and Highbridge
Area (km^2)	541
Total available water (Ml d^{-1})	635
Recharge (Ml d^{-1})	602 (406mm a^{-1})
Discharges (Ml d^{-1})	12
Abstractions (Ml d^{-1})	125
River flow (Ml d^{-1})	503
Baseflow (Ml d^{-1})	474
Imbalance (Ml d^{-1})	18

Table 4.9 Gauging station data from selected sites on rivers in east Hampshire (source: Marsh and Lees, 2003).

Station name (river name)	**Grid reference**	**Catchment area (km^2)**	**Period of record**	**Mean annual rainfall (mm)**	**Mean flow (m^3 s^{-1})**	**Q_{10} (m^3 s^{-1})**	**Q_{95} (m^3 s^{-1})**	**Base flow index**
Frogmill (Hamble)	SU 52 14	56.6	1972–2000	882	0.42	0.8	0.10	0.67
Mislingford (Meon)	SU 58 14	72.8	1958–2000	930	0.97	2.0	0.20	0.93
North Fareham (Wallington)	SU 58 07	111.0	1951–2000	855	0.62	1.6	0.04	0.41

lowest formations are usually poorly permeable and inhibit recharge. Run-off from the Palaeogene deposits is directed into surface watercourses that flow onto the Chalk at discrete points, thus providing a mechanism for enhanced local dissolution of the Chalk. The effect can be exacerbated if the water has picked up an acidic chemical signature from the Palaeogene strata. Enhanced dissolution features (e.g. dolines) are, for example, observed on the northern edge of the outcrop of the Palaeogene deposits of the Bere Forest Syncline, where the topography is undulating, locally permitting run-off to the north onto the Chalk outcrop.

The existence of these karstic features suggests that some groundwater can move rapidly along highly developed but relatively thin, solution-enhanced fractures at the Chalk–Palaeogene boundary, passing below the Bere Forest Syncline to re-emerge near sea level through the Chalk of the Portsdown Anticline. That such rapid transit systems exist in certain topographically/structurally controlled situations is well shown by the major spring supplies of Bedhampton and Havant. These form the largest public supply spring source from the Chalk in the UK and are reputed to be the largest group of springs used for public supply in Europe. They produce between 53 and 170 million litres of water every day (Portsmouth Water website: www.portsmouthwater.co.uk). Rapid karstic groundwater flow from the north under the Bere Forest Syncline to the springs has been shown by a tracer study (see Chapter 3 for description). Similar rapid flows under the syncline are considered to occur further east, along the syncline axis, at Fishbourne and possibly as far west as the Wallington valley.

Further westwards, the flexuring becomes much less marked, so that the Chalk outcrop becomes narrower and then disappears beneath the Palaeogene cover west of the Meon valley. The increasing thicknesses of low-permeability, Palaeogene, clay-dominant strata in this direction removes outlet opportunities away from the incised axes of the main rivers crossing the structural grain. This reduces the scope for highly productive flow systems to have developed and it is therefore less likely that well-developed, connected, solution-enhanced flow horizons persist far beneath the feather edge of the Palaeogene cover west of the Meon valley.

4.6.3.1 Water level variations and groundwaterflow

There is an extensive north–south, dry-valley network across the outcrop of Chalk. The water table here is well below the valley bottoms and only in exceptional circumstances does water flow in these valleys. An example of this was during spring of 1994, when surface flows were noted in certain valleys and the potentiometric level was measured some 20 m higher than average (Hopson, 2000). This resulted in flooding in the villages of Hambledon, Finchdean and Stoughton.

Groundwater flow pathways are generally from north to south. Between catchments, flow pathways can be in other directions: for example, between the Meon and upper Itchen catchment to the east, groundwater flow is initially to the north (Institute of Geological Sciences, 1979a and 1979b). As with most Chalk catchments, the depth to the water table will vary considerably between interfluve areas, where the unsaturated zone is thickest (sometimes exceeding 40 m), and valley areas, where the unsaturated zone is thinnest. Valleys tend to provide the best sites for boreholes because it is here that there has been maximum fracture development.

4.7 ISLE OF WIGHT

4.7.1 Catchment geology

The Isle of Wight lies on the southern, steeply dipping limb of the synclinal Hampshire Basin. Here, the Chalk forms a spine running west–east across the island and bedding has been rotated to near-vertical along much of the outcrop in a structure known as the Purbeck–Isle of Wight Monocline. The Chalk is some 300 m in thickness on the Isle of Wight and extends as high as the Upper Campanian Portsdown Chalk Formation beneath the Palaeogene unconformity. Mortimore et al. (2001) provide descriptions of the complete Chalk succession from the classic coastal exposures at Compton Bay and between Sandown Bay and Whitecliff Bay. The spine of Chalk crossing the island is generally narrow with a dip approaching vertical, but in the area south-west of Newport the Chalk crop expands to form the broad Idlecombe Down where bedding in the Chalk does not dip more than 10 degrees. This broad area of low dips creates an offset in the narrow steeply dipping Chalk spine and is thought to reflect an offset in the underlying faults whose reactivation controlled the uplift and rotation of the Chalk (Underhill and Patterson, 1998). The northern part of the island is underlain by Palaeogene strata contained within the Hampshire Basin whose dip is steep close to the Purbeck–Isle of Wight Monocline but which flattens out rapidly to the north. To the south of the Purbeck–Isle of Wight Monocline, near horizontal Upper Greensand, Lower and Middle Chalk outcrop within the Southern Downs of the Isle of Wight.

4.7.2 Surface water flows

The River Medina and Eastern Yar on the Isle of Wight have their origins on the chalklands of the Southern Downs on the island. They flow northwards, initially across an extensive crop of gently inclined Lower Greensand, before cutting

Table 4.10 Gauging station data from selected sites on rivers in the Isle of Wight (source: Centre for Ecology & Hydrology, 2003).

Station name (river name)	Grid reference	Catchment area (km^2)	Period of record	Mean annual rainfall (mm)	Mean flow ($m^3 s^{-1}$)	Q_{10} ($m^3 s^{-1}$)	Q_{95} ($m^3 s^{-1}$)	Base flow index
Upper Shide (Medina)	SZ 50 87	29.8	1965–2000	857	0.27	0.5	0.08	0.63
Burnt House (Eastern Yar)	SZ 58 85	59.6	1982–1999	831	0.41	0.8	0.04	0.48

through the central chalk ridge formed by the Isle of Wight Monocline. Surface water flow data are given in Table 4.10.

4.7.3 Hydrogeology

The Chalk and Upper Greensand aquifer system in the Isle of Wight falls into three distinct parts: the Southern Downs, the steeply dipping central 'spine' and the central Chalk–Upper Greensand area.

The Southern Downs are composed of a gently southward dipping, almost planar, surface. Groundwater occurs mostly within the Upper Greensand, with the overlying Chalk being generally unsaturated. Groundwater discharge is to the headwaters of the Eastern Yar and Medina and to the (unstable) landslip area on the southern coast of the island. Flow within the Upper Greensand is likely to be strongly influenced by the presence of an upper fractured sandstone (Malm Rock), intervening fractured chert beds and by underlying silty sands, the Passage Beds.

Steeply dipping Chalk forms a 'spine' across the Island and groundwater flow must be strongly influenced by the dip. There are spring outflows on the down-dip side at Afton (Freshwater) and at Brading, but there are 'overflow' springs at Ashey, Knighton (historically), Shalcome and Brighstone (Buddlehole) and, at high water levels, at points along the northern Chalk–Palaeogene contact. It is likely that the Chalk is highly fractured in these areas. There is a flow of groundwater out of the high elevation 'Plateau gravels' at St George's Down, just east of Newport onto the Chalk and down a sinkhole.

In the Central Chalk–Upper Greensand area, there are numerous dry valleys and the only significant stream is the Lukely Brook, which discharges to the north-east through Carisbrooke. The Bowcombe valley is underlain by a remarkable historic water gathering structure — the Idlecombe main, which is part adit and part pipe. The other discharge areas are to the Caul Bourne, the Sheat Stream (Chillerton), the Shorwell stream and Gatcombe stream. There is an internal spring in the Central Downs area at Froglands Farm (just south of Carisbrooke Castle) at the Upper Greensand–Chalk contact, so the hydraulic connectivity between Chalk and Upper Greensand must be low. Some sources (Bowcombe) abstract from the Upper Greensand as well as from the Chalk.

5 Hydrogeochemistry

5.1 INTRODUCTION

The chemical characteristics of groundwater in the Chalk are determined by a wide variety of processes, but the dominant features (such as hardness) are acquired through water–rock interactions with the chalk matrix. The fine-grained nature and composition of the Chalk (see Box 3) make it highly reactive to incoming solutions. The initial solute inputs to the aquifer are derived from rainfall, which contains mainly marine-derived salts. Most rainfall is slightly acidic due to the presence of dissolved carbon dioxide from the atmosphere. The chemistry of rainfall has, in recent decades, been affected by anthropogenic inputs, which may have increased its acidity due to the formation of low concentrations of sulphuric and nitric acid. As rainfall percolates through the soil, it picks up additional CO_2 from soil respiration and organic matter decomposition and concentrations are often 10 to 100 times that of atmospheric CO_2.

The soil zone provides an important control on the chemistry of shallow waters in the Chalk due to the high CO_2 concentrations developed as a result of biological activity. The CO_2 and the extent to which the system remains open with respect to CO_2 is a major control on determining the evolution of waters in carbonate terrains. The CO_2 dissolves to produce carbonic acid (H_2CO_3), which reacts with the carbonate minerals. The kinetics of this reaction are very rapid; the acidity is quickly neutralised by reaction with the carbonate-rich chalk soils and saturation with calcite is generally reached within the top few metres of the Chalk. The pH of water in the soil zone overlying chalk is typically 7.5 to 8.3 (Price et al., 1993). The chemistry of most groundwaters is dominated by reactions of the carbonate system.

Other reactions which are important in controlling baseline water quality include redox reactions and ion exchange reactions, although the strongest influence of these is within the confined parts of the aquifer.

This chapter aims to characterise the groundwater chemistry in the Chalk aquifer of the Wessex Basin and to determine the dominant geochemical processes that control the spatial variations in hydrochemistry. The source of the data used is a combination of Environment Agency and water company data and detailed studies carried out by the BGS (Buckley et al., 1998; Edmunds et al., 2002).

BOX 3 MINERALOGY OF THE CHALK GROUP

Chalk is a microporous limestone comprising mainly coccolithic fragments with lesser amounts of other fossils (e.g. foraminifera) and shelly debris. The coccoliths are composed of a relatively pure calcite ($CaCO_3$). However, small amounts of other elements (Mg, Sr, Mn) are present in the calcite structure, which helped to stabilise the calcite in the marine environment. This low-Mg calcite is relatively stable at low temperature and pressure and little recrystallisation has occurred within the matrix, except at depths greater than 1000 m (Downing et al., 1993). The Chalk in the south Dorset area has undergone intense deformation and parts of the Chalk in this area have undergone significant recrystallisation. Original biogenic silica has undergone extensive diagenetic processes to form the typical 'flint' bands of the Chalk.

The non-carbonate fraction of the Chalk generally comprises clays but minor amounts of zeolite, quartz, collophane, dolomite, feldspar and barite have been noted (see Hancock, 1993 for summary). Significant amounts of clay and terrigenous material are present in the Lower Chalk, dominantly smectite and quartz (Bath and Edmunds, 1981). Montmorillonite forms the dominant clay in most formations but is particularly abundant in the Upper and Middle Chalk (Morgan-Jones, 1977) where it often forms distinct marl bands which may contain as much as 30 per cent clay (Hancock, 1993). The origin of the montmorillonite has been the subject of debate with both neoformational origin and volcanic origin being suggested. Kaolinite is less abundant and often considered to be detrital in origin (Morgan-Jones, 1977) although it may in part be derived from alteration of glauconite. The presence of muscovite and illite is also considered to be detrital in origin.

Knowledge is limited concerning the complex structures and mineralogy developed on fracture surfaces and in the weathered mantle immediately below the soil horizon. The development of secondary mineral phases on shallow chalk fracture surfaces is generally very extensive and is typified by clays and Fe and Mn sesquioxides (Shand and Bloomfield, 1995).

5.2 PREVIOUS HYDROCHEMICAL STUDIES

Alexander (1981) presented a summary of unconfined and confined Chalk groundwaters of south Dorset and discussed the different chemical facies in the area. No clear patterns in major ion groundwater chemistry appeared from this study and the groundwaters tended to be of a similar type and clustered together, dominantly of a Ca-HCO_3 type. Alexander defined two groups of groundwaters: Group I waters from the South Winterbourne catchment and the western edge of the outcrop areas, and Group II waters from around the Lulworth area, with Group I waters containing slightly higher Na levels than those of Group II. Edmunds (1996) analysed Chalk groundwaters in the Lulworth–Poole area from both public abstraction sources and BGS cored boreholes. The results showed that groundwaters from the outcrop and near outcrop areas had very similar compositions with low salinity and generally contained high nitrate and low iron concentrations. The limited data from the confined aquifer showed that these waters were more reducing, contained high Fe and nitrate was below the detection limit. Interstitial water at depth in the aquifer near the coast (in a borehole at Lulworth) was fresh, suggesting that fresh water had flowed to greater depths in the aquifer during late Pleistocene times when the sea level was lower. In general, more saline water is found in the pore space whilst fresher water flows through the fissures to depths of at least 250 m (Edmunds, 1996).

Buckley et al. (1998) undertook geophysical logging and depth sampling of groundwaters in the confined aquifer in the region around Wareham. They showed that there is significant hydrochemical stratification in the aquifer with waters evolving from Ca-HCO_3 to Na-HCO_3-Cl-dominated waters deeper in the aquifer. The chemistry of the groundwaters of Dorset was studied by Edmunds et al. (2002) who discussed the spatial variations and geochemical controls on groundwaters, mainly in the unconfined Chalk of Dorset. This Dorset report is in a series describing baseline groundwater quality and is complemented by a study of the Palaeogene of the Wessex Basin (Neuman et al., 2004).

5.3 HYDROCHEMICAL CHARACTERISTICS OF THE UNSATURATED ZONE

Several processes occur in the unsaturated zone which affect the pore-water chemistry including:

- evapotranspiration, which may significantly concentrate solutes
- uptake of solutes by biomass
- dissolution of aquifer matrix minerals
- precipitation of minerals (e.g. calcite, clays, sesquioxides)
- ion-exchange reactions

The last three processes may significantly modify both the character and reactivity of fracture surfaces. It has been found that enhanced porosity may occur to a depth of 1 to 1.5 mm away from fractures in the Chalk, related to carbonate dissolution (Bloomfield, 1997). Fracture surfaces are likely to be important loci for both dissolution and precipitation. Shand and Bloomfield (1995) found extensive Fe-rich clays and oxide minerals coating fracture surfaces in the shallow, unconfined Chalk and concluded that this may exert an important control on flow through the unsaturated zone. Fracture minerals may also be indicators of flowpaths through the Chalk, e.g. the presence of abundant manganese spots on the surfaces of marl horizons implies that these may be important for the lateral movement of water.

There are no major or trace-element data for pore waters from the unsaturated zone of the Chalk in the Wessex Basin. However, pore-water samples were collected from a borehole at Gussage, near Blandford Forum, for tritium analyses by Geake and Foster (1989). Tritium was produced in the 1960s during thermonuclear testing and acts as a tracer for the water molecule with the maximum concentration occurring in 1963. Cores obtained from the Gussage Borehole in 1970 were sampled subsequently to provide information on the rate of movement of water through the unsaturated zone. The three sets of samples showed how the tritium peak has moved down the profile. The preservation of the peak, although decreasing in size by radioactive decay over time (modified by dispersion), showed that piston flow is an important process in water transfer through the matrix of the Chalk. The rate of flow was estimated to be around 1 m per year. Elsewhere in southern England, the slow transfer of nitrate and sulphate in the unsaturated zone beneath agricultural land has been shown (Foster et al., 1982), which poses a future risk to groundwater quality.

5.4 HYDROCHEMICAL CHARACTERISTICS OF GROUNDWATERS

A total of around 190 chemical analyses from groundwaters covering much of the Wessex Basin (Figure 5.1) have been used to characterise the groundwater chemistry and a summary of the data is shown in Tables 5.1 and 5.2. The tables show minimum and maximum concentrations as well as statistical averages (mean and median).

5.4.1 Physicochemical characteristics

The groundwaters show a significant range of temperatures (from 8 to 17ºC) although the majority lie in the range 10 to 12ºC. The pH is typically between 7.0 and 7.6 (median pH is 7.4) but some of the confined groundwaters are as high as 8.7. Specific electrical conductance (SEC) is typically

Figure 5.1 Location of samples used in the present study.

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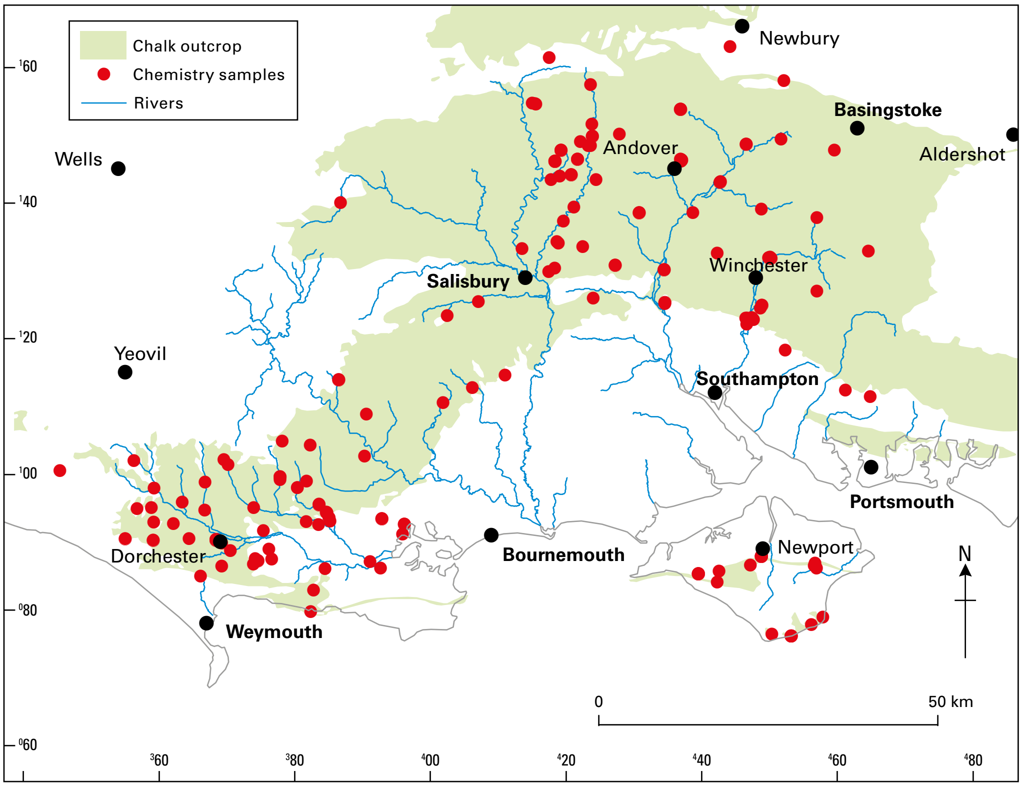

Table 5.1 Summary of chemical analyses of Chalk groundwaters from the Wessex Basin.

Parameter	Units	Minimum	Maximum	Mean	Median	N
T	°C	7.6	17.2	11.3	11.1	111
pH		6.66	8.65	7.38	7.30	163
Eh	mV	–16	884	455	503	35
DO	mg l^{-1}	<0.1	13.6	7.8	8.4	101
SEC	µS cm^{-1}	343	1409	545	520	151
^{2}H	‰	–47	–36	–42	–41	37
^{18}O	‰	–7.2	–5.8	–6.6	–6.5	37
^{13}C	‰	–16.2	–3.8	–13.0	–14.2	38
Ca	mg l^{-1}	50	176	101	103	173
Mg	mg l^{-1}	0.76	22	3.0	2.2	172
Na	mg l^{-1}	5.0	155	14	9.9	143
K	mg l^{-1}	0.07	7	1.5	1.2	117
Cl	mg l^{-1}	4.5	223	23	19	188
SO_4	mg l^{-1}	2.5	69	17	14	143
HCO_3	mg l^{-1}	107	400	274	280	152
NO_3-N	mg l^{-1}	<0.03	18	5.6	5.6	188
NO_2-N	mg l^{-1}	<0.001	0.057	0.005	0.005	125
NH_4-N	mg l^{-1}	<0.003	0.31	0.019	0.010	184
P	mg l^{-1}	<0.02	0.163	0.04	0.031	62
TOC	mg l^{-1}	0.49	5.8	1.6	1.2	30
DOC	mg l^{-1}	0.25	4.2	1.1	0.748	56
F	mg l^{-1}	0.03	4.3	0.237	0.090	122
Br	mg l^{-1}	0.010	0.289	0.076	0.069	66
I	mg l^{-1}	0.002	0.047	0.007	0.004	39
Si	mg l^{-1}	3.3	13.5	5.5	5.0	147

between 400 and 600 µS cm^{-1} in the unconfined part of the aquifer, increasing to a maximum of 1409 µS cm^{-1} in the confined part. The redox status of the groundwater largely reflects the presence or absence of confining conditions with oxidising conditions (dissolved oxygen present, high Eh) in the unconfined aquifer and reducing conditions in the confined part of the aquifer.

5.4.2 Major element characteristics

The Wessex Basin Chalk groundwaters have been plotted on a Piper diagram (Figure 5.2), which illustrates the relative proportions of major elements and the groundwater composition. The vast majority of groundwaters are from the unconfined aquifer and these are of Ca-HCO_3 type with low Mg/Ca ratios similar to the solid chalk matrix. Groundwaters in the confined aquifer trend towards higher relative proportions of Mg and Na. A similar trend towards higher relative Cl also occurs but is less pronounced than that towards Na. Sulphate concentrations are generally low in these groundwaters and only two groundwaters plot towards sulphate dominance. There appear to be two trends on the central Piper plot: a few groundwaters trend towards the upper part due to relatively high Ca and Cl and several sites trend towards the lower right due to relatively high Na, HCO_3 and Cl.

The range in concentrations is highlighted using box plots (Figure 5.3) and cumulative probability plots (Figure 5.4). These highlight the considerable range of concentrations in the groundwaters of the Chalk. It is apparent that the data are not generally log normal but often show bimodal or multimodal distributions. Calcium and HCO_3 are the dominant solutes and display a relatively linear distribution limited by the solubility of calcite. Nitrate varies over three orders of magnitude with low concentrations present in the confined groundwaters.

5.4.3 Minor and trace element characteristics

The ranges in concentrations of minor and trace elements are shown in Table 5.2 and on Figures 5.5 and 5.6. Iron and Mn concentrations are generally low but reach relatively high concentrations in the confined groundwaters. The concentrations of most metal species are low because of their low solubility in circumneutral, oxidising groundwater.

5.4.4 Depth variations

Samples obtained from pumped boreholes often represent mixtures of water, possibly of different ages and chemistry. They are also derived largely from fractures, which often have different chemistry from water contained within the pores of the matrix. There are limited data on depth variations in individual boreholes in the region, however, Edmunds et al. (2002) reported porewater chemistry from a borehole at Lulworth in unconfined Chalk and Buckley et al. (1998) analysed depth samples collected from boreholes in the confined aquifer in the region of Wareham.

Table 5.2 Summary of trace element analyses of Chalk groundwaters from the Wessex Basin.

Parameter	Units	Minimum	Maximum	Mean	Median	N
Ag	μg l^{-1}	<0.05	6.0	0.32	0.03	68
Al	μg l^{-1}	<1	927	14	2.5	150
As	μg l^{-1}	<0.2	75	1.1	<0.2	122
Au	μg l^{-1}	<0.05	<0.05	<0.05	<0.05	34
B	μg l^{-1}	<20	399	32	20	93
Ba	μg l^{-1}	2.50	135	21	13	158
Be	μg l^{-1}	<0.05	0.50	0.22	<0.05	66
Bi	μg l^{-1}	<0.05	0.07	0.03	<0.05	39
Cd	μg l^{-1}	<0.05	0.50	0.11	0.10	101
Ce	μg l^{-1}	<0.01	0.04	<0.01	<0.01	39
Co	μg l^{-1}	<0.01	15	0.77	0.46	66
Cr	μg l^{-1}	<0.05	4.0	0.89	<0.5	96
Cs	μg l^{-1}	<0.01	0.04	<0.01	0.01	39
Cu	μg l^{-1}	0.20	370	9.5	2.0	101
Dy	μg l^{-1}	<0.01	<0.01	<0.01	<0.01	39
Er	μg l^{-1}	<0.01	<0.01	<0.01	<0.01	39
Eu	μg l^{-1}	<0.01	0.01	<0.01	<0.01	39
Fe	μg l^{-1}	0.20	36600	401	10	172
Ga	μg l^{-1}	<0.05	<0.05	<0.05	<0.05	39
Gd	μg l^{-1}	<0.01	0.02	<0.01	<0.01	39
Ge	μg l^{-1}	<0.05	0.32	0.05	<0.05	39
Hf	μg l^{-1}	<0.02	<0.02	<0.02	<0.02	34
Hg	μg l^{-1}	<0.1	0.50	<0.01	<0.1	60
Ho	μg l^{-1}	<0.01	0.01	<0.01	<0.01	39
In	μg l^{-1}	<0.01	<0.01	<0.01	<0.01	34
Ir	μg l^{-1}	<0.05	<0.05	<0.05	<0.05	34
La	μg l^{-1}	<0.01	0.02	<0.01	<0.01	39
Li	μg l^{-1}	0.20	179	12	1.4	43
Lu	μg l^{-1}	<0.01	<0.01	<0.01	<0.01	39
Mn	μg l^{-1}	<2	726	13	4.2	173
Mo	μg l^{-1}	<0.1	2.8	0.30	0.05	39
Nb	μg l^{-1}	<0.01	0.01	<0.01	<0.01	34
Nd	μg l^{-1}	<0.01	0.02	<0.01	<0.01	39
Ni	μg l^{-1}	<0.2	20	2.2	0.80	39
Os	μg l^{-1}	<0.05	<0.05	<0.05	<0.05	34
Pb	μg l^{-1}	<2	22	1.3	<2	102
Pd	μg l^{-1}	<0.2	<0.02	<0.2	<0.2	34
Pr	μg l^{-1}	<0.01	0.01	<0.01	<0.01	39
Pt	μg l^{-1}	<0.01	<0.01	<0.01	<0.01	34
Rb	μg l^{-1}	0.71	6.1	1.7	1.5	39
Re	μg l^{-1}	<0.01	0.02	<0.01	<0.01	34
Rh	μg l^{-1}	<0.01	<0.01	<0.01	<0.01	34
Ru	μg l^{-1}	<0.05	<0.05	<0.05	<0.05	34
Sb	μg l^{-1}	<0.05	1.4	0.30	0.20	94
Sc	μg l^{-1}	<0.4	3.0	1.2	1.4	56
Se	μg l^{-1}	<1	2.9	<1	<1	120
Sm	μg l^{-1}	<0.5	<0.05	<0.05	<0.05	39
Sn	μg l^{-1}	<0.5	0.21	0.08	0.07	34
Sr	μg l^{-1}	142	3570	467	237	78
Ta	μg l^{-1}	<0.05	<0.05	<0.05	<0.05	36

Continued overleaf

Table 5.2 *(cont)* Summary of trace element analyses of Chalk groundwaters from the Wessex Basin.

Parameter	Units	Minimum	Maximum	Mean	Median	N
Tb	μg l^{-1}	<0.01	<0.01	<0.01	<0.01	39
Te	μg l^{-1}	<0.05	0.10	<0.05	<0.05	34
Th	μg l^{-1}	<0.05	<0.05	<0.05	<0.05	39
Ti	μg l^{-1}	<10	<10	<10	<10	34
Tl	μg l^{-1}	<0.01	0.08	0.02	0.01	39
Tm	μg l^{-1}	<0.02	<0.02	<0.02	<0.02	39
U	μg l^{-1}	<0.05	1.4	0.31	0.26	39
V	μg l^{-1}	<1	3.0	<1	<1	83
W	μg l^{-1}	<0.1	<0.1	<0.1	<0.1	34
Y	μg l^{-1}	<0.01	0.15	0.02	<0.01	39
Yb	μg l^{-1}	<0.01	0.01	<0.01	<0.01	39
Zn	μg l^{-1}	0.80	1460	56	15	112
Zr	μg l^{-1}	<0.5	<0.5	<0.5	<0.05	34

5.4.4.1 Interstitial waters of the Lulworth Borehole

Interstitial waters were extracted from a research borehole at Lulworth drilled during the late 1970s to a depth of 170 m below OD (Edmunds et al., 2002). Geophysical logging carried out in 1997 was used to determine the groundwater flow at this site using the change of gradient of the temperature log (Figure 5.7). The base of the present-day flow system was interpreted to be around 65 m; below this depth, the temperature increases linearly with the geothermal gradient, whilst at shallower depths the temperature is disturbed by active groundwater flow. The SEC below this depth decreases slightly showing that fresh groundwater exists to a depth of around 130 m along the Dorset coast.

The presence of relatively high NO_3-N in the top 65 m of the borehole indicates the penetration of modern, polluted groundwater. Selected data from the deeper part of the

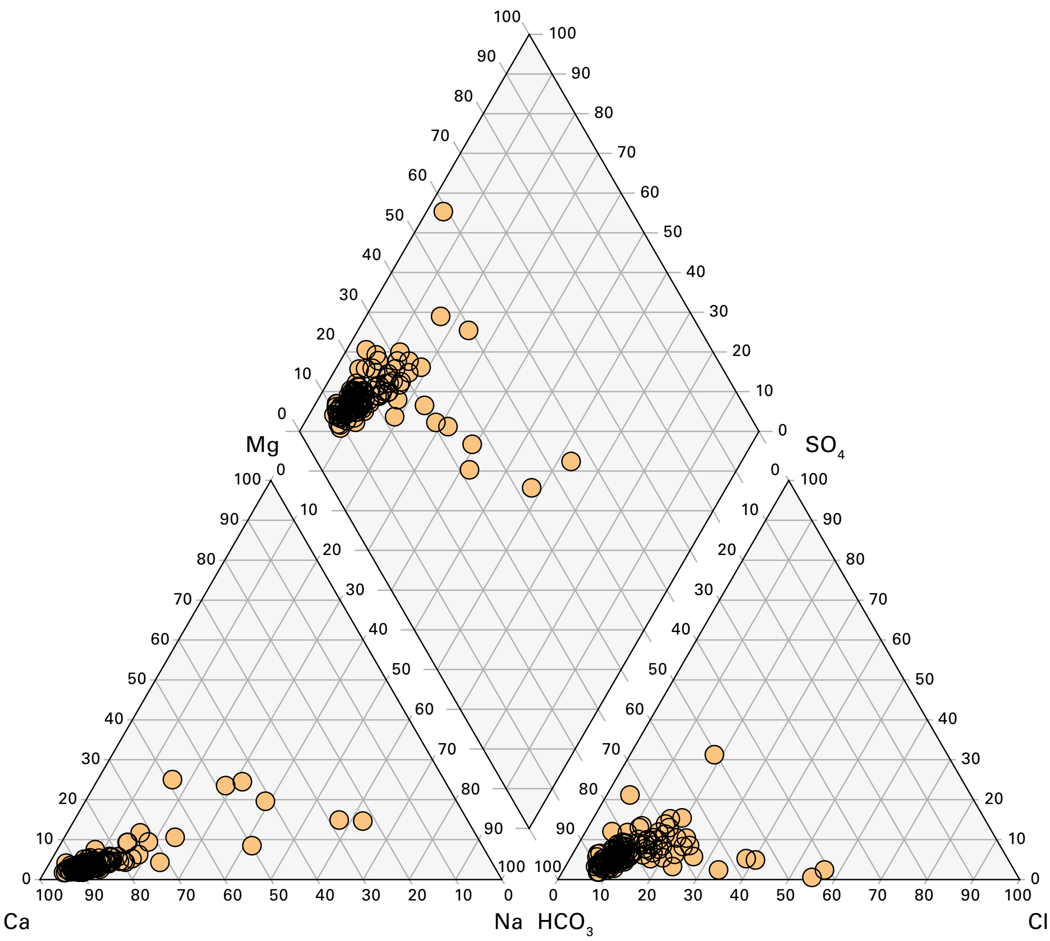

Figure 5.2 Piper diagram showing the relative proportions of major cations and anions in Wessex Basin groundwaters.

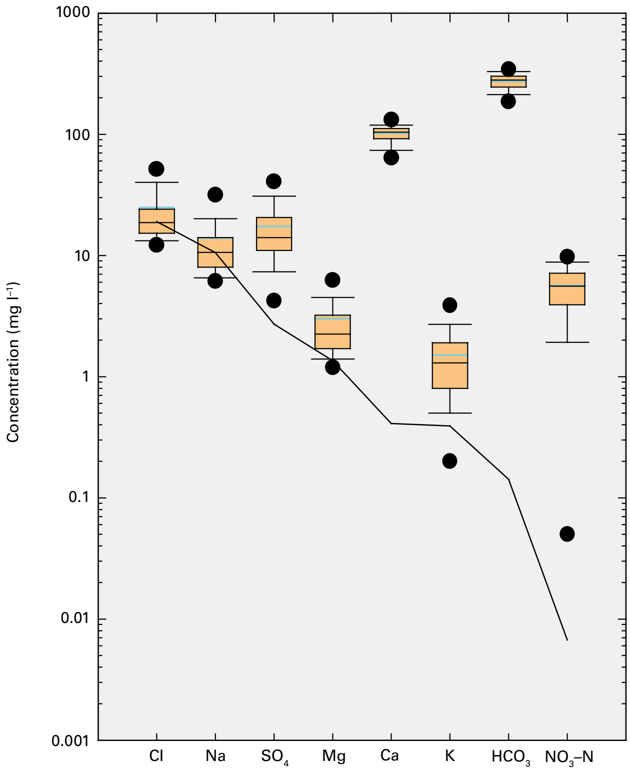

Figure 5.3 Box plot showing ranges in concentration of major elements in groundwaters of the Wessex Chalk.

borehole are shown in Table 5.3 where it can be seen that nitrate is present at much lower (probably baseline) concentrations. There is additionally an increase in some elements (e.g. Sr) below a depth of around 140 m, possibly indicating that a more mature groundwater is present at depth.

5.4.4.2 Depth samples from the confined aquifer

Groundwater samples were collected from three boreholes drilled into the confined aquifer west of Poole Harbour: Bulbury, Lytchett Minster and Holton Heath. These were analysed during a preliminary study of the potential for aquifer storage and recovery (ASR) in the confined Chalk of Wessex (Buckley et al., 1998; Gaus et al., 2002). The depths of the boreholes increase from Bulbury through Lytchett Minster to the deepest at Holton Heath and selected data have been plotted on Figure 5.8. There is a general increase in Na and Cl with depth, both in individual boreholes and between boreholes. This is also seen to a lesser degree with HCO_3, K and several trace elements (F, B, Ba, Li) but Ca displays a decrease with depth (Figure 5.8). The high concentrations of F in these boreholes, increasing with depth, is of particular note and is discussed further in Chapter 6. An increase in ^{13}C and the ratios Sr/Ca and Mg/Ca indicate that the extent of water–rock interaction is greater in the deeper groundwaters. The increase in Na and decrease in Ca results from ion-exchange reactions. The stable isotopes ^{2}H and ^{18}O are consistent with a dominantly Holocene age but a slight decrease may imply that an older component of Pleistocene water is present.

5.4.5 Temporal variations

There is a lack of long-term data available for the study area. Examples of available data are shown on Figures 5.9 and 5.10 for one spring and one borehole. The Litton Cheney spring [SY 55 90]) lies at the western part of the outcrop and has been monitored (by the Environment Agency) since 1992. Although there are no long-term trends in SEC, these do vary seasonally, most likely indicating that at least one source of the spring is of short residence time (probably weeks or months). This seasonal trend is seen to a lesser degree for SO_4 and Cl. The seasonal changes may reflect greater, less dilute recharge in the late winter months when evapotranspiration is lower. Nitrate also shows seasonality with higher concentrations during the times of lower SEC. In contrast to the other elements, NO_3-N shows an increasing trend with time as well as a seasonal trend (Figure 5.9).

Data from a shallow borehole (West Houghton [ST 82 04]) are shown on Figure 5.10. The Cl concentration is slightly lower than for the Litton Cheney spring and may reflect the decrease in maritime influence (Edmunds et al., 2002) but seasonal trends or long-term trends are not apparent. As with Litton Cheney, NO_3-N shows an increase in concentration with time, reflecting increased N-loading or higher N en route from the recharge area. Such increases are often found in the Chalk aquifer where it is unconfined.

The natural baseline for species such as nitrate are difficult to determine from modern data. Some data (unconfined aquifer) from the BGS archives and from Whitaker and Edwards (1926) are shown on Table 5.4 and indicate that NO_3-N concentrations were much lower in the early part of the twentieth century.

5.5 AGE OF THE GROUNDWATER

For the deeper, confined groundwaters, direct determination of groundwater age using ^{14}C is difficult in aquifers such as the Chalk because of problems with correction for carbon derived from the Chalk matrix. However, the indications are that most of the groundwaters beneath Wareham, to a depth of 300 m below OD, are of Holocene age (around 11 000 years to present) (Edmunds et al., 2002) but are likely to be several thousand years old since they only contain traces of ^{14}C.

Several indicators improve understanding of the residence time of groundwater in the unconfined aquifer, for example the seasonality of springs, tritium data and

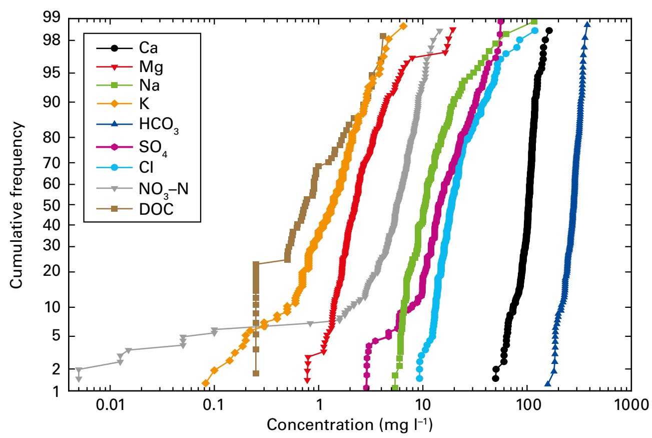

Figure 5.4 Cumulative probability plot showing the ranges in concentration of major elements in groundwaters of the Wessex Chalk.

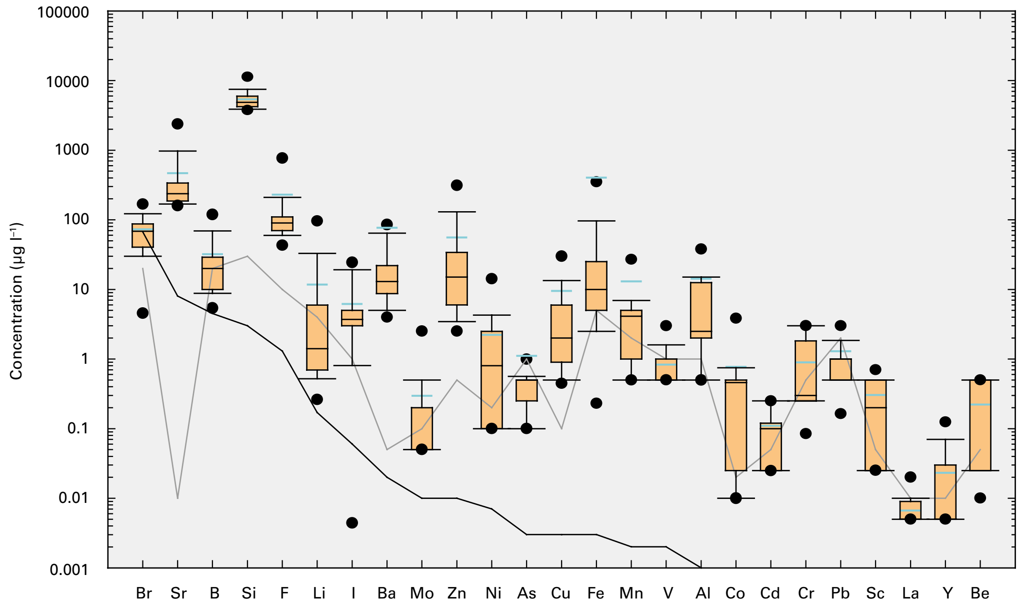

Figure 5.5 Box plot showing the ranges in concentration of minor and trace elements in groundwaters of the Wessex Chalk.

the presence of a wide range of introduced contaminants. The abstraction of groundwater is likely to have modified the natural groundwater flow, distorting the original age structure and promoting mixing of waters of different ages. The presence of nitrate and other introduced contaminants shows the degree to which the shallow groundwater has been affected by modern (post 1940s) recharge. However, detailed studies (e.g. using CFCs and other dating tools) are required to assess the age stratification with depth. Seasonal oscillations in the hydrochemistry of springs (e.g. Figure 5.9) and boreholes also show that at least some of the groundwater is of recent origin.

The available evidence therefore suggests that the unconfined groundwaters are relatively young (or contain a substantially younger component) and that the confined groundwaters are much older, of the order of thousands of years. This is also substantiated by the chemical changes that have occurred along the regional flow direction.

5.6 DOWN-GRADIENT EVOLUTION OF CHALK GROUNDWATER

Groundwater in the Chalk aquifer evolves with time as a result of time-dependent reactions and changes in geochemical environment. Such changes, often seen down the hydraulic gradient, highlight the geochemical processes occurring spatially and with time in the aquifer.

Hydrochemical changes are due both to mixing with continued recharge (especially in the unconfined aquifer), mixing with older formation water and reaction with the chalk matrix. These changes along the hydraulic gradient are illustrated using a section from upland areas of Chalk in the west to the coast close to Poole (Figures 5.11 and 5.12). However, it should be borne in mind that changes also occur with depth and some of the differences may be due to different borehole depths and borehole completions. In addition, recharge occurs over the entire outcrop area. Nevertheless, the general trends are considered to be due to time-dependant reactions, age and mixing as the waters move along the hydraulic gradient.

The groundwaters within the unconfined aquifer are of Ca-HCO_3 type with low Mg/Ca (and Sr/Ca) ratios similar to the chalk matrix (Figures 5.2 and 5.12). The groundwater in the Chalk reaches saturation rapidly with calcite, controlled by the congruent dissolution of calcite:

$$Ca_x(Mg,Sr)1_{-x}CO_3 + CO_2 + H_2O = xCa + 1_{-x}(Mg,Sr) + 2HCO_3$$

Calcium, Mg and HCO_3 show little change in the unconfined aquifer reflecting the above reaction, but the confined groundwaters show an increase in Mg and Sr that reflects the change from congruent to incongruent dissolution of calcite.

This highlights the fact that calcite continues to be dissolved, but in order to maintain chemical equilibrium a similar amount is reprecipitated. Magnesium, Sr and other ‘impurities’ are effectively lost to solution as a purer calcite is precipitated. This change is most evident in groundwaters of the confined aquifer and implies a distinct age difference between the unconfined and confined groundwaters. The change is also shown by an increase in ^{13}C: the groundwaters of the unconfined aquifer are around -16 to -12 representing a mixture of C of biogenic origin from the soil (^{13}C of -25) and from the chalk matrix C (ca. +2.4). There is a trend deeper in the confined aquifer

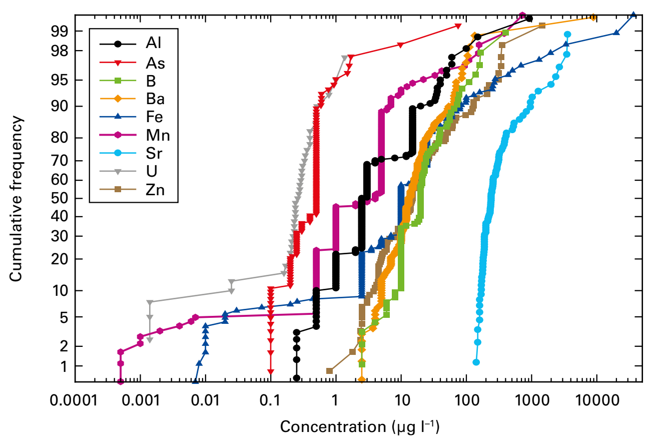

Figure 5.6 Cumulative probability plot showing the ranges in concentration of major elements in groundwaters of the Wessex Chalk.

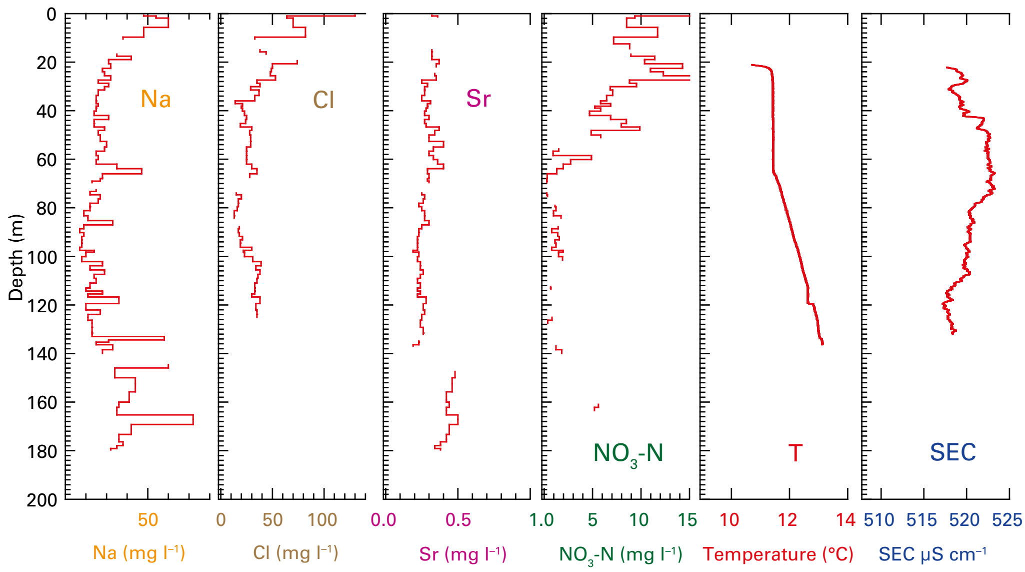

Figure 5.7 Interstitial water chemistry, temperature and SEC profiles from the research borehole at West Lulworth (from Edmunds et al., 2002).

towards the Chalk reaching -2 in the deep Holton Heath Borehole close to Wareham. Groundwaters with relatively high Mg/Ca and Sr/Ca ratios are due to a much greater amount of reaction and are, therefore, indicative of a longer residence time.

Chloride concentrations are generally low but variable in the unconfined aquifer. Many are slightly higher than expected for rainfall that has undergone evapotranspiration and these probably reflect some degree of anthropogenic input e.g. agricultural, domestic pollution or road salt application. The deeper confined groundwaters show an increase in Na and Cl (Figure 5.11) indicating that these older waters contain a component of chalk formation water which has not been flushed from the aquifer. Nevertheless, Cl concentrations remain relatively low and are typically less than 100 mg l^{-1} Cl, which indicates that the aquifer is well flushed of any original connate water.

The increase in Cl in the confined groundwater is reflected in a similar increase in Na, but Na/Cl ratios are slightly higher than expected for a marine-derived source indicating an additional source of Na (Figure 5.12). The confined groundwaters (pumped and depth samples) from around Wareham show a decrease in Ca concomitant with the increase in Na. The changes in Na and Ca (one mole of Ca for every two moles of Na) are consistent with ion exchange of Ca in solution for Na on exchange sites (probably clay minerals). This explains the trends observed on the Piper diagram, which are intermediate between that expected for mixing and ion exchange of a freshening aquifer (Figure 5.2). Chalk porewaters present in isolated parts of the aquifer, which are probably very old, may show extreme ion exchange with concentrations of Ca as low as 3 mg l^{-1} (Shand, 1999).

Fluoride concentrations are generally low in the unconfined aquifer but increase in the confined groundwaters (Figure 5.12). The source of fluoride is most likely to be derived from apatite or fluorapatite (present mainly as fossils in the Chalk and particularly associated with marl horizons), which have slow dissolution kinetics. This implies that there is a significant difference in residence time between the groundwaters of the unconfined and confined aquifer. Saturation with respect to the mineral fluorite is reached in some of the deeper groundwaters. Detailed studies have shown that in some areas where very old groundwaters are present (Shand, 1999) fluorite and amorphous F-rich phosphate minerals (with rapid dissolution kinetics) are present. These minerals may explain the excess F noted during aquifer storage and recovery trials in the confined Chalk (Gaus et al., 2002).

Strontium and Ba also increase along the hydraulic gradient. The Sr is derived dominantly from the calcite matrix, but unlike Ca it is not limited in these groundwaters by saturation with respect to any mineral phase. Barium is likely to be derived either from the chalk matrix or the mineral baryte (Shand and Bloomfield, 1995). Most metals are present at low concentrations, their solubility being limited at the circum-neutral pH typical of the chalk groundwaters.

Dissolved oxygen and redox potential are uniformly high in the unconfined groundwaters (Figure 5.11). There is a distinct change in these parameters close to the unconfined–confined boundary where a redox boundary has been established. The groundwaters in the confined aquifer are reducing and denitrification has led to loss of nitrate from the groundwater. The reducing nature of the groundwater has also led to high concentrations of dissolved Fe and an increase in NH_4 (Figure 5.11). Sulphate concentrations are generally low but show no distinct pattern along the hydraulic gradient and it appears that sulphate reduction is not a dominant control on sulphate concentrations in these groundwaters.

Table 5.3 Chemistry of deep interstitial waters from the Lulworth Borehole (after Edmunds et al., 2002).

	Depth (m bgl)		
Parameter	**69.6**	**104.9**	**125.1**
pH	7.40	7.84	7.58
Ca (mg l^{-1})	67	70	68
Mg (mg l^{-1})	2.1	1.8	2.0
Na (mg l^{-1})	23	22	21
K (mg l^{-1})	2.7	1.0	1.3
HCO_3 (mg l^{-1})	179		
Cl (mg l^{-1})	27	34	35
NO_3-N (mg l^{-1})	1.2	7.1	3.6
Sr (mg l^{-1})	0.30	0.24	0.25

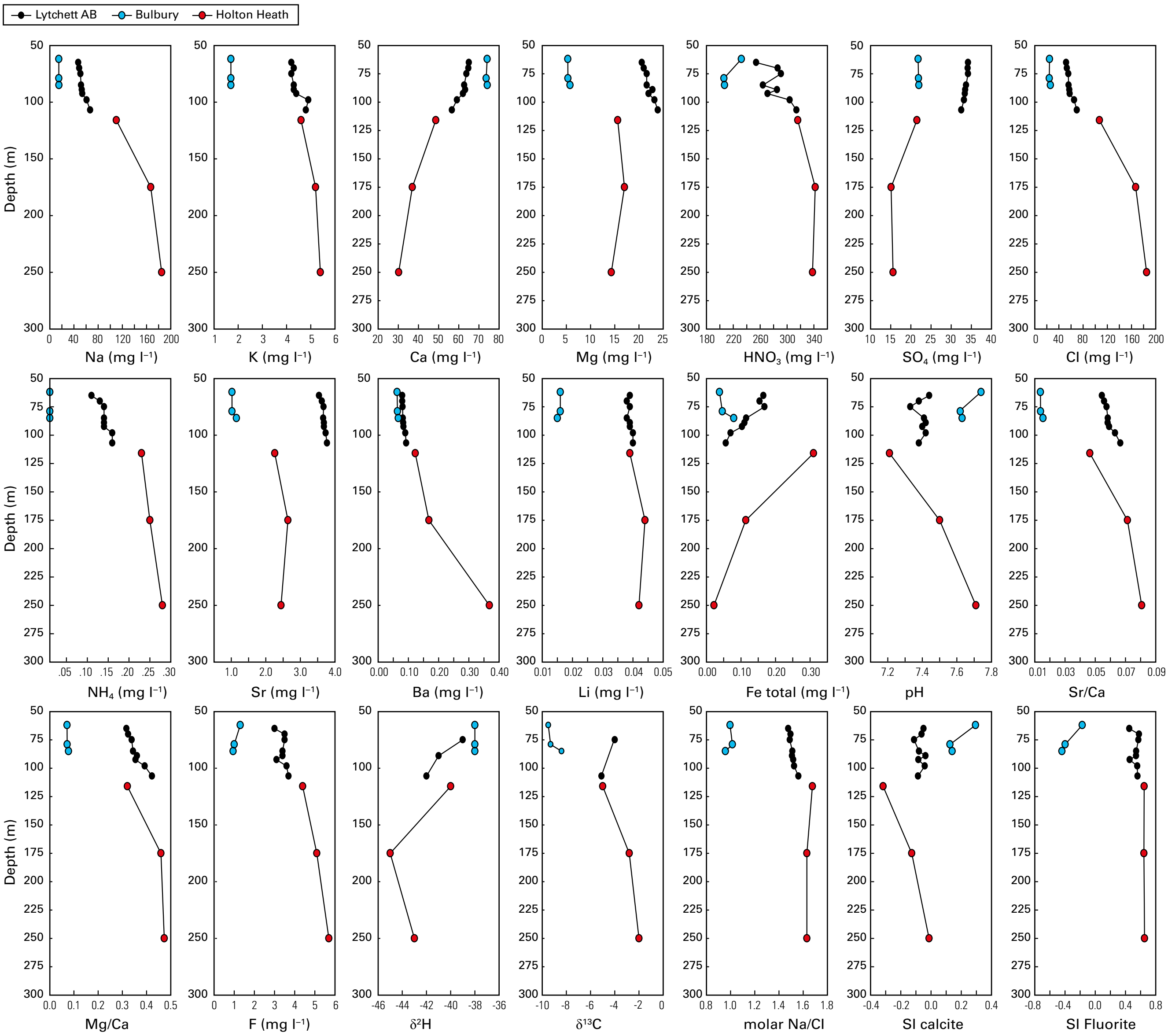

Figure 5.8 Depth variations in groundwaters of the confined aquifer in the Wareham area of the Wessex Basin.

5.7 SPATIAL VARIATIONS IN CHALK GROUNDWATERS IN THE WESSEX BASIN

The geochemical evolution along the detailed section described above can also be seen regionally across the aquifer. Selected parameters have been plotted on Figures 5.13 to 5.17. The unconfined groundwaters are oxidising and have low to moderate electrical conductance (Figure 5.13). Although data for the confined aquifer are limited, the groundwaters typically have much higher electrical conductance and low dissolved oxygen concentrations.

Sodium and Cl distributions (Figure 5.14) are similar, with concentrations being higher in the confined groundwaters, reflecting mixing with formation water, although there is tendency for higher Na and Cl in unconfined groundwaters on the Isle of Wight and towards the Dorset coast, which may reflect a higher marine (sea salt) input. Higher Na/Cl ratios in the confined groundwaters are due to ion exchange (Na for Ca) as discussed previously. In contrast, one of the samples to the east of Southampton, sampled from the confined aquifer close to the edge of the Palaeogene, contains low Na, but high Cl. This also had the highest specific electrical conductance (SEC). The Cl is balanced by high Ca and it is possible that this unusual composition is related to ion-exchange of Na for Ca.

Distributions for Ca and Mg are shown on Figure 5.15. The highest Ca is generally in areas close to the junction with the Greensand but there is otherwise little consistent variation across the outcrop area. Lower concentrations of Ca are present in groundwaters in the deeper part of the confined aquifer around Wareham (where ion exchange has occurred). Magnesium, in contrast, has the highest concentrations in the confined groundwaters as incongruent dissolution increases with residence time. The minor elements Sr and F (Figure 5.16) both reflect residence time and typically display a rapid increase in concentration where the groundwaters are confined.

The effects of diffuse pollution are reflected in high NO_3 concentrations in the outcrop areas (Figure 5.17), which are stable under the oxidising conditions prevalent where the aquifer is unconfined. Nitrate concentrations decrease in the confined aquifer due to denitrification and are typically below

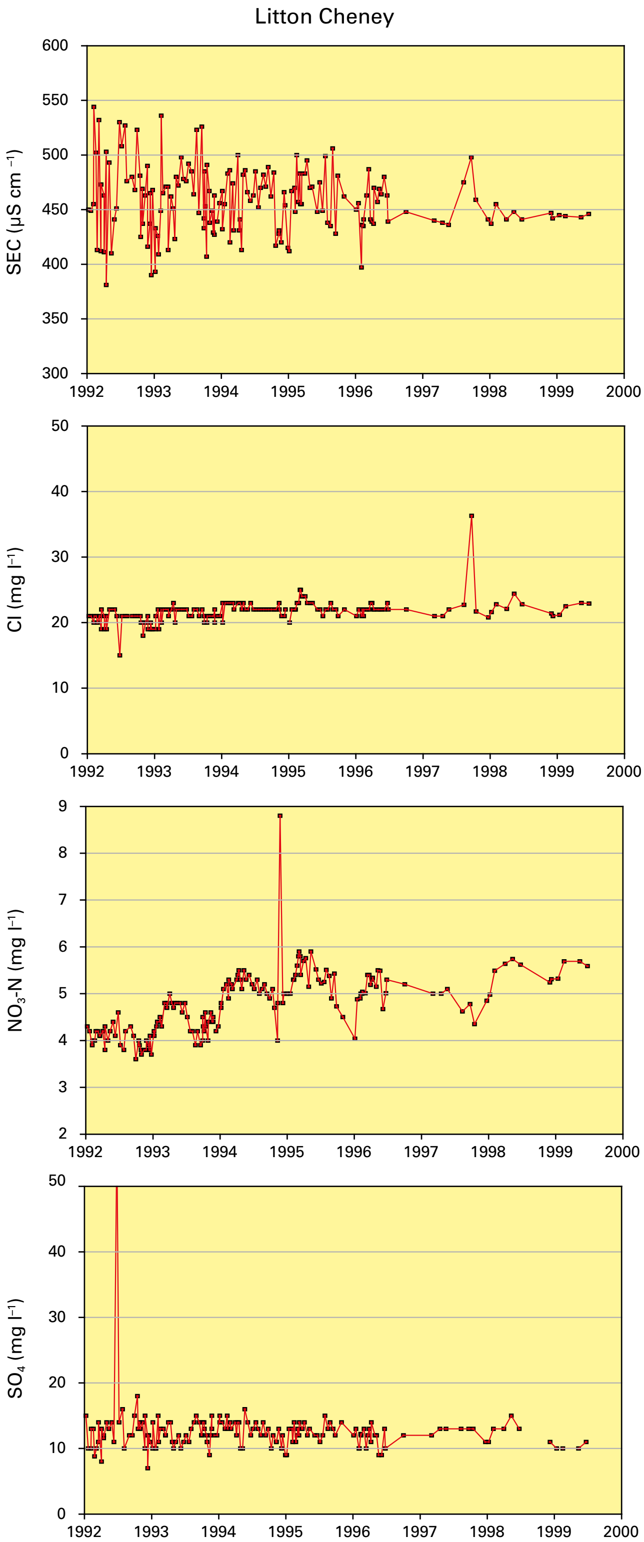

Figure 5.9 Temporal variations in hydrochemical parameters in the Litton Cheney spring [SY 55 90] (from Edmunds et al., 2002).

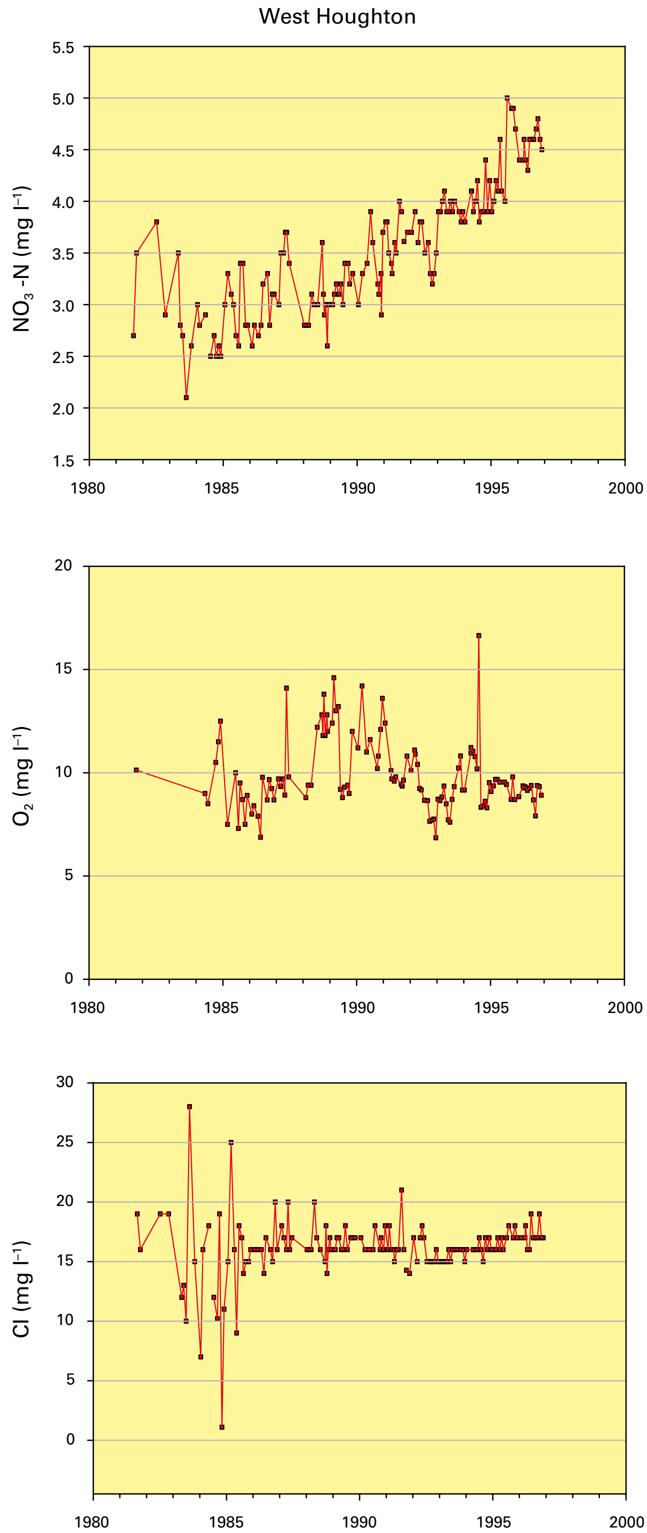

Figure 5.10 Temporal variations in hydrochemical parameters from the West Houghton Borehole [ST 82 04] (from Edmunds et al., 2002).

detection limit in the deep groundwaters sampled around Wareham. Some locally high concentrations of metals do occur (e.g. As, Ni) but may simply be a consequence of not filtering during sampling.

A summary of the dominant processes affecting groundwater quality in the Wessex Basin is illustrated on the schematic cross-section through the Chalk of Dorset in Figure 5.18. The major element chemistry of the Chalk groundwaters is controlled by the carbonate system and the groundwaters in the outcrop areas are of Ca-HCO_3 type. Mixing with remnant formation water (probably within the chalk matrix) has led to an increase in salinity in the deepest, oldest waters. Ion exchange of Na for Ca in these waters has led to a trend intermediate between that of Na-HCO_3 and

Table 5.4 Selected historical nitrate and chloride data from BGS borehole archives.

Site	Date (year)	NO_3-N (mg 1^{-1})	C1 (mg l^{-1})
Corfe Mullen	1908	1.0	30
Durweston	1911	1.3	17
Upwey	1910	0.88	23
Sutton Poyntz	1913	0.73	19
Alton Pancras	1946	1.5	–

Na-Cl types. The largest changes in water chemistry occur where the aquifer becomes confined beneath the overlying Palaeogene sediments. A redox boundary has been established close to this boundary and beyond this zone the groundwaters are reducing and contain low concentrations of nitrate. The reducing nature of the system has, however, led to an increase in Fe and Mn. There are limited data on trace metals over much of the aquifer but the available information indicates that concentrations are generally low, a notable exception being F, which generally exceeds the EU-MAC for drinking water in confined parts of the aquifer. The large chemical differences between the unconfined and confined groundwaters in the Wessex Basin are consistent with differences in residence time and indicate that they may be controlled by different flow systems.

5.8 HYDROCHEMISTRY AND SURFACE – GROUNDWATER INTERACTIONS, BOURNE CASE HISTORY

5.8.1 Introduction

A preliminary study of the hydrochemistry of the Bourne catchment was undertaken by the BGS as a contribution to the Environment Agency's hydrogeological investigation. The purpose of the hydrochemical study was to assess spatial variations and provide some constraints on flow pathways in the Bourne catchment.

Samples were collected both from the River Bourne and from boreholes along most of the catchment area (Figure 5.19) between April 1999 and February 2000. A number of parameters were measured on site including temperature, SEC, total alkalinity (as bicarbonate) by titration, pH, Eh and dissolved oxygen (DO). Filtered samples were then taken for subsequent laboratory analysis.

5.8.2 Hydrochemical characteristics

The surface and groundwaters of the Bourne catchment are all of Ca-HCO_3 type and show remarkably little variation in the relative proportions of major elements on a Piper diagram (Figure 5.20). The Mg/Ca ratio increases with water–rock interaction (and hence residence time) due to incongruent dissolution and the low ratios in the Bourne waters indicates that the waters are relatively immature. The pH of the groundwaters is neutral to slightly alkaline (7.03 to 7.54) and typical of those found in the Chalk. Dissolved oxygen and Eh are both moderate to high and indicate that the waters are all oxidising. The groundwaters are moderately mineralised with SEC showing some variation: 552 to 718 µS cm^{-1} in the river and 417 to 640 µS cm^{-1} from groundwaters.

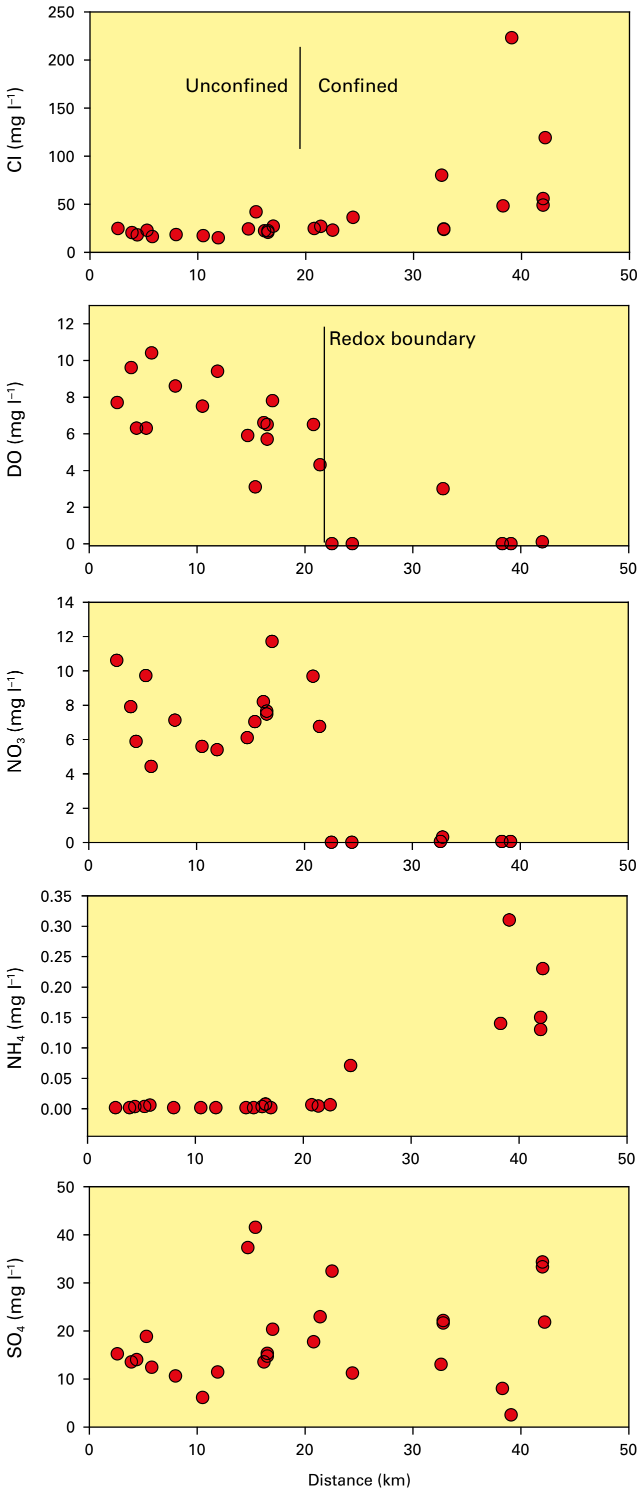

Figure 5.11 Major and minor element characteristics of Chalk groundwaters along a line of section between Powerstock and Wareham (from Edmunds et al., 2002).

The groundwaters of the Bourne catchment may be expected to show variations in baseline chemistry as the waters evolve with increased residence time in the aquifer. A comparison with surface waters will also indicate the role of groundwater discharge to the river. The groundwater chemical data have been plotted against northing in Figures 5.21 and 5.22 because this is the general direction of surface water flow (north to south), however, the groundwater catchment and flow may be very different from that of the surface.

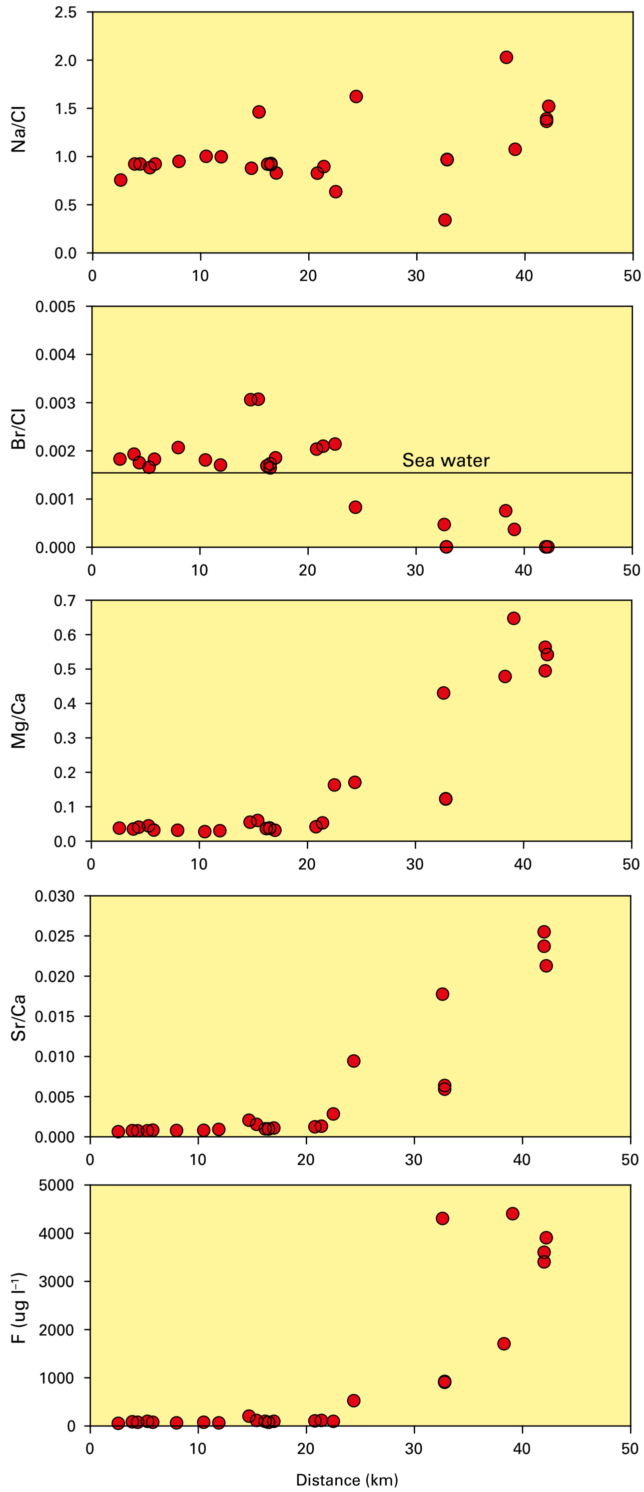

Figure 5.12 Hydrochemical characteristics of Chalk groundwaters along a line of section between Powerstock and Wareham (after Edmunds et al., 2002).

The chemistry of the river water and the Idmiston Spring have also been plotted for comparison. Note that the Upavon boreholes are within the Avon surface water catchment.

Several discharges are present within the Bourne catchment and are likely to affect both surface water and groundwater quality. However, it is not possible to quantify these because of the lack of data on discharge chemistry. Anthropogenic inputs are clearly seen for the elements P, NO_3, Cl and SO_4.

5.8.3 Comparison between groundwaters and River Bourne

The pH of the groundwaters shows no significant trend along the Bourne valley (Figure 5.21). The higher pH values in the river waters occur as a consequence of the degassing of CO_2 from this groundwater-dominated river. The pH of the river rises between Collingbourne Kingston (northing 5500) and Tidworth (5000) as CO_2 degasses with time, leading to oversaturation with respect to calcite. However, the river pH is lower downstream of the central part of the catchment where the river often dries (i.e. between northings 5000 and 4000), implying more recent discharge from the groundwater. There is significant overlap in several major (Ca, HCO_3, Na) and minor (F, Sr, Ba) elements between the groundwaters and the river (Figures 5.21 and 5.22), which indicates that, at the time of sampling, the rivers were dominated by groundwater inputs. In addition, the same spatial trends present in the rivers are a good indication that the river is dominated by local inputs from the groundwater system. If the river water represented a continuous accreting discharge, the concentrations would be different from the local groundwater because they would consist of a mixture of all inputs upstream of the sampling point. The concentrations of some dissolved components in the river do show significant differences to the local groundwater: e.g. higher concentrations of Cl, SO_4, P and NO_3 were present in the river (Figures 5.21 and 5.22) and indicate some anthropogenic input to the River Bourne but it is difficult to quantify volumes due to lack of knowledge of the input chemistry. However, the concentrations of these elements varied significantly at sites where sampling was repeated (e.g. Newton Tony where NO_3 varied between 15 and 41 mg l^{-1}), in contrast to most major and trace elements, probably indicating a shallow source of short residence time.

5.8.4 Regional variations and chemical evolution

In general, groundwaters normally show an evolution of increasing total dissolved solids (TDS) along flowlines and with depth, related to increased water–rock interaction and residence time. The chemical trends present in the Bourne catchment are anomalous in that the highest TDS waters are present near the top of the catchment, with the freshest waters close to the confluence with the River Avon. The following general observations may be made:

- There is a general decrease in SEC, Cl, Ca, HCO_3, SO_4, Si and Sr between Leckford Bridge in the north and Winterbourne Gunner in the south. There are no significant trends for elements such as K, Mg, F, NO_3 and Ba.
- The river waters and groundwaters show similar trends.

It is difficult to envisage a process whereby the groundwaters in the south of the catchment can have directly evolved from those in the north. Although the precipitation of mineral phases (e.g. calcite, which would lower Ca and HCO_3) is feasible, there is no geochemical reason for this to occur. In addition, Sr (which is derived initially from calcite) does not precipitate with calcite and would be expected to increase with progressive reaction and time. The lower Sr southward cannot be due to differences in the host Chalk as Sr has been found to increase towards the top of the Chalk[7] (this may explain the slightly higher Sr/Ca south of Cholderton). Similar arguments can be

Figure 5.13 Regional plot for electrical conductance in the Wessex Basin Chalk.

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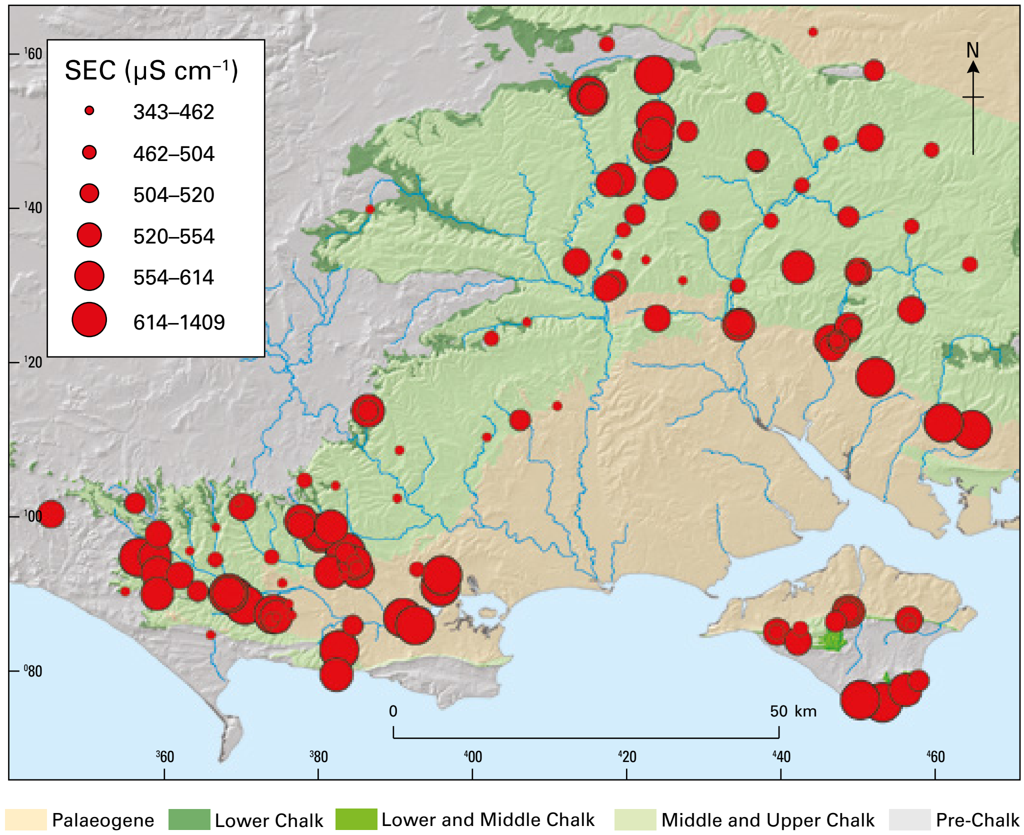

applied to Cl, which behaves as a conservative element, and other elements such as SO_4. Therefore, it is not possible to produce a direct evolutionary sequence along the postulated flowlines and the changes must be due to different sources of groundwater. The source of higher SEC waters in the upper reaches of the catchment may well be a consequence of contributions from the Upper Greensand. This is consistent with hydrochemical data collected from a borehole at Aughton [SU 23 57] where discharge was partly from the Upper Greensand (Figures 5.21 and 5.22).

5.8.5 Summary

The groundwaters of the Bourne catchment show significant changes in hydrochemistry along a north–south traverse, these changes being mirrored to a large degree by the water chemistry of the River Bourne. This implies that the river waters, at the time of sampling, are dominated by groundwater inputs. This is consistent with physical measurements, which show that the unsaturated zone is close to zero in the valley areas and reaches depths of greater than 60 m in the interfluves. The evidence that river chemistry trends are closely linked to groundwater chemistry also implies that discharge to the river system is dominated by local inputs of groundwater.

The chemical trends of decreasing concentration of many elements down the catchment shows that the groundwaters in the lower reaches of the catchment cannot be directly derived from those of the upper catchment. The hydrochemical trends from north to south may imply mixing between two (or more) end members that have evolved independently. The simplest explanation for this is that higher SEC waters originating from the Upper Greensand are affecting the composition of the Chalk groundwater in the upper part of the catchment, but that these groundwaters do not generally flow to the lower part of the catchment, where groundwaters are fresher and of relatively local origin. This explanation would concur with the conceptual model of the Bourne summarised in Chapter 4, in which groundwaters in the upper parts of the catchment tend to diverge to the adjacent Avon and Test catchments at lower elevations. Such an interpretation is also supported by the fact that when the central section of the Bourne is dry there are some differences between the River Bourne chemistry upstream and downstream of the dry river bed. This implies that after recharging the aquifer, the upstream river flow does not re-emerge further downstream, but rather tends to join groundwater flowing to the Avon and Test catchments.

[7] For example Sr increases above the Chalk Rock at Banterwick Barn in the Berkshire Downs (Murphy, 1998).

Figure 5.14
a) Regional plot for Cl in the Wessex Basin Chalk. b) Regional plot for Na in the Wessex Basin Chalk.
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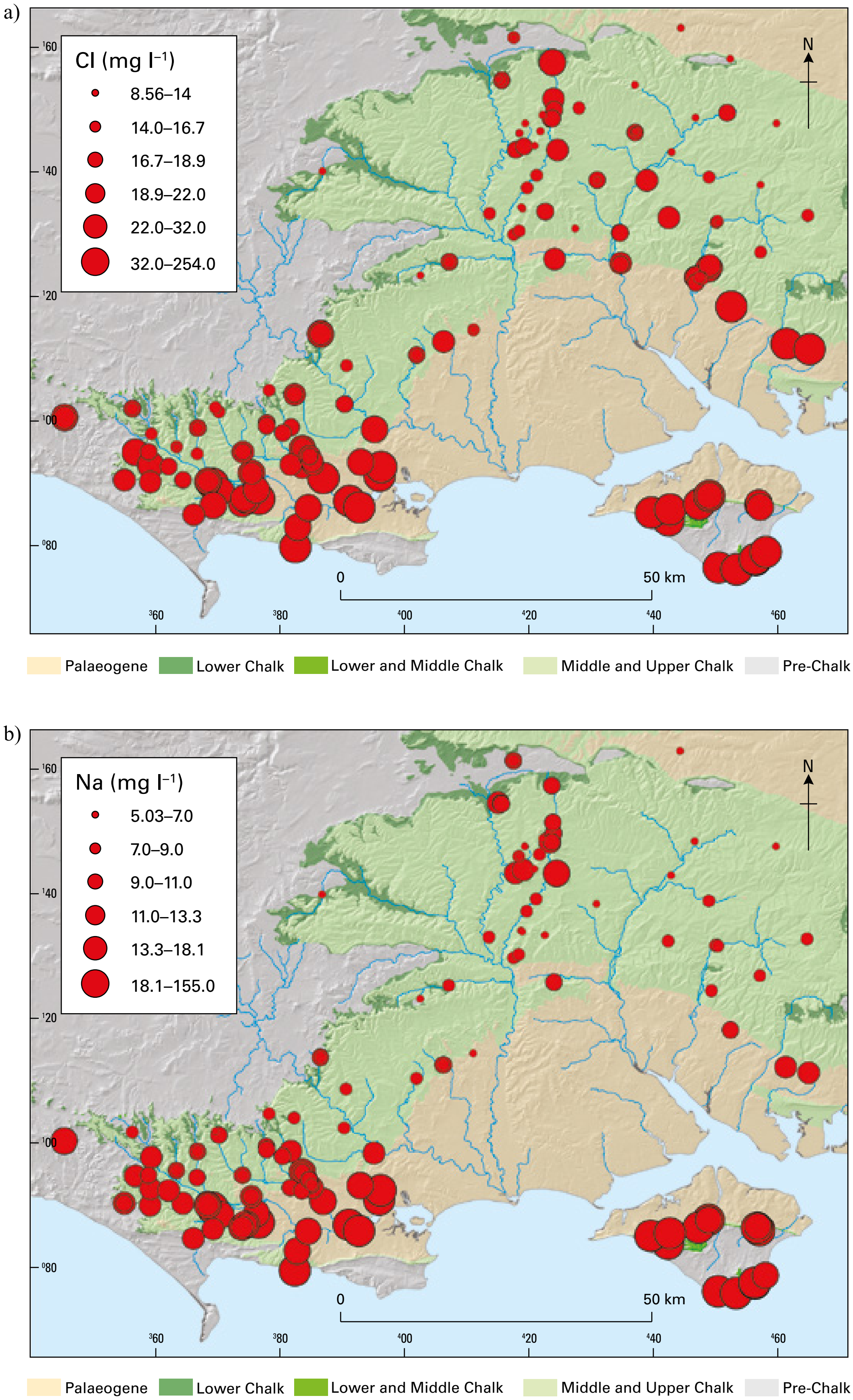
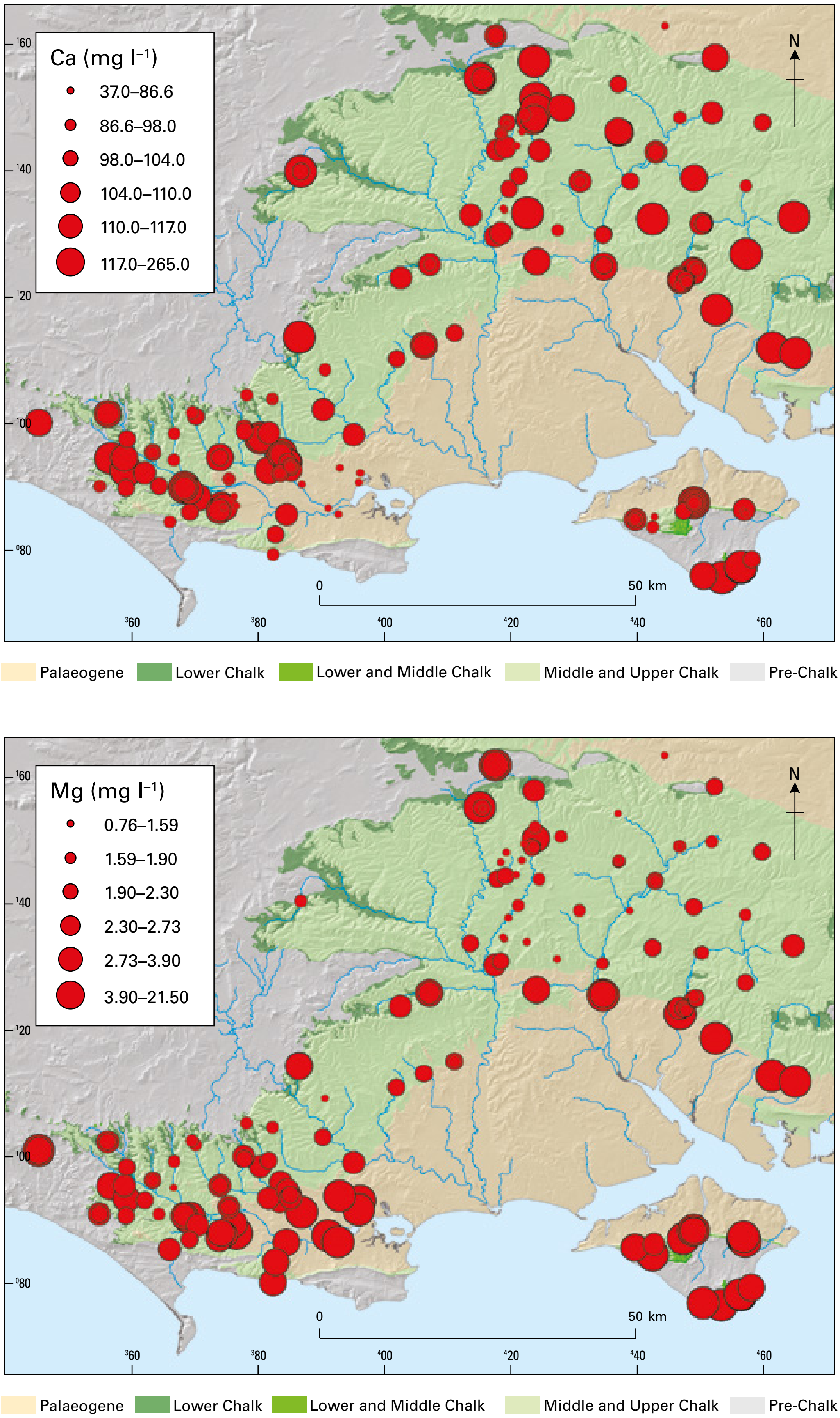


Figure 5.15
a) Regional plot for Ca in the Wessex Basin Chalk. b) Regional plot for Mg in the Wessex Basin Chalk.

a)

b)



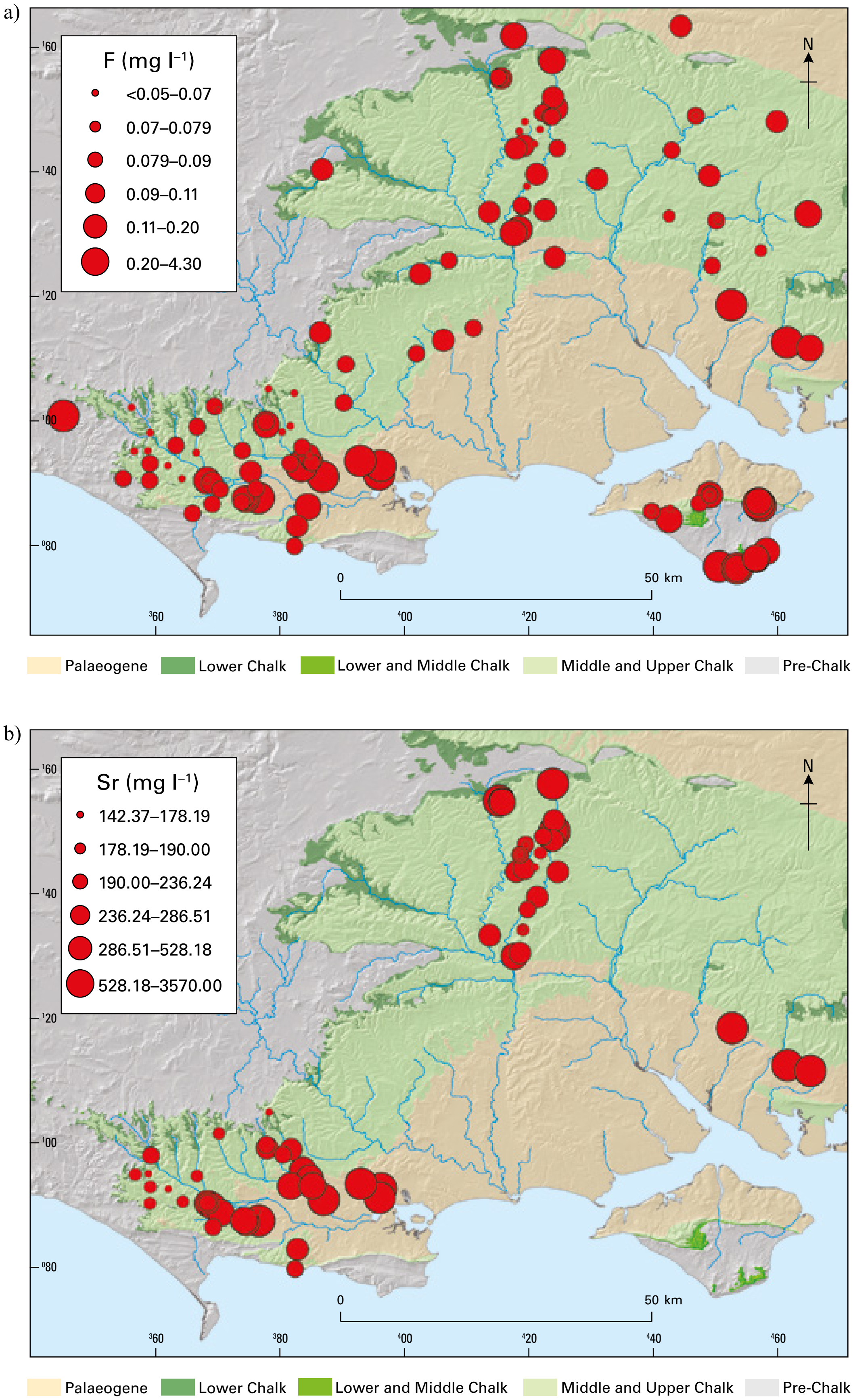


Figure 5.16
a) Regional plot for F in the Wessex Basin Chalk. b) Regional plot for Sr in the Wessex Basin Chalk.

Figure 5.17
Regional plot for NO_3-N in the Wessex Basin Chalk.
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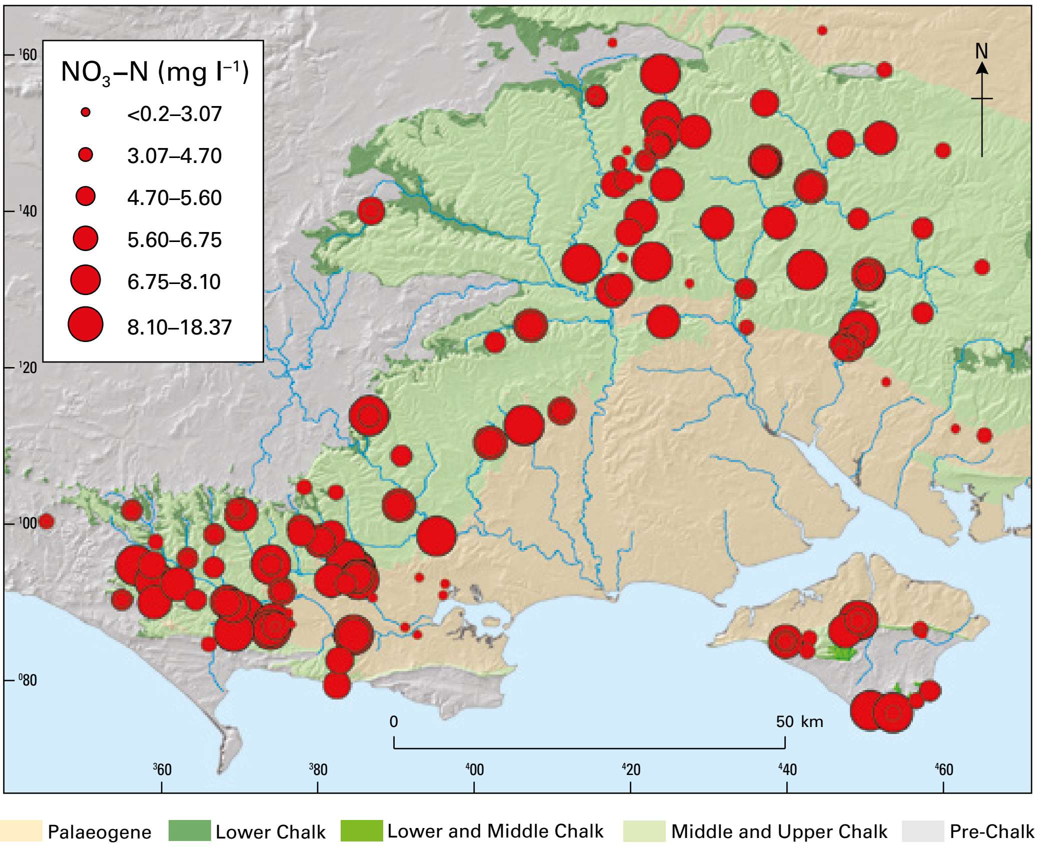

Figure 5.18
Conceptual diagram of the Chalk aquifer of Dorset highlighting the main geochemical processes controlling water quality (after Edmunds et al., 2002).

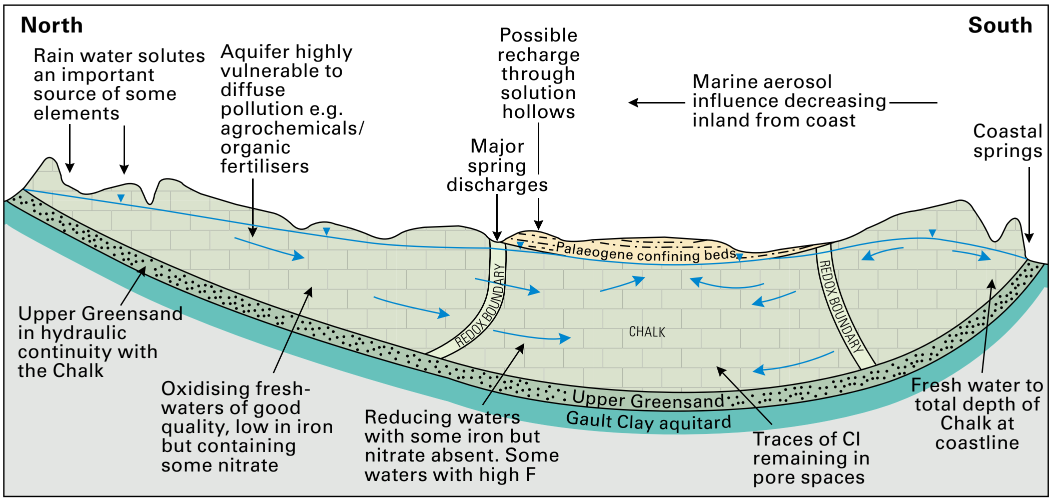

Figure 5.19 Bourne hydrochemistry sampling sites.
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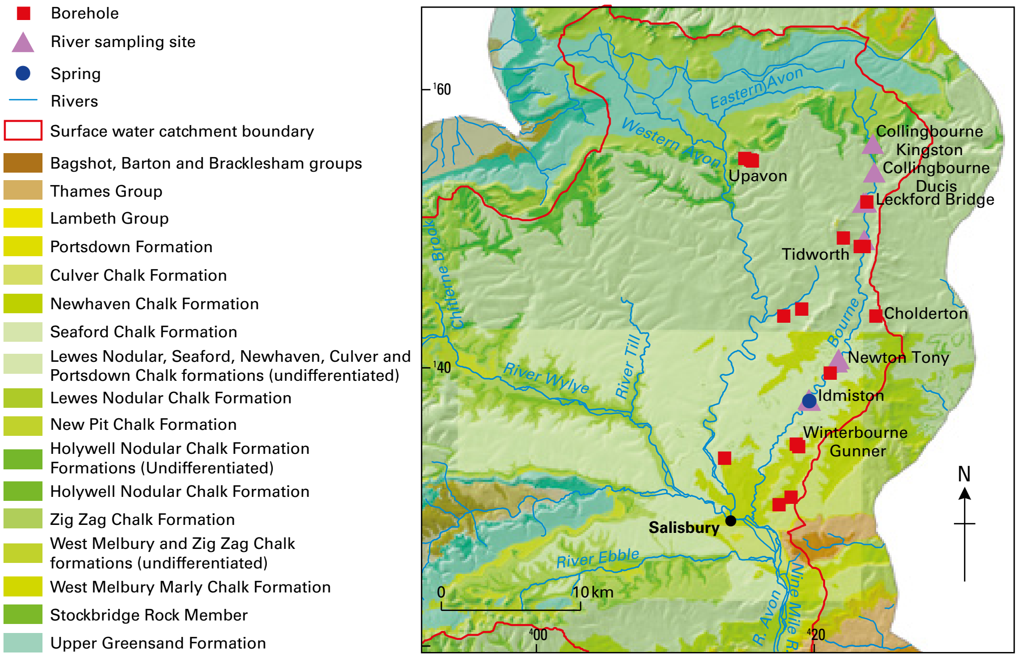
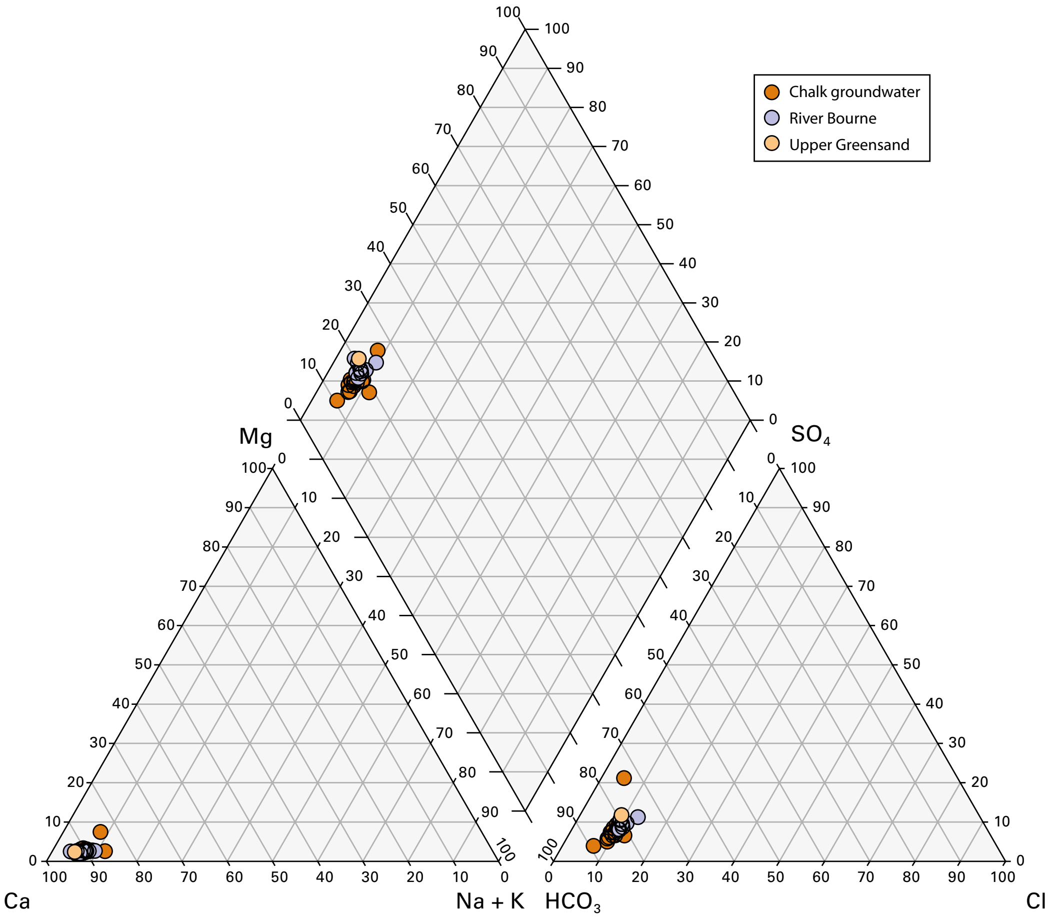


Figure 5.20 Piper diagram showing samples of the River Bourne and groundwaters collected in the study.



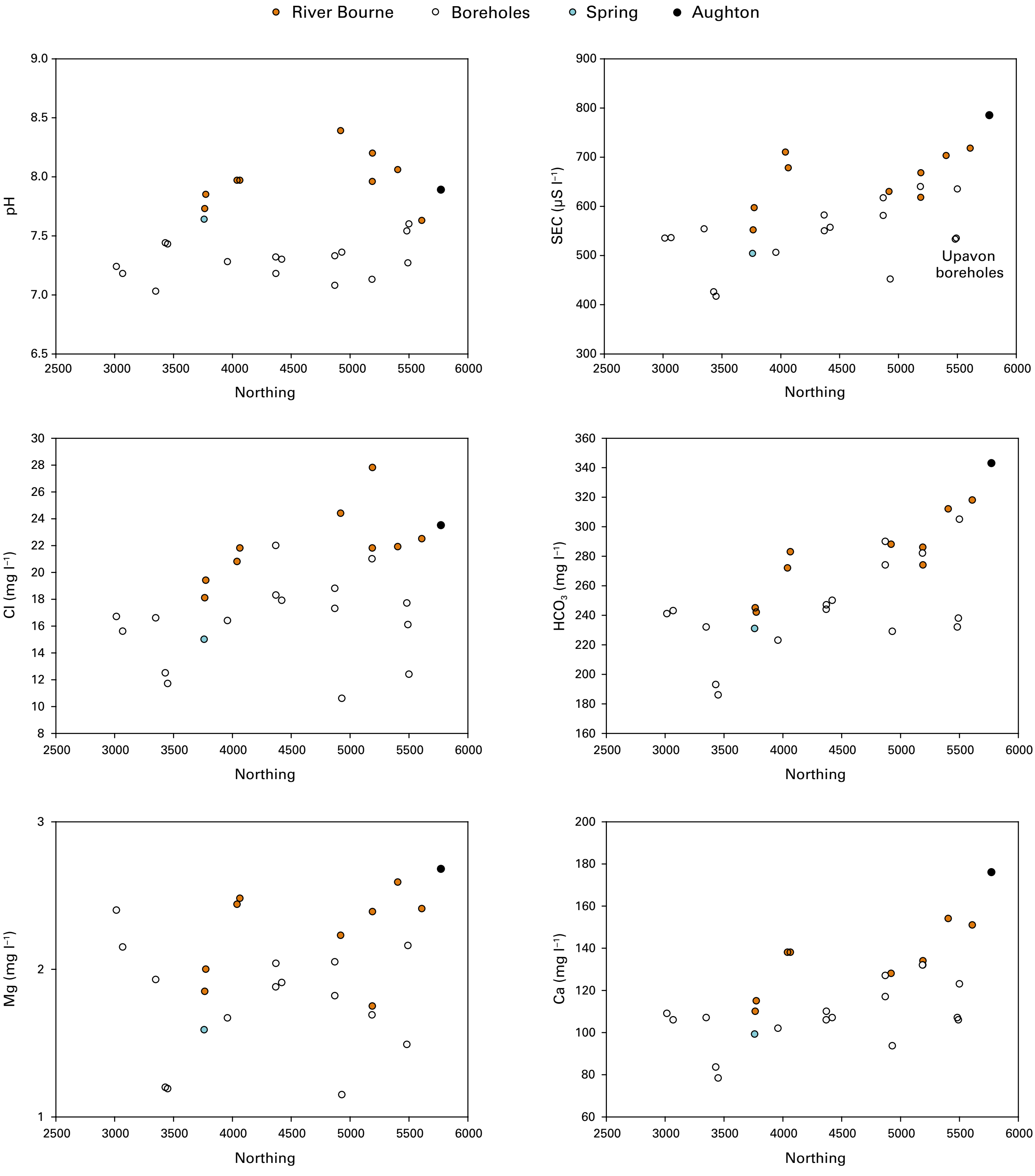


Figure 5.21 Hydrochemical measurements and major element concentrations for surface waters and groundwaters in the Bourne catchment.

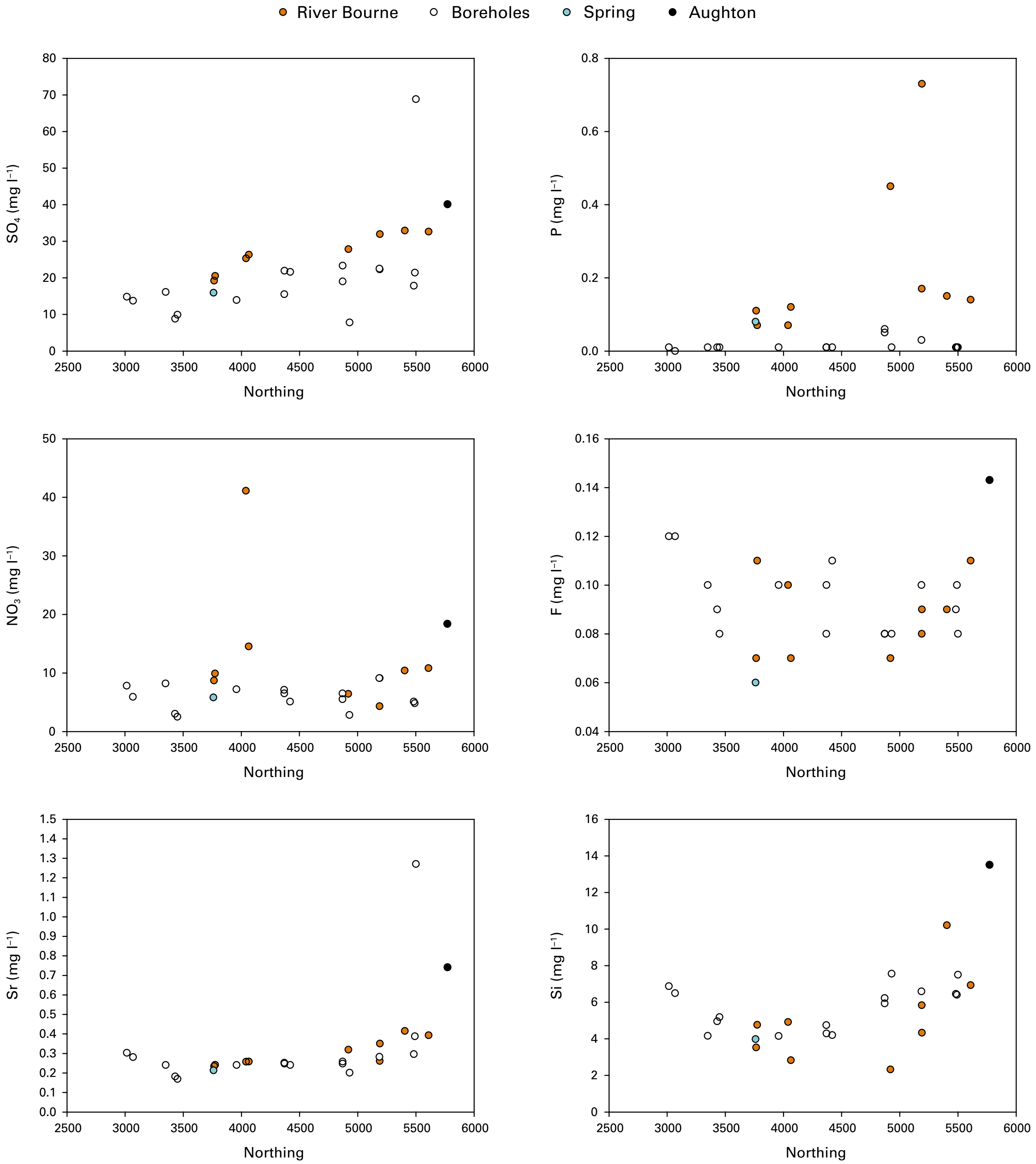


Figure 5.22 Selected major, minor and trace element concentrations for surface waters and groundwaters in the Bourne catchment.

6 Groundwater management

6.1 INTRODUCTION

Groundwater management is essential in order to maintain a balance between meeting water demands and safeguarding the environment and the resource. Where groundwater is readily available, it is normally less expensive to use than surface water as it usually needs less treatment. However, over-abstraction of groundwater can lead to problems such as reduced baseflow to rivers, with consequent impacts on ecology and amenity value; reduced well yields, and movement of saline water into the aquifer. In addition to managing abstraction, it is also vital to protect the quality of groundwaters by, for example, preventing or limiting activities that are likely to pollute the aquifer.

Groundwater management is therefore of great importance in a region such as the Wessex Basin, where groundwater from the Chalk aquifer forms a vital (and commonly the principal) source of water supply. In addition, much of the water abstracted from surface sources has also passed through the groundwater system (as shown by the high baseflow indices of many of the rivers) and this further increases the importance of groundwater management.

6.1.1 Historical perspective

In Hampshire, water supply has evolved from the use of spring and surface water to a mixture of springs, boreholes/wells and river takes (Whittaker, 1910). For example, in the latter part of the 19th century, Southampton obtained its water from the River Itchen and Bournemouth took its water from the River Stour; nowadays groundwater abstractions are important. In many parts of the Wessex Basin, abstractions from the Chalk aquifer have grown to become an essential component of water supply. For example, water in the Andover region is entirely sourced from groundwater. The significant springs near Portsmouth at Havant [SU 71 06] and Bedhampton [SU 70 06] were first used in 1741. As many as 25 individual springs can be used providing what is believed to be the largest spring water supply used for public consumption in the world, with a combined yield of between 53 and 170 Ml d^{-1} depending on Chalk groundwater levels (http://www.portsmouthwater. co.uk/).

In addition to rivers, surface water sources include the Blashford Lakes, situated near Ringwood in Hampshire, which are a series of water-storage reservoirs created from worked-out gravel pits. The lakes store water for use during the high-demand summer period and act as a backup to other sources in case of an emergency. They are filled from the nearby River Avon when river conditions are suitable, usually during the winter months.

In Dorset, spring sources and shallow wells were commonly used, the former especially on the more elevated areas of the Chalk catchments where springs form the headwaters of the main rivers. Along certain rivers, it was necessary to deepen boreholes because the river flows decreased during the summer periods. For example, in parts of the Winterbourne, the water levels were noted to be up to 30 m deep in summer but overflowing in winter (Whitaker and Edwards, 1926). The gradual increase in use of boreholes has led to the decline in usage of natural spring sources.

Historically, water use in the Avon and Dorset area of the Wessex Basin was chiefly agricultural with light industry in the towns and cities. Water-meadow construction was a common practice in order to produce an early crop of grass. The water was returned to the watercourse downstream of the intake point. This type of industry has now virtually ceased because of a change in agricultural practice to larger-scale crop production. Similar types of agriculture also predominated in the Hampshire countryside in the Wessex Basin. Cress cultivation was undertaken on the rivers close to the major springs, dairy and arable farming on the upland areas of Chalk and intensive horticulture on the heathlands, typically found on Palaeogene cover (Hampshire River Authority, 1970).

Several water companies were established in the nineteenth century that exploited groundwater resources in the Wessex Basin. For example in 1809, the Farlington Waterworks Co. was established and constructed a pumping station at Farlington Marshes. Also in this year, the Portsea Island Water Company was started. The two companies merged as the Portsmouth and Farlington Waterworks Co. in 1840. In 1857, this company became the Borough of Portsmouth Waterworks Co.

Bournemouth Water (established 1863) and West Hampshire Water (established 1893) were two former statutory water companies established by an Act of Parliament. The companies merged in 1994 through Schemes of Arrangement under the Water Industry Act 1991, to become Bournemouth and West Hampshire Water Plc.

Following the 1963 Water Resources Act (see Box 4) the Wessex Basin lay within the remit of the Avon and Dorset, and Hampshire river authorities. In 1970 there were nine statutory water undertakings in the Avon and Dorset River Authority area, together with the licence-exempt Ministry of Defence supplies. Of these, the Dorset Water Board was the largest and supplied the area including Poole in the south-east, Bridport in the west and Blandford Forum in the north. Other undertakings were the West Wiltshire Water Board, South Wiltshire Water Board, North Wiltshire Water Board, West Hampshire Water Company, Bournemouth and District Water Company, East Devon Water Board, Wessex Water Board and the Lulworth Castle Estate (Avon and Dorset River Authority, 1970).

The Hampshire River Authority in 1970 contained whole or part of a number of water undertakings: Southampton Undertaking (covering the largest area), Portsmouth Water Company, West Hampshire Water Company, South Wiltshire Water Board, Swindon Undertaking, Thames Valley Water Board, Mid Wessex Water Company, Wey Valley Water Company, Lymington Undertaking and Winchester Undertaking.

At the present time, the Chalk aquifer of the Wessex Basin (to the south of the Thames Region groundwater divide) lies within the areas covered by the Southern Water and Wessex Water Service Companies. The main water-supply companies operating in the Wessex Basin are: Bournemouth and West Hampshire Water, Portsmouth Water and Cholderton and District Water Company (Figure 6.1).

BOX 4 MAIN WATER LEGISLATION

In 1945 the Water Act defined national water policy for the first time, including some abstraction control (in areas recognised as being over-pumped or where this was considered likely to occur) and data collection.

The 1963 Water Resources Act created 29 catchment-based River Authorities to provide regional, integrated management of water resources and introduced abstraction licensing. For the Chalk of the Wessex Basin, the western section of the aquifer fell into the Avon and Dorset River Authority area and the eastern part lay within the Hampshire River Authority's region.

The 1973 Water Act formed ten Regional Water Authorities to provide complete regional management of the water cycle. These were given responsibility for, amongst other things, water supply, sewage disposal, prevention of pollution and land drainage. For the Chalk aquifer of the Wessex Basin the western half of the aquifer lay within the Wessex Water Authority's region and the eastern side fell within that of the Southern Water Authority.

The 1989 Water Act disbanded the Regional Water Authorities. Their utility functions were transferred to water service companies; for the Wessex Basin these comprised Wessex Water and Southern Water. Under the Act, the National Rivers Authority was created as an independent regulatory body, later (1995) to be subsumed into the Environment Agency. Currently under the Water Resources Act 1991, the Environment Act 1995, and The Water Environment (Water Framework Directive) (England and Wales) Regulations 2003, the Environment Agency has a duty to conserve, redistribute or otherwise augment water resources and secure their proper use. The Wessex Basin Chalk aquifer falls into the Environment Agency's South West and Southern regions.

The main European legislation that intended to protect groundwater from contamination was the Groundwater Directive 80/68/EEC, until it was repealed by the Water Framework Directive in 2013. In December 2000 the European Water Framework Directive (2000/60/EC) came into force. This is the most significant piece of European legislation relating to water management for at least two decades. The Directive was a response to the fragmented nature of existing legislation relating to water and aims to provide a framework to integrate this and to expand the scope of water protection to all waters, and aimed to achieve 'good status' (involving both quantitative and qualitative aspects) by 2015. A significant feature of the Directive is the emphasis on ecological objectives, to be used as measures of the success of water management strategies.

Under the Water Framework Directive, the Groundwater Daughter Directive (2006/118/EC) became effective. This Directive addresses the discharge of polluting matter to groundwater, particularly with regards to certain harmful substances. These pollutants are classified under hazardous and non-hazardous substances. Hazardous pollutants must be prevented from entering groundwater, while discharge of non-hazardous substances must be controlled to ensure that pollution of groundwater is avoided. In England and Wales the Water Framework Directive is implemented by Environment Agency through The Water Environment (Water Framework Directive) (England and Wales) Regulations 2003.

6.1.2 Current water supply in the Wessex Basin

The eastern part of the basin is supplied mainly by Portsmouth Water. The company supplies water to around 290 000 domestic and commercial customers in an area from the River Meon in Hampshire to the River Arun in West Sussex. The average demand is around 180 Ml d^{-1}, around 50 per cent of which is supplied from boreholes and wells in the Chalk, 35 per cent from the major springs at Havant and Bedhampton and the remainder from an abstraction on the River Itchen (Portsmouth Water, 2006). Further west, the Test and Itchen catchments are mainly served by Southern Water, with the area split into northern (Hampshire Andover) and southern (Hampshire South) water resource zones. The southern zone, extending from the Solent as far as Winchester, serves a population of around 600 000 (260 000 customers) with an average daily demand of nearly 160 Ml. Eight groundwater abstractions from the Chalk are used, with two surface water abstractions. Water is also transferred from this water resource zone to the Isle of Wight via the cross-Solent main (up to 12 Ml d^{-1}). To the north, the Hampshire Andover water resource zone serves a much smaller population of 65 000 (27 500 customers). Average daily demand typically averages 17 Ml and is supplied entirely from six groundwater stations (Southern Water, 2006).

The Isle of Wight water resource zone serves a population of 135 000 (63 000 customers), with an average daily demand of 37 Ml. Water is supplied from eight groundwater abstractions from the Chalk and Lower Greensand aquifers (which are generally low yielding) and a surface-water abstraction. Supplementary water is supplied by the cross-Solent main (Southern Water, 2006).

Bournemouth and West Hampshire Water supplies a population of around 420 000 (nearly 184 000 customers) with an average demand of around 160 Ml d^{-1}. Water is supplied from four groundwater sources (three of which are in the Chalk aquifer), three surface water sources and one joint groundwater/ surface water source; surface water provides most of the supply (Bournemouth and West Hampshire Water, 2006).

Within the total area covered by Wessex Water (which extends to the west beyond Taunton and north to include Malmesbury), the company supplies on average 365 Ml d^{-1} of which 80 per cent is derived from groundwater sources. In the Wessex Basin, the area supplied by Wessex Water includes most of the upper Avon catchment and the Stour and Frome/Piddle catchments. The Wessex Water area is divided into four zones, of which two — the east and south zones — broadly encompass the Chalk outcrop in the Wessex Basin. The south resource zone (mainly the Avon catchment) is supplied by groundwater sources and by a river intake and reservoirs near Ringwood. Water can be transferred from Poole across to Dorchester and Weymouth. The east resource zone (mainly the Dorset part of the Wessex Basin) comprises six discrete areas of demand with limited transfers between them. The sources in these zones are exclusively groundwater, with typically only two sources in each of these subzones (www.wessexwater.co.uk).

6.2 GROUNDWATER RESOURCE ISSUES AND PRESSURES

There are a number of issues that are important to the management of groundwater resources in the Wessex Basin. Quantitative issues are discussed below, while those relating to quality are addressed in the subsequent section on groundwater pollution and protection.

6.2.1 Increasing demand

The demand for water for public supply increased from the 1950s as industrial, agricultural and per capita demand rose,

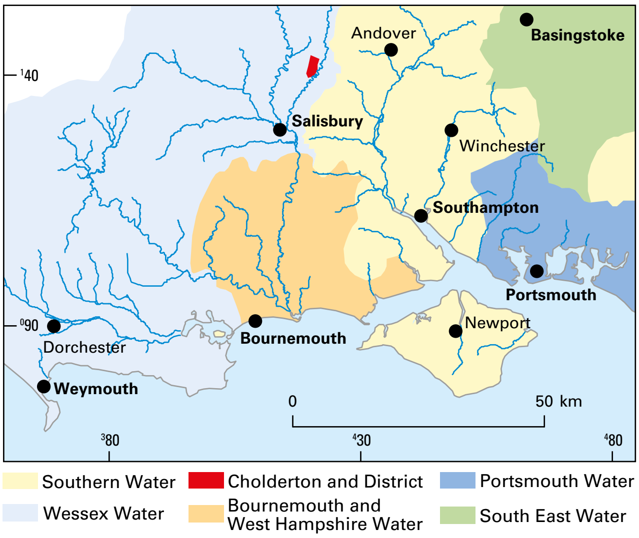


Figure 6.1 Water supply map of the Wessex Basin (boundaries approximate).
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and probably peaked in Wessex in the 1980s. In the Portsmouth Water area, for example, demand for public supply water has declined significantly since 1988 (Environment Agency, 1999c). This is thought to be largely due to both a reduction in leakage and reduced demand. However, it is likely that demand for water over much of the Wessex Basin will increase in the future. This is likely to result partly from an increase in population, which in Hampshire for example is forecast to rise by 11 per cent between 2001 and 2021 (Hampshire Water Partnership, 2003).

The additional water consumption from such a population increase is likely to be enhanced by the current trend of reducing numbers of occupants per household and the increasing use of household appliances such as power showers. As a result, the domestic daily use of water per person in Hampshire is predicted to rise from the current value of 160 litres to between 178 and 228 litres by 2025 (Hampshire Water Partnership, 2003).

The Isle of Wight has historically suffered water supply problems due to its limited surface water and groundwater sources and high summer population. During droughts and in particular in 1976, the island suffered unreliability in public water supplies. This led to a significant investment in mains reinforcement, leakage reduction and development of new sources of supply, which included bringing water under the Solent from the Testwood Reservoir in Hampshire. The Environment Agency predicts that licensed water resources, together with support from the cross-Solent main, are sufficient to meet the demand for water on the island for the foreseeable future (Environment Agency, 1999b).

6.2.2 Environmental issues

Many rivers across the Wessex Basin are supported by Chalk groundwaters and these tend to have clear waters with a stable temperature regime, characteristic plant communities and a rich diversity of invertebrates. The UK Biodiversity Action Plan (www.ukbap.org.uk) lists Chalk streams as a 'high priority' habitat.

In addition to providing baseflow to rivers, groundwater feeds certain wetlands that are important habitats for wildlife. Protection of wetlands is of particular importance, as the number of wetlands and wetland species of plants and animals is diminishing globally. Important sites are protected by the RAMSAR designation (RAMSAR sites are wetlands of international importance designated under the RAMSAR Convention). There are a number of RAMSAR sites in Wessex (Figure 6.2a) including the Arun and Avon valleys.

Other designations such as Sites of Special Scientific Interest (SSSI) and Special Protection Areas (SPA, designated under the EC Birds Directive) are relevant to groundwater. There are many groundwater-dependant wetlands that are classified as SSSIs in Wessex, in recognition of their importance and the fact that they support many different communities of plants and aquatic life forms, including the Frome, the Itchen, the Moors and the River Avon (Figure 6.2b). The locations of SPAs in the Wessex Basin are shown in Figure 6.2c.

An important element of environmental legislation is the 1992 Habitats Directive, whose main aim is to help to ensure biodiversity by requiring member states to take measures to maintain or restore natural habitats and wild species at a favourable conservation status. The Directive introduced significant protection for those species or habitats of European importance. Special Areas of Conservation (SAC) are specified under the Directive and are shown in Figure 6.2d. The Directive has been an important reason for groundwater investigations in the Wessex Basin in recent years (for example, studies in the Hampshire Avon and Itchen). In addition to providing habitats for plants and wildlife, rivers support fisheries and provide an important resource for recreational activities; there are therefore economic, ecological and amenity interests to consider. The Environment Agency has the responsibility of setting targets for river flows, but given the fact that the majority of the rivers across the basin have been significantly altered by humans, setting targets raises many economic, technical and environmental issues, such as whether the aim is the protection of the current condition of the river or the improvement of the river environment and its associated benefits.

Judging the worth of environmental improvement schemes is a complex problem. In order for cost-benefit analyses of schemes to be performed, it is necessary to understand how flows affect the parameters of interest and how to measure the environmental quality of a river. One approach, for example, is a Lotic-invertebrate Index for Flow Evaluation (LIFE) technique, which links the population of invertebrates in a river (considered to be useful indicators of the 'health' of a river) to the river flow regime (Extence et al., 1999). A strong correlation has been observed between the LIFE index and mean summer flows for Chalk streams.

6.2.2.1 Habitats Directive

The 1992 EC Habitats Directive requires the Environment Agency, as a 'competent authority', to maintain a 'favourable conservation status' of those habitats that are afforded international protection, and which may be affected by Agency activities or authorisations. Special Areas of Conservation (SAC) are specified under the Directive and are shown in Figure 6.2d. Decisions must be based on a sound understanding of the key species, including the flow requirements of aquatic plants, salmonids and other fauna, by working closely with water companies, other companies and Natural England. Water companies also act as a competent authority and as such are required to identify the impacts of their comments and authorisations. An example is the Test and Itchen (Environment Agency, 1999a), where the Agency must contribute to maintaining the favourable conservation status of the River Itchen SAC. This applies to all responsibilities as an operator, regulator and influencer,

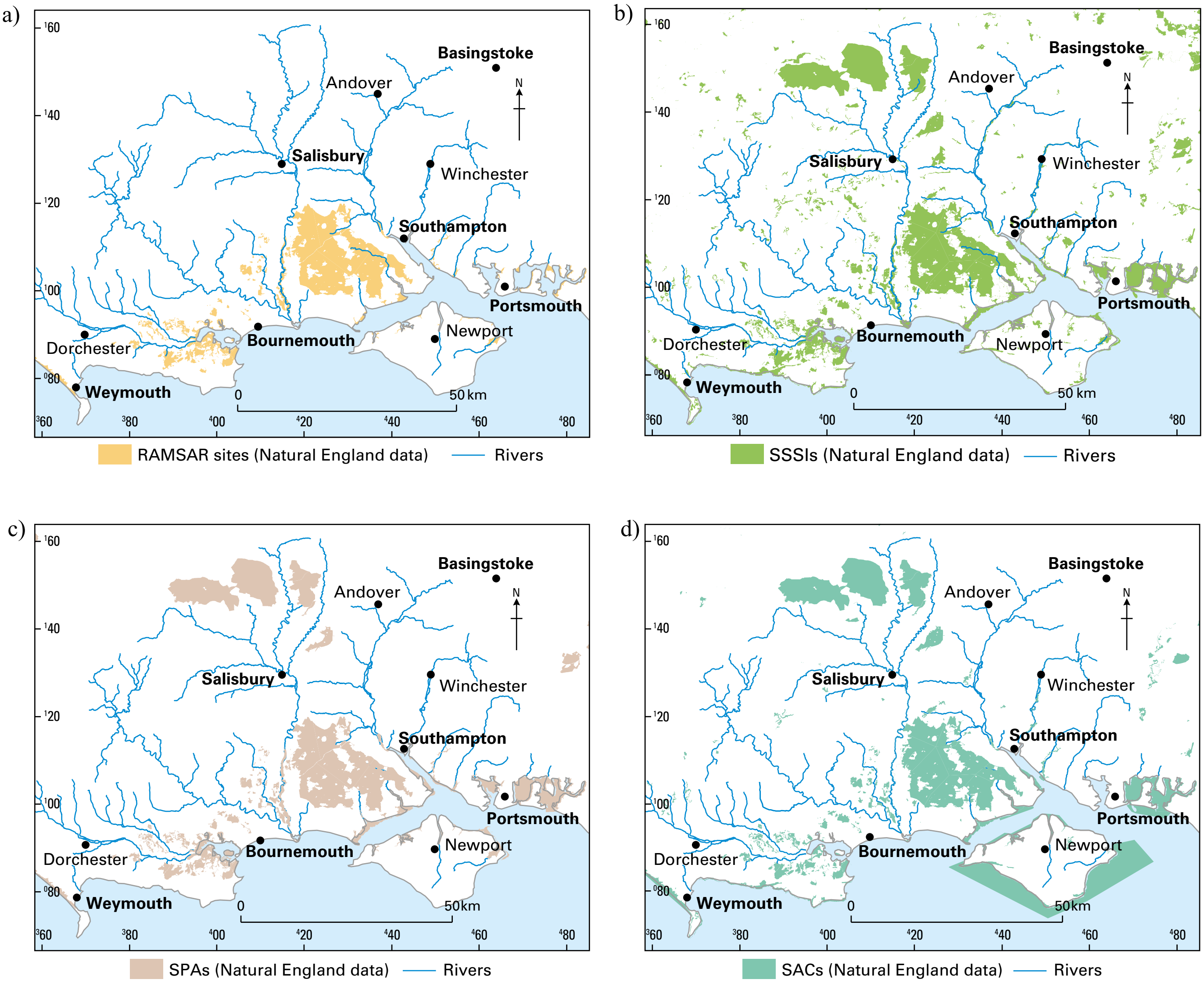

Figure 6.2 Examples of protected sites in Wessex. a) RAMSAR designated sites. b) Sites of special scientific interest (SSSIs). c) Special protection areas (SPAs). d) Special areas of conservation (SACs).

and the Agency is required to review all existing consents and authorisations that may have a significant impact upon the site. The Agency must also properly assess the likely effect of new applications and plans.

6.2.3 Climate change

While the precise nature of climate change in southern England is uncertain, there is growing consensus that winters will be wetter, summers will be drier and that annual temperatures will increase. The likelihood of extreme events such as droughts and storms will also increase. Predictions from the UK Climate Impacts Programme suggest that if high fossil-fuel use continues, then by 2080 summer precipitation in the south-east of England could reduce by up to 60 per cent with winter precipitation increasing by up to 30 per cent. The net effects of these changes on total water resources are not known — for example the extent to which enhanced infiltration caused by increased winter rainfall will be offset by higher evapotranspiration caused by higher temperatures and the higher soil moisture deficit resulting from lower summer rainfall — but it is likely that seasonal stresses on water resources will increase, for example by lower streamflows and higher demand in summer. In addition it is likely that for an aquifer with a low specific yield and rapid response, such as the Chalk, a small reduction in the length of the recharge season could significantly reduce the groundwater stored above the outflow base level.

6.2.4 Drought

A drought may cause both environmental effects and deficiency in water supplies and the balance between supply and demand may be affected in different ways by different droughts. For example, in the Southern Water area in 1976, low groundwater levels and river flows were experienced because of the preceding very dry winter and this, coupled with high summer demand, resulted in a shortage of resources (Southern Water, 2006). In the same region during 1989 to 1992, a succession of dry winters and somewhat elevated summer demands put groundwater sources under stress, whereas in 1995, while groundwater levels were high after a wet winter, unprecedented summer demand caused problems. Between 2004 and 2006, prolonged dry periods and below-average winter rainfall resulted in both reduced river flows and low groundwater levels.

Groundwater and surface water sources tend to react differently to winter drought. While the lack of recharge resulting from low winter rainfall will cause groundwater sources to suffer, the large storage capacity of aquifers gives sources some resilience against a single winter with low rainfall, although two or more dry winters will result in reduced yield. Surface sources, however, can be severely affected by one dry winter, where this results in significantly reduced baseflow in the following year. Summer drought tends to affect both groundwater and surface water sources, as demand is increased.

6.2.5 Groundwater flooding

Groundwater flooding is a common natural phenomenon that occurs when the natural storage capacity of an aquifer is exceeded. It can arise in two main ways as discussed in Chapter 3. The first is associated with river floodplain deposits and results in water flowing onto the floodplains when the flow in a watercourse exceeds its capacity and river alluvium becomes fully saturated. These natural floodplains provide extra capacity for storage and allow floodwater to pass downstream; they are also important for species dependent on seasonal flooding. The combination of building in the floodplain and an expansion of impermeable surfaces has increased the flood risk from this type of flooding in some areas.

The second type of groundwater flooding occurs when the water level in consolidated, unconfined, rock aquifers rises to emerge at the surface as springs and seepages. The low specific yield of the Chalk means that if the transmissivity of the aquifer and imposed head gradient are insufficient to cope with increased recharge, then water levels may rise substantially. In the winter of 2000/2001 over one hundred villages in Hampshire, in addition to roads and fields, were flooded by groundwater after a long period of heavy rain caused groundwater levels to rise substantially (Hampshire Water Partnership, 2003). The north-west of the county suffered again in the winter of 2002–2003. In 2012, between April and September, unusually high rainfall affected the area of the Wessex Basin leading to groundwater levels close to or above long-term maximum values in most areas of Dorset, south Wiltshire and Hampshire, and even groundwater flooding in west Dorset and Hampshire. These areas were again affected by groundwater floods during the winter of 2012/2013 due to continuous rainy conditions, low soil-moisture deficit values and exceptionally high groundwater levels, which followed from the unexpected recharge of the previous wet summer. In January 2014, groundwater floods affected areas susceptible to groundwater flooding, where monitored groundwater levels showed maximum recorded values for January in several boreholes on the Chalk outcrop. This flooding event was a result of persistent rainfall that continued from December 2013 for several weeks, showing the heaviest rainfall ever recorded since 1766 for England and Wales. Such flooding can carry on for long periods until groundwater levels fall sufficiently, and can be a particular danger to public health where the water is polluted from overflowing cesspits and septic tanks.

6.3 GROUNDWATER MANAGEMENT STRATEGIES

Groundwater resource management has, in recent years, increasingly moved towards recognition of the need to manage groundwater in the context of the whole water cycle. Thus recent legislation, such as the Water Framework Directive, requires that the condition of the resource is assessed by taking into account recharge, abstraction and the effects of groundwater discharge on surface-water ecologies and dependent terrestrial ecosystems.

6.3.1 Licensing and sustainable development

While abstractors must be protected from drought, it is also important to minimise the impact of abstraction on the environment. The term ‘sustainable development’ has been used to mean a balanced approach to abstraction, allowing groundwater to be exploited for purposes such as public water supply, industrial and agricultural uses, while avoiding unacceptable derogation of surface water sources, groundwater quality and the environment, so that future generations continue to have access to these resources. Abstractions of greater that 20 m^3 d^{-1} are subject to licensing by the Environment Agency and this forms an important mechanism for managing groundwater resources in the Wessex Basin.

6.3.2 Sustainable abstraction — river augmentation and alleviation of low flows

6.3.2.1 River regulation

Following the Water Resources Act of 1963 the newly created Water Resources Board, tasked with the planning of water resource development on a national scale, instigated several major regional studies of England and Wales. A number of subsidiary studies, including specific groundwater resource studies, were also undertaken as part of the programme. The most important of the groundwater resource studies were schemes in the Thames, Great Ouse, Severn, Waveney and Itchen valleys. The purpose of these schemes was to assess the feasibility of regulating rivers by pumping groundwater into them for abstraction in their lower reaches while maintaining river flows for other environmental requirements (Downing, 1993).

The Candover scheme was the initial phase of a proposal to regulate the Itchen. The purpose of the scheme was to use seasonal groundwater abstraction to augment low river flows and allow direct river abstraction for public water supply near the tidal limit of the river. It was considered that Hampshire was ideally suited for such a scheme because the northern part of the county is underlain by Chalk and is drained by rivers flowing south towards population centres. The scheme involved the construction of six abstraction boreholes (in three pairs) sited away from the perennial head of the Candover stream, but linked to it by a pipeline. After six months, pumping during the dry summer of 1976, the cumulative net gain was an encouraging 80 per cent of the total pumped volume of 5.1 x 106 m^3, representing 60 mm of rainfall over the 65 km^2 catchment (Headworth et al.,1982). The second stage of the scheme, in the Alre valley, gave a lower net gain because of a low storage coefficient of the aquifer (Downing, 1993).

6.3.2.2 Low flows in rivers

Across the Wessex region, several rivers have been identified as requiring measures to be implemented to alleviate low flows. Examples in Hampshire include the Rivers Hamble, Meon and Itchen, and the Candover stream. Modelling of these catchments has shown that abstraction in this area is aggravating the problem of low flows.

Wessex Water’s abstractions for public water supply were found to be causing unacceptably low river flows in the rivers Wylye, Piddle and Upper Bristol Avon, which affects the ecology, fisheries and amenity value of these rivers. It also has detrimental effects on the chalk river species for which the Wylye is designated an SSSI and a candidate SAC. To resolve these issues, the Environment Agency proposed a staged approach with the result that abstraction from the Chitterne and Cowbridge boreholes stopped and abstractions were reduced from the Alton Pancras Borehole, to restore flows in the Wylye, Upper Bristol Avon and Piddle respectively.

The River Allen has been identified as a low-flow river and is one of the top 20 low-flow sites in England and Wales (Environment Agency, 1997). Investigations conducted by the Environment Agency concluded that the principal reason for derogation of the flow of the River Allen was from the Bournemouth and West Hampshire Water abstraction borehole at Stanbridge. In 1993, after a lengthy investigation, the National Rivers Authority (NRA) proposed an action plan that identified the need for a reduction for the licence at Stanbridge, in association with the setting of revised flow targets for the management of stream-flow support from existing boreholes.

The River Tarrant has historically experienced parts of the river drying up during the summer months. In 1995, the river dried along all of its length and in 1996, it dried up downstream of Tarrant Keyneston. Data gathered by local concern groups indicates that in nine of the 22 years from 1974 to 1996, the river dried up below Tarrant Monkton, and also that the lower reaches have dried up. In 1995, a major fish rescue operation was mounted as the river progressively dried out both from the source and from its confluence with the Stour, leaving little flow in the vicinity of Tarrant Rushton (Environment Agency, 1997). There has been concern about the effects of Wessex Water abstractions in the Tarrant catchment and the effects that these may have had on the river flow. These abstractions are located at Stubhampton, at the head of the river, and at Shapwick in the Stour valley. Investigations have concluded that the Stubhampton source has little influence on the natural occurrence of events, but there may be a connection with the Shapwick source (Environment Agency, 1997).

On the Isle of Wight, the Chalk aquifer is heavily exploited for public water supply. This has an impact on the flows of Chalk streams, particularly in summer months, and results in minimum flow conditions, which restrict abstractions from Bowcombe, Chillerton and Calbourne pumping stations when flows in the adjacent rivers fall below a certain level. The Medina–Yar Transfer Scheme and the Lower Greensand Scheme are used to augment river flows for subsequent abstraction at Sandown.

6.3.3 Catchment management plans and LEAPs

The NRA produced catchment management plans (CMPs) for individual river catchments in the 1990s. The purpose of CMPs was to provide a focus for the development and implementation of NRA policies and a decision framework with guidelines on the sustainable use of catchments.

The plans described the physical nature of each of the catchments, together with catchment statistics and details of the catchment usage. They then highlighted key issues and management proposals to be addressed by the NRA. Finally, the management plans incorporated an ‘action plan’ with suggested timings for completion together with a broad indication of the costs involved in implementing the actions. Several of these reports were produced for river catchments across the Wessex Basin.

With the formation of the Environment Agency in 1995 and its inception in 1996, the work of the NRA’s CMPs was developed into local Environment Agency plans (LEAPs) that fulfilled the same role, by highlighting specific issues for particular catchment systems through consultation documents and summarised in action plans.

The LEAP reports describe the main environmental issues in the plan areas, and the state of the environment at the time of publication. The Wessex Chalk aquifer system was covered by several catchment-based LEAP reports, which set out the work that the Environment Agency and others planned to undertake to protect and enhance the environment in the plan area over the following five years. The LEAP reports also set out water resources management actions for the future, such as demand management.

Two main issues were highlighted in the Wessex LEAP reports that are relevant to groundwater: low summer flows in rivers fed by baseflow and groundwater quality.

6.3.4 Catchment abstraction management strategies

Catchment abstraction management strategies (CAMS) are a more recent approach to managing water resources in England and Wales, and are developed on an area-by-area basis (Environment Agency, 2002b). The CAMS areas have been based mainly on surface-water catchments.

The CAMS operate on a six-year review cycle, during which time the Environment Agency undertakes a detailed assessment of the catchment, including total available resource, environmental requirements, licensed quantities and actual abstracted quantities. The balance between the committed and available resources determines the ‘resource availability status’ for each water-resource management unit within the area i.e. whether further abstraction licences can be granted without derogating the environment or other users (Table 6.1). The following ‘sustainability appraisal’ process considers what the resource availability status for each unit should be at the end of the six-year cycle. For

Table 6.1 Definition of the CAMS ‘resource availability status’ classifications.

Indicative resource availability status	Definition (relating to the availability of water for abstraction licences)
Water available	Water likely to be available at all flows including low flows. Restrictions may apply.
No water available	No water available for further licensing at low flows although water may be available at higher flows with appropriate restrictions.
Overlicensed	Current actual abstraction is resulting in no water available at low flows. If existing licenses were used to their full allocation, they would have the potential to cause unacceptable environmental impact at low flows.
Overabstracted	Existing abstraction is causing unacceptable environmental impact at low flows. Water may still be available at high flows with appropriate restrictions.

example, in a catchment that is 'overabstracted', the Agency may attempt to recover some licences.

An important aspect of the CAMS process is that it is designed to enable interested parties such as abstractors and environmental organisations to become involved in managing the water resources of a catchment. CAMS documents are also be open to the public, providing more open access to information than was available in the past.

There are 129 CAMS areas covering England and Wales. For the Wessex Basin Chalk aquifer south of the Thames Region catchment divide, the relevant CAMS areas are shown in Figure 6.3 and Table 6.2.

Within the CAMS framework, new licences are of finite duration. Existing licences will gradually be brought under this new system and converted to time-limited status.

6.3.5 The Water Framework Directive

An important feature of the Water Framework Directive is that the management of waters will be based upon the concept of integrated river basin management. All waters will be managed within 'river basin districts', with groundwater assigned to 'groundwater bodies' within these. Groundwaters in the Chalk aquifer of the Wessex Basin fall within one of two river basin districts: a western district including the Avon and catchments to the west, and an eastern district including the Test and catchments to the east.

Central to the Directive is the requirement to produce a strategic management plan for each river basin district setting out how the Directive's environmental objectives are to be achieved. Environmental objectives are specified for surface waters, groundwaters and protected areas. For groundwaters these are essentially to:

- implement necessary measures to prevent or limit the input of pollutants into groundwater and to prevent the deterioration of the status of all bodies of groundwater
- protect, enhance and restore all bodies of groundwater and ensure a balance between abstraction and recharge of groundwater, with the aim of achieving good groundwater status 15 years at the latest after the date of entry into force of the Directive
- implement necessary measures to reverse any significant and sustained upward trend in the concentration of any pollutant resulting from the impact of human activity in order to progressively reduce pollution of groundwater.

For groundwater, the term 'status' in the Directive is a measure of the condition of the groundwater body and has both quantitative and qualitative components. Good 'quantitative status' for a groundwater body broadly means that the rate of groundwater abstraction is not sufficient to adversely affect the environmental (essentially ecological and chemical) objectives of associated surface waters or to damage terrestrial ecosystems or cause saline intrusion. Good 'chemical status' broadly means that pollutants in the groundwater body do not exceed specified standards and also are not sufficient to adversely affect the environmental (as above) objectives of associated surface waters or to damage terrestrial ecosystems.

The river-basin management plan to achieve the environmental objectives must be based on an analysis of the pressures (both quantitative and qualitative) on the water bodies within the river basin and an assessment of their likely impact. For water bodies at risk of failing to meet the environmental objectives, a more detailed analysis is required. This allows a comprehensive programme of measures to be drawn up, tailored to the specific circumstances in each river basin district, and in particular to target those water bodies most at risk of failing to meet their environmental objectives. The initial assessment of whether a groundwater body is at risk of failing to meet its environmental objectives ('initial

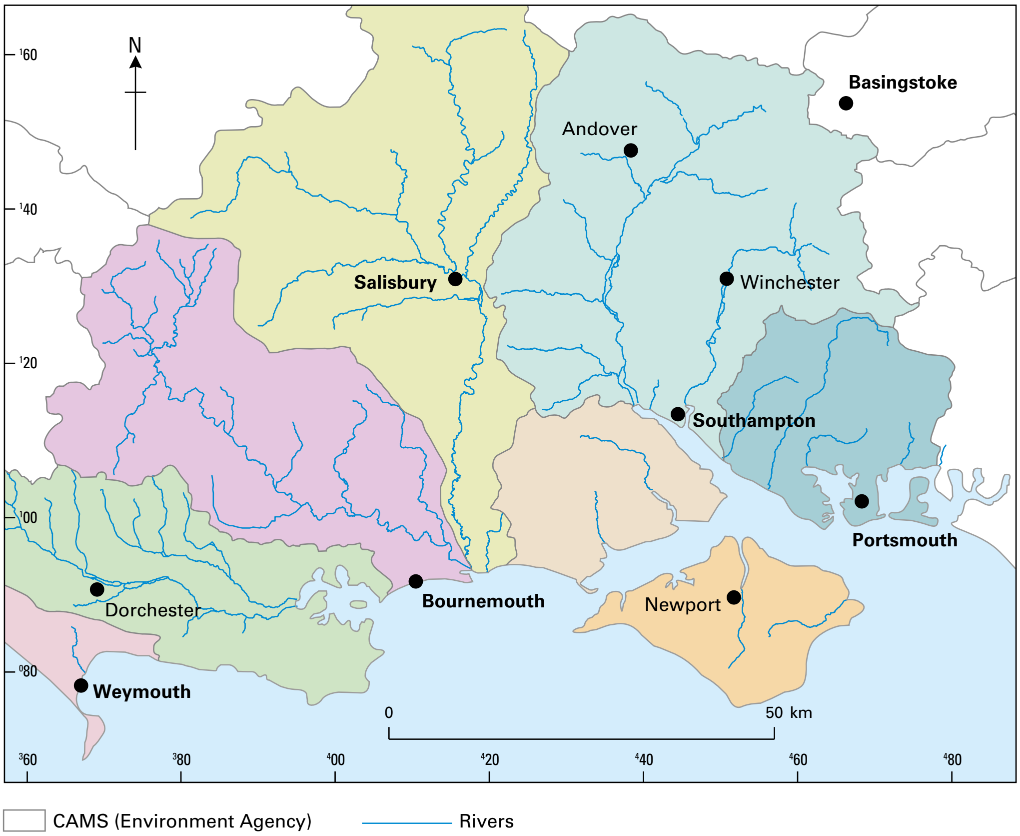

Figure 6.3 CAMS boundaries in Wessex.

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Table 6.2 CAMS areas for the Wessex Basin Chalk.

CAMS area number	CAMS area name
65	East Hampshire
66	Test and Itchen
67	New Forest
68	Isle of Wight
69	Hampshire Avon
70	Dorset Stour
71	Frome, Piddle, Poole Harbour and Purbeck
72	West Dorset streams

characterisation') was carried out by December 2004. Groundwater monitoring programmes were established and river basin management plans, including programmes of measures designed to enable the environmental objectives to be achieved, were finalised in late 2009. By December 2015 good status must have been achieved for all groundwater bodies, except where derogations have been agreed.

6.3.5.1 Results of initial characterisation

The results of initial characterisation for groundwater bodies in the Chalk of the Wessex Basin were reported in the Article 5 summary characterisation reports covering the south-west and south-east river basin districts (Defra 2005a, 2005b). In terms of the Chalk aquifer, the groundwater bodies identified during the characterisation study were in general delineated by the surface outcrop of the Chalk and then by CAMS boundaries. Each of the resulting groundwater bodies was assessed as to whether it was at risk of failing to meet its environmental objectives.

The results indicated that, in terms of abstraction pressures, much of the groundwater in the Chalk outcrop fell into the category of being 'probably at risk'of failing to meet good status by 2015. Only one Chalk groundwater body was classified as 'probably not at risk', and no groundwater bodies fell into the 'not at risk' category. To the north-east of Portsmouth, the groundwater bodies extending to the east, away from the Wessex Basin, towards Brighton, were assessed as being 'at risk' as a result of abstraction pressures.

Pressures from diffuse pollution[8] were considered to render almost all of the eastern side of the basin as 'at risk' as well as the Chalk on the Isle of Wight. To the west this designation includes the Avon catchment; beyond this, the bodies in the south-west of the basin (i.e the Dorset Stour catchment and beyond) were classified as 'probably at risk'. No chalk groundwater bodies in the basin were classified as 'not at risk' from diffuse pollution pressures. Point-source pollution pressures are not considered sufficient to render any of the groundwater bodies at risk and all were designated as probably not at risk.

In summary therefore, given the range of pressures considered during the characterisation process, all of the groundwater bodies in the Chalk of the Wessex Basin from the Avon eastwards, including the Isle of Wight, are considered to be at risk, principally as a result of diffuse-pollution pressures. Those from the Stour to the Dorset coast were classified as probably at risk.

The subsequent river basin management plans covering the Wessex Basin (Environment Agency 2009a, 2009b) showed overall groundwater status (combined chemical and quantiative status) to be classified as poor in essentially all of the unconfined Chalk groundwater bodies across the basin.

6.3.6 Aquifer storage recovery

The principle of aquifer storage recovery (ASR) is to use aquifers, including those containing poor-quality water, to store good-quality water during periods when there is excess and then to recover the water when it is required. The technique works by injecting the water into the aquifer via boreholes, creating a volume of clean water around the injection borehole from which the native water has been displaced. Later, when the water is required, it is pumped from the aquifer, using the injection borehole as an abstraction source. Given that some mixing between injected water and native groundwater will occur, it is not possible to recover the same volume of water as that injected before water quality deteriorates; however, the ratio of useable abstracted water to injected water can be high, particularly after several injection–abstraction cycles, and a number of successful schemes have been undertaken in the USA. Given that ASR can provide storage in parts of aquifers that are otherwise unused, it potentially offers a useful way of enhancing water resources, provided that acceptable levels of environmental impact and water quality can be achieved.

A major ASR trial was undertaken in the Wessex Basin in the confined Chalk aquifer at Lytchett Minster, near Poole in Dorset, in the late 1990s by Wessex Water in conjunction with CH2M Hill and the BGS. An existing production borehole was modified to form an ASR borehole and several initial cycle tests and full-scale tests were undertaken. After analysis of the results of the tests, two main conclusions were reached (Eastwood and Stanfield, 2001).

1. Hydraulically, the injection and recovery cycles caused very little environmental impact. Injection of water into the aquifer tended to increase the net volume of storage rather than displacing water at the margins of the Palaeogene, and recovery of water from the aquifer tended to utilise aquifer storage. Thus an ASR scheme would be likely to have little impact on rivers either on the Palaeogene deposits or at the margins where the Chalk is unconfined.
2. The quality of abstracted water, however, was poor, compared with required standards, as a result of high fluoride levels. The groundwater in the Chalk in the Lytchett Minster area has a fluoride concentration of 4 mg l^{-1} while the current drinking water standard is 1.5 mg l^{-1}, and a maximum safe threshold of 0.7 mg l^{-1} had been proposed for seasonal ASR operation. During initial cycle testing the fluoride concentration in recovered water tended to stabilise at around 2 mg l^{-1} and did not improve during the main full-scale cycle tests. The results of water quality modelling suggested that most (80 per cent) of the fluoride response was caused by mixing with native groundwater rather than by water–rock interaction.

Thus, while the ASR trial indicated that, as a resource management technique, ASR in the confined part of the

[8] The diffuse-pollution pressures considered by the characterisation process were nutrients, pesticides and sheep dip, sediment, urban land use, acidification and mines and minewaters. Although not specified in the Defra characterisation reports, it is assumed that nutrients and pesticides and sheep dip would provide the causes of pollution pressure in the Wessex Basin Chalk aquifer.

Wessex Basin would have little detrimental environmental effect, the recovered water would not be of sufficient quality to be used for public supply, although the water quality would be significantly better than that of the local aquifer.

6.4 GROUNDWATER POLLUTION AND PROTECTION

6.4.1 Groundwater pollution

One of the main advantages of groundwater for water supply is its generally favourable and consistent quality, which reduces the need for water treatment. However, urbanisation, industrial growth and widespread, intensive agricultural activity can have a serious impact on groundwater quality. Groundwater is particularly vulnerable to long-term pollution as water movement through the Chalk can be slow and therefore current groundwater quality may reflect pollution events from many years or even decades ago.

6.4.1.1 Karstic chalk and pollution

The Chalk can possess high transmissivities and flow is predominantly via fractures, so there is the potential for rapid flow between sources of contamination and abstraction points, particularly where the Chalk has a karstic nature. For example in Hampshire, the springs at Bedhampton and Havant are heavily used for public water supply and represent a valuable and irreplaceable public asset. However, swallow holes in the Chalk at Lovedean, Cowplain, Horndean and Rowlands Castle are in direct connection with the springs and need to be protected against contamination. Flow measurements using tracers (Atkinson and Smith, 1974) have shown that the speed of groundwater movement to the springs is very fast and capable of travelling more than 2 km in 24 hrs.

Where conditions on the Chalk are suitable, weathering occurs from the surface down to the water table. This forms solution features that allow surface water to migrate rapidly both vertically and horizontally into the aquifer. Some work has been done on identifying areas vulnerable to pollution due to these solution features around Otterbourne and Tangley, but further work is required to identify all the areas at risk.

In the clay-with-flint domains, the high clay-mineral content (usually between 50 and 70 per cent) and iron-oxide content has the ability to attenuate contaminants by sorbtion and cation-exchange reactions. However, solution features beneath, and sandy horizons within, the deposits focus surface run-off adjacent to clay-with-flints deposits, and may actively promote recharge to the groundwater system. Superficial coverings of clay-with-flints are found over much of the south Dorset area, covering about 10 per cent of the Chalk at the surface. There is a tendency both for lower angle slopes (commonly the Chalk dip slopes) and, to the north of the Frome valley, for south-facing slopes to be preferentially covered with these deposits. Larger areas of clay-with-flints occur on the interfluve areas (Klinck et al., 1998).

One implication of rapid groundwater flow is that travel times between sources of pathogens and abstraction points may not be long enough for all pathogens to be removed. Abstracted water is therefore routinely disinfected at all public water supply sources to remove any potential pathogens. Some pathogens (notably *Cryptosporidium parvum*) are resistant to the normal methods of disinfection and legislation (the Water Supply (Water Quality) (Amendment) Regulations 1999) requires a risk assessment to be carried out for each public water supply source in England and Wales. Any sources considered to be at a significant risk of *Cryptosporidium* contamination have a more frequent raw-water monitoring regime for the *Cryptosporidium* oocysts in accordance with the regulations. Sophisticated treatment plants that are capable of removing the infective oocysts may then be required.

6.4.1.2 Urban areas

Most urban areas tend to be associated with a wide range of human activities that are potentially polluting to groundwater. Sources of pollution can include leaking sewers (where bacterial contamination, e.g. *Escherichia. coli,* is of concern in the highly vulnerable Chalk aquifer), run-off from roads, sanitary waste disposal, industrial activities and weed control. Even essentially residential districts may contain dispersed small-scale service industries.

Solid waste disposal

Solid waste disposal can be an important source of the subsurface contaminant load. Under EC water quality directives on groundwater protection and landfill, there has been a move away from 'dilute and disperse' sites, which rely on natural processes to attenuate pollutants to acceptable levels, towards artificial containment with natural or artificial barriers. Although modern landfills are engineered to minimise the risk of leachate reaching the water table, many existing facilities remain a potential source of pollution, particularly where sites are located in areas with shallow water tables. The greatest risk occurs where disposal sites are located directly on Chalk, whereas Palaeogene or recent cover may reduce the opportunity for leachate to access the water table. The development of new landfills is now steered away from the most vulnerable areas.

In the Chalk the carbonate rocks buffer the leachate and thus reduce heavy-metal mobility. The high buffering capacity of the Chalk has also been found to be conducive to microbial metabolism (Blakey and Towler, 1988), which may further attenuate leachate components.

Road run-off

The quality of first-flush urban storm run-off may contain a wide range of compounds such as hydrocarbon derivatives from exhaust gases and oil spills, heavy metals from engines and sulphate from tyre wear (Christensen et al., 1978).

Road drainage is therefore potentially a pollution risk wherever major roads cross the catchments of public supply sources. The risk is minimised by trying to route roads outside the public supply protection zones. Where this is not possible, full drainage for new roads is typically provided rather than soakaways. Elsewhere, soakaways are kept as shallow as possible, to make use of the maximum thickness of the unsaturated zone, and are provided with interceptors to prevent the ingress of petroleum compounds.

Non-agricultural pesticides

Weeds are widely controlled by the application of a variety of herbicides, the majority of which are applied to paved areas, industrial sites and railways, and may be integrated within rapid run-off events. The possibility of infiltration to groundwater is greatly enhanced where surface drainage is directly to soakaways, bypassing the biologically active soil zone.

Industrial impact

Inorganic pollution occurs in many of the major urban areas of the UK where groundwater is unconfined. The dominant contaminants are chloride and nitrate. Many organic compounds have been identified in UK urban groundwaters. Subsurface transport and attenuation of these chemicals is more complex than for inorganic compounds and many are soluble and stable in groundwater. Of main concern are industrial solvents and petroleum hydrocarbons that have limited aqueous solubility and may accumulate in the subsurface as a separate phase, acting as a long-term subsurface source. Chlorinated solvents are a particular problem: they are widely used and their low viscosity and solubility coupled with their high relative density means that rapid and deep penetration of an aquifer can occur.

Heavy industry is largely absent from the Wessex Basin region (apart from petrochemical works and other waterside plants). Point-source pollution incidents are now commonly associated with the storage of industrial chemicals, heating oil and with the construction industry. Spillage or illegal disposal of some toxic substances, such as industrial solvents, can cause serious pollution of aquifers and may result in the closure of groundwater abstractions — as has happened in Hampshire (Hampshire Water Partnership, 2003). Isolated historical problems also exist, as for example in the Andover area due to the effects of historical solvent contamination (Hampshire County Council, 2000).

6.4.1.3 Agriculture

The quality of groundwater in the Wessex Chalk aquifer system is generally good, although the intensification of agriculture in the second half of the 20th century has produced changes in quality as a result of diffuse pollution. Nitrate and pesticide concentrations are of particular concern and have required costly treatment at some UK public water supply sources. The intensive production of watercress is common in the region, particularly in Hampshire, and requires the use of pesticides and fertilisers, which may result in the pollution of surface and groundwaters.

Farm-waste storage can lead to point-source pollution, however, over recent years there have been significant improvements by farmers in farm-waste storage facilities. For example, these have resulted in a significant reduction in the numbers of point-source pollution incidents attributed to dairy-farming practices in the Stour catchment (Environment Agency, 1997).

Pesticides

Crop rotation avoids continuous heavy application of single compounds to individual fields. This lessens the danger of accumulation of pesticide residues in the soil and subsurface environment. The most rapid growth in pesticide use has been in certain herbicides and fungicides. The greatest threat to groundwater is generally the herbicides as these are relatively soluble. As weed growth is less intense on light, thin soils typical of the Chalk outcrop than it is on clayey soils, the increased vulnerability of the chalk soils may be countered by lower rates of herbicide application.

The natural processes that control the fate and transport of pesticides include leaching, sorption, volatilisation, degradation and plant uptake. The mode of application and action of the pesticide are important with regard to leaching potential as those targeted at plant roots and soil insects are usually significantly more mobile than those acting on the leaves. Many herbicides are applied to the soil before the weeds emerge and some insecticides are used for soil treatment. Given the timing of these applications, they are sufficiently persistent to remain in the soil for significant periods, so that leaching may occur.

Most pesticide compounds have water solubilities in excess of 10 mg l^{-1}, and the mobility of pesticides in soil solution will vary with affinity for organic matter and/or clay minerals. Pesticides that are strongly sorbed onto organic matter or clay particles are likely to remain in the soil zone rather than leaching to groundwater, with the possible exception of transport through fractures. Pesticide compounds may also degrade in the soil zone to produce (ultimately) simple compounds such as ammonia and carbon dioxide. Soil half-lives for commonly used pesticides range from 10 days to years, although the most mobile pesticides are normally less than 100 days. It is unlikely that matrix transport rates in the unsaturated zone exceed 1 m a^{-1} and only the most persistent pesticides are able to reach the water table. However, under certain conditions, rapid bypass flow may occur. This could permit low to moderately persistent components to reach the water table relatively rapidly.

Nitrate

Dissolved nitrate in groundwater is of concern because of potential human-health issues caused by the uptake of nitrogen in the blood after the ingestion of water containing high concentrations of nitrate. These concerns have resulted in a nitrate standard of 50 mg l^{-1} NO_3 (equivalent to 11.3 mg l^{-1} N) being set in the UK by the Drinking Water Inspectorate. The source of anthropogenic nitrate in groundwater is principally artificial fertilisers and animal manure; it is also produced by the dissolution of nitrous oxide released from vehicles and industry. Dissolved nitrate also results from the decay of humic acids in soils and is present as a natural constituent in most groundwaters (see Chapter 5).

Most nitrate leaching in the UK occurs during the autumn and winter when the soil reaches field capacity and recharge occurs. Furthermore, nitrate accumulated in the soil prior to the onset of recharge is transported through the unsaturated zone by the infiltrating water. Careful management of the land at this time is important to reduce the amount of nitrate that is available to be leached.

The Environment Agency (and its predecessor organisations) have monitored nitrate levels in groundwater from the Dorset and Hampshire Chalk aquifer for over 30 years as part of its remit to prevention pollution of groundwater under UK and European legislation. In a recent study[9] (Roy et al., 2007) an initial assessment was made of spatial and temporal variations in the groundwater nitrate concentration dataset (of over 8000 values) for the Dorset and Hampshire Chalk aquifer.

The data indicated a clear seasonal variability (which was seen to be most pronounced in the east of the aquifer) with the highest nitrate values in late winter and spring and lowest values between summer and early winter. The data suggested that seasonal cycles were superimposed on a long-term trend of rising nitrate concentration, and the rate of increase of nitrate in groundwater in the dataset as a whole was determined to be 0.12 mg N l^{-1} a^{-1}. Both the seasonal variation in nitrate and the increasing trend with time are well illustrated by the Litton Cheney spring data discussed in Chapter 5 (Figure 5.9).

Contour plots of five-yearly mean nitrate data from the Environment Agency study (Figure 6.4) showed significant increases with time, with an average increase of 30 per cent in the period 1976 to 2006, and at one site the increase

[9] The study also noted that phase lags between effective precipitation, groundwater level and nitrate peaks of about two to three months suggested that piston flow within the Chalk matrix is the main transport mechanism for nitrate to the saturated zone.

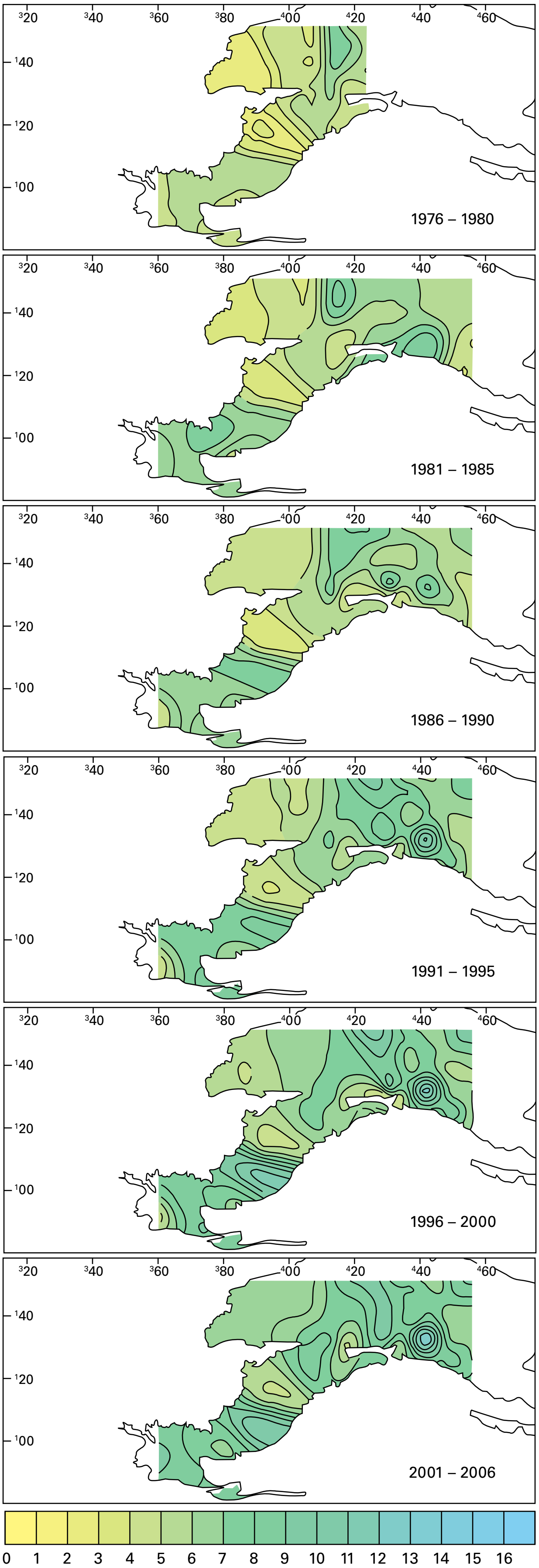

Figure 6.4 Mean nitrate (as mg nitrogen from nitrate per litre) in Chalk groundwater in the Wessex Basin for consecutive five-year periods since 1976 (after Roy et al., 2007).

reached 115 per cent. By comparing the data with land-use information, it was seen that higher groundwater nitrate levels were more likely to be associated with arable and urban land use than with managed grassland.

In conclusion, both basin-wide contouring and time-series data imply that the nitrate problem in the Chalk of the Wessex Basin is likely to worsen with time, with breaches of the quality limits likely to occur with increasing frequency, especially during the winter.

6.4.2 Groundwater protection

If groundwater does become polluted, low flow rates and limited microbiological activity restrict self-purification, and remediation is often expensive and difficult and, in some cases, impossible. It is therefore very important that groundwater resources are protected both with regard to aquifer vulnerability and source protection.

6.4.2.1 Groundwater protection policy

The powers and duties of the Environment Agency for the protection of groundwater were set out in the Water Resources Act 1991. For groundwater quality these were to:

- achieve statutory quality objectives for groundwater
- control discharges to groundwater (discharge consents process)
- prevent pollution (through regulations)
- enforce against pollution events
- take remedial action once pollution has occurred.

In addition, the Environment Agency has indirect powers enforced through other bodies under the Environmental Protection Act 1990 and the Control of Pollution Act 1974 to control certain discharges to natural waters and to control waste disposal to land where pollution of water resources might result.

In 1992, the National Rivers Authority (NRA) adopted a policy framework for protecting groundwater, which was intended to cover all types of threat to groundwater of whatever size, from point or diffuse sources, and by both conservative and degradable pollutants (National Rivers Authority, 1992b). This policy was updated in 1998 by the Environment Agency's framework document 'Policy and Practice for the Protection of Groundwater', (Environment Agency, 1998b), in which two approaches to groundwater protection were set out. Given that both European and national legislation require that all groundwater should be protected, one approach was to assess the vulnerability of aquifers to pollution. In addition, it was recognised that protection may be required for specific sources and therefore groundwater source protection zones were introduced involving consideration of each source catchment area.

Aquifer vulnerability

In its framework document (Environment Agency, 1998b), the Environment Agency discussed the vulnerability of groundwater resources to pollution in the context of groundwater-resource protection. Factors defining groundwater vulnerability were given as:

- presence and nature of overlying soil
- presence and nature of superficial deposits
- nature of strata
- thickness of unsaturated zone.

While acknowledging that a full assessment of groundwater resource vulnerability can only be achieved by local studies using a range of investigations and data types, the Environment Agency considered it valuable to use existing soil and geological data to produce groundwater vulnerability maps for England and Wales. To that end in the 1990s, the NRA and its successor the Environment Agency produced vulnerability maps covering the whole of England and Wales. The methods used are described in the document ‘Policy and Practice for the Protection of Groundwater’ (Environment Agency, 1998b).

Geological strata are classified as major, minor or non-aquifers depending on their permeability, the nature of the aquifer (e.g. whether it is fractured) and its productivity. The vulnerability of aquifers to contamination is then classified by assessing the type and thickness of overlying soils. Superficial deposits with low permeability (e.g. till, soliflucted material, peat, lacustrine deposits, clay-with-flints and brick earth) are identified by a distinctive stipple overlay. The maps for Wessex include all or part of the following Environment Agency Groundwater Vulnerability maps: Southern Cotswolds (Sheet 37); Somerset Coast (Sheet 42); East Somerset and South West Wiltshire (Sheet 43); North West Hampshire (Sheet 44); West Sussex and Surrey (Sheet 45); East Devon and South Somerset (Sheet 50); Dorset (Sheet 51), and Southern Hampshire (Sheet 52).

Figure 6.5 shows the groundwater vulnerability over the Wessex catchment. As would be expected, the Chalk outcrop across most of Wessex is highly vulnerable where it is overlain by less than five metres of overburden. However, these classifications can be misleading, as they do not take into account important factors such as the thickness of low-permeability superficial deposits and the thickness of the unsaturated zone. Such factors are important and need to be considered when dealing with site-specific issues. In 2010, the Environment Agency groundwater protection policy started to use aquifer designations consistent with the Water Framework Directive. Aquifers are designated as ‘principal’ or ‘secondary’ and subdivided into ‘superficial’ or ‘bedrock’ materials.

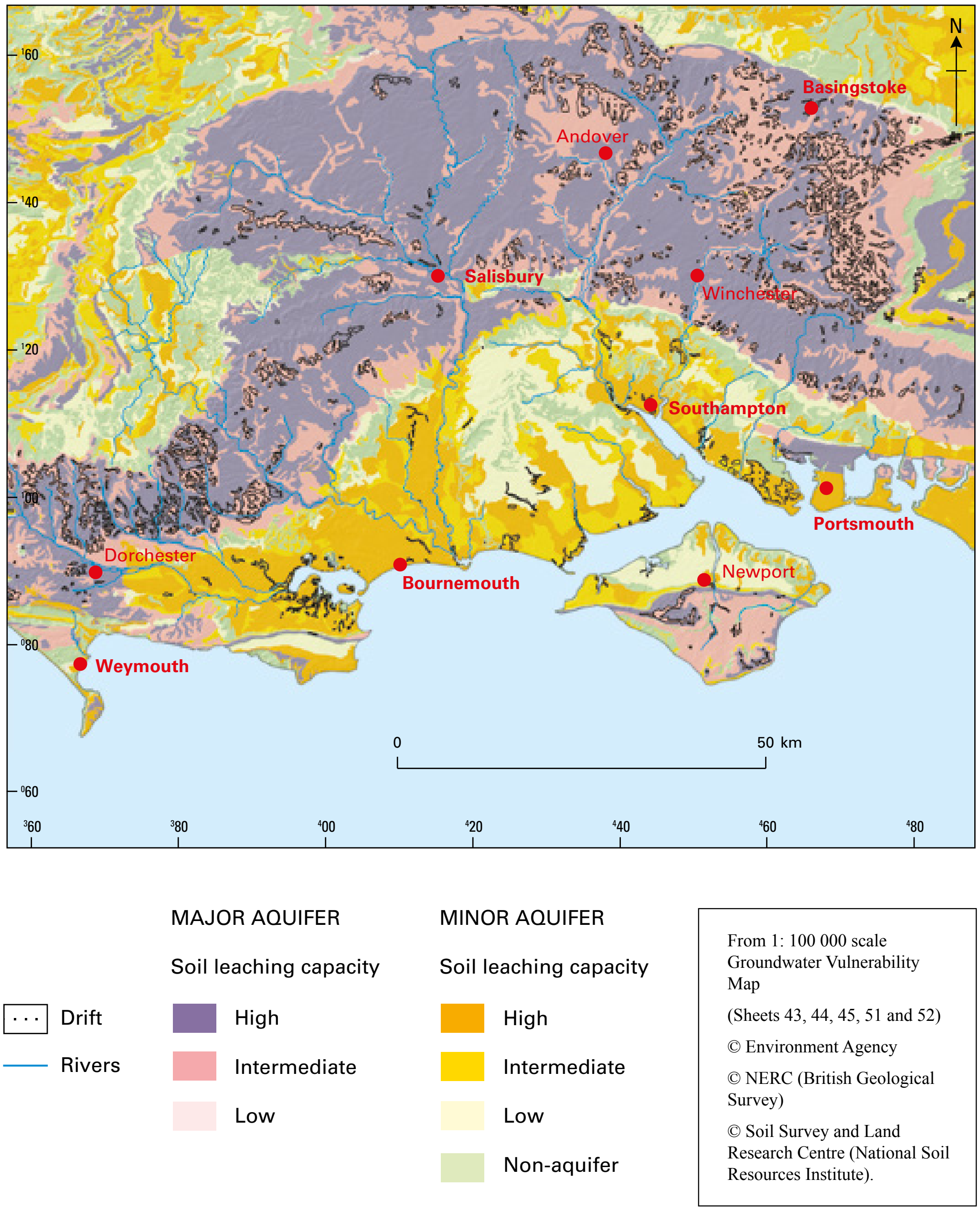

Figure 6.5 Groundwater vulnerability map for the Wessex Basin.
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Source protection zones

In addition to the groundwater vulnerability approach to protecting groundwater resources, the Environment Agency developed a methodology for protecting groundwater sources using source protection zones. The approach is based on the concept that the proximity of a potentially polluting activity to a groundwater abstraction source is likely to be one of the most important factors in assessing the risk of source pollution. Therefore, principle zones based on groundwater travel time drawn around a source can be used to assess pollution risk and to guide pollution prevention measures.

Source protection zones (SPZ) have been defined by the Environment Agency for nearly 2000 groundwater sources (wells, boreholes and springs) used for public drinking water supply in England and Wales. The SPZs provide an indication of the risk to groundwater supplies, for which SPZs have been defined, that may result from potentially polluting activities and accidental release of pollutants. Three zones (an inner, outer and total catchment) are usually defined although a fourth zone (zone of special interest) is occasionally used. The zones are defined based on travel times, i.e. how long it would take recharge reaching the water table to arrive at the source. Zone 1 is delineated by a travel time of 50 days, the time over which faecal-indicator bacteria are reduced to very low or non-detectable concentrations by die-off and dilution. Any recharge contaminated with pathogenic microbes occurring within this zone may therefore cause an unacceptable concentration of viable microbes at the groundwater source. It is therefore wise to minimise potentially polluting activities within this zone and thus activities like sewage sludge spreading or landfilling of waste are not permitted in Zone 1. Zone 2 is the 400-day travel time zone, while Zone 3 contains the entire catchment for the source.

The direction of groundwater flow and the properties of the surrounding strata determine the orientation, shape and size of the SPZ. The zones are delineated by numerical modelling or semi-analytical techniques that assume uniform permeability and transmissivity to calculate travel times. Further information about this process is given by the NRA (1995b) and Keating and Packman (1996). However, in reality, the Chalk aquifer has a spectrum of velocities associated with the various apertures and distribution of the fractures, but this is poorly understood. The manner in which the SPZs have been delineated in the Chalk aquifer is therefore simplified as a consequence of the lack of knowledge regarding the range of velocities. This means that recharge may be able to reach a borehole more quickly than predicted by the SPZ. The Agency undertook a research and development project to assess existing methods to develop a rigorous and defensible methodology for deriving SPZs in fractured/fissured aquifers (Robinson and Barker, 2000).

6.5 NITRATE VULNERABLE ZONES

In the late 1990s, two schemes were developed to protect groundwater through changes in farming practice to reduce the amount of excess nitrate leached from the soil, the nitrate vulnerable zone (NVZ) and nitrate sensitive area (NSA) schemes. Farmers volunteered to participate in the NSA scheme, for which compensation was offered. The groundwater NVZ designation is compulsory where groundwater quality is significantly threatened by nitrate from agricultural sources. They are defined as areas where groundwater contains or could contain, if preventative measures are not taken, nitrate concentrations greater than 50 mg l^{-1}. Farmers who are farming land within NVZs are required to comply with measures to control and reduce leaching of nitrate to rivers and groundwater.

In the Wessex Basin, essentially all of the Chalk outcrop is currently classified as NVZ.

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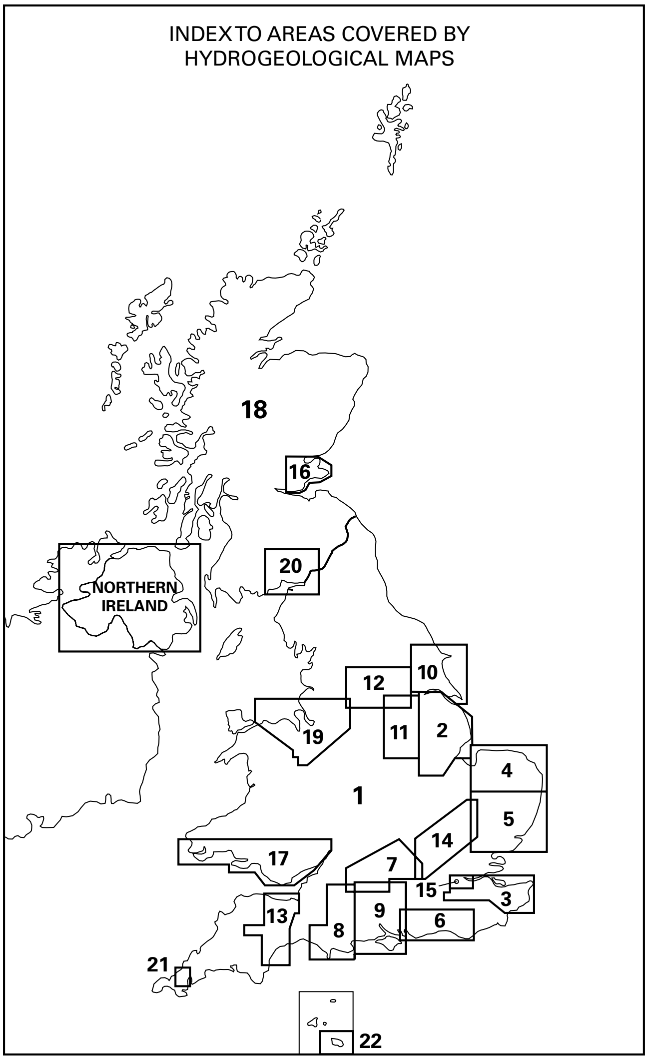
Appendix

List of boreholes and shafts

Borehole name	Grid Ref	SOBI No.
Abbotstone	SU 55 34	SU53SE1
Alton Pancras	ST 70 01	ST70SW17
Aughton	SU 23 57	SU25NW10
Axford 1A	SU 61 42	SU64SW1
Axford 1B	SU 61 42	SU64SW43
Blackhorse Farm	SU 56 14	SU51SE152
Bradley 2A	SU 62 41	SU64SW3
Bradley 2BS	SU 62 41	SU64SW2
Brixton Deverill	ST 85 38	ST83NE5
Chilgrove House	SU 83 14	SU81SW7
Chitterne	ST 99 45	ST94NE2
Compton House	SU 77 14	SU71SE10
Corfe Mullen	SY 97 98	SY99NE1C
Durweston	ST 84 08	ST80NW6
East Holton Farm	SY 95 91	SY99SE232
Figheldean	SU 15 46	SU14NE17
Fonthill Bushes	ST 95 35	ST93NE43
Itchen Down 2	SU 54 33	SU53SW4
Itchen Down Farm	SU 54 33	SU53SW3
Leckford Bridge	SU 23 51	SU25SW16
Lower Wield Farm	SU 63 40	SU64SW21
Lulworth West	SY 82 80	SY88SW3
Lymington	SZ 30 96	SZ39NW22
Marchwood 1	SU 39 11	SU31SE227
Musseldean Copse	ST 90 36	ST93NW7
Padnall Grange	SU 70 11	SU71SW62
Raglington Farm	SU 54 13	SU51SW114
Sandhills	SZ 45 90	SZ49SE3
Sompting	TQ 16 06	TQ10NE80
Stoborough	SY 92 86	SY98NW298
Sutton Poyntz	SY 70 84	SY78SW9
Totford	SU 56 38	SU53NE1
Upwey	SY 65 85	SY68NE97
Wareham Common	SY 91 87	SY98NW297
West Houghton	ST 82 04	ST80SW27
West Woodyates Manor	SU 01 19	SU01NW92
Wield 3A	SU 61 40	SU64SW4
Wield 3B	SU 61 40	SU64SW5
Willoughby Hedge	ST 86 33	ST83SE62
Wilmingham	SZ 36 87	SZ398NE9
Woodside	SU 33 56	SU35NW39

HYDROGEOLOGICAL MAPS

Hydrogeological maps have been published at various scales. They are colour-printed maps, supplied as either flat sheets or folded sheets in plastic sleeves, and are available only from the BGS.



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1 England and Wales, 1977
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(two sheets)

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17 South Wales, 1986

1:100 000
6 South Downs and part of the Weald, 1978
7 South West Chilterns, 1978
8 Chalk of Wessex, 1979
9 Hampshire and Isle of Wight, 1979
10 East Yorkshire, 1980
11 Northern East Midlands, 1981
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