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The Chalk aquifer of the South Downs

Cover photograph
Chalk cliff at Beachy Head, Sussex (Photographer: Paul Tod).

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The Chalk aquifer of the South Downs

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Preface

The Chalk aquifer of the South Downs comprises one of the most heavily utilised and strictly managed groundwater resources in Britain. It is appropriate, therefore, that the South Downs aquifer was chosen for the first systematic regional review to be carried out within the National Groundwater Study. The study aims to compile available hydrogeological information, at least by reference or database address, and to provide a summary in report form as well as populating the National Water Well Archive and associated data listings on a regional basis.

The South Downs study was carried out collaboratively by the British Geological Survey Hydrogeology Group, the University of Brighton, the Environment Agency —Southern Region, the Southern Water Group, and others within BGS. The work was carried out between 1992 and 1994 and has subsequently been collated into this report. Much of the book is a review of earlier work, not least of the history of groundwater management in the region, but there are also a number of original contributions including the association of structure and groundwater flow patterns as well as the new lithostratigraphy of the Chalk, the role of down-hole geophysics in monitoring saline intrusion, and the most recent resource-management policy.

This report is intended to provide information for future workers on the Chalk aquifer of the South Downs. As such, it concludes with a vision of the work that is required for the South Downs Aquifer to keep pace with the modern day stresses applied to it. It is the first in a new series of books describing regional components of the major aquifers, and will be followed by a description of the hydrogeology and hydrogeochemistry of the Chalk of Yorkshire, and later by regional reports of the Triassic sandstones and other major aquifers. National hydrogeology is described in a separate Special Memoir Series.

The National Groundwater Study brings together hydrogeologists with a diversity of interests and roles, mapping geologists, tectonic and structural engineering geologists, hydrogeochemists, environmentalists and economists. This book reflects this multidisciplinarity so that the South Downs aquifer is portrayed as a dynamic and renewable resource which is capable of satisfying demand, provided that it is appropriately and sensibly managed.

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Frontispiece Ditchling Beacon, view of the characteristic dipslope Chalk uplands of the South Downs. [A13383].

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1 Introduction

INTRODUCTION

The South Downs is the prominent physiographical feature along the south coast of England between Eastbourne in the east and Havant in the west (Figure 1). It has an average width of some 10 km, and extends for almost 100 km in length, with a maximum elevation of 271 m above ordnance datum at Butser Hill. The Downs are composed of chalk, comprising part of the lithostratigraphic unit known as the Chalk. The outcrop forms part of the southern limb of the eroded Wealden Anticline, and dips south towards the coast into the Hampshire–Dieppe Basin, much of which lies below the eastern part of the English Channel (Figure 1). The northern edge of the Downs is marked by a prominent escarpment. To the south of this, the gentler dip slope falls to the coastal plain, where extensive urban developments exist along the coastal fringe of East and West Sussex.

The Chalk of the South Downs is one of the major aquifers in the United Kingdom, supplying groundwater to the urban areas of Brighton, Worthing, Eastbourne, Chichester and Portsmouth, as well as many rural centres. The location of public supply pumping stations is shown in Figure 1. Chalk groundwater supplies a total population of about 700 000 — much of which is concentrated along the coastal fringe — and represents approximately 70% of the water supplied in the area.

The limits of the aquifer are defined by the scarp face to the north, by the sea to the east and south, and by the groundwater divide between Portsmouth and Chichester to the west. Groundwater flows in a southerly direction, towards the coast (see Figure 2). The aquifer is geographically and geologically isolated, and can be divided into five blocks by southward flowing rivers that rise in the Weald.

The Chalk is a fractured rock with a very fine-grained matrix. Because of the nature of the matrix, much of the water held within the chalk pores cannot be drained by gravity, and the aquifer properties are controlled by fractures and larger pores. This results in a highly-transmissive, but relatively low-storage aquifer which is at risk from contamination (by sea-water or agrochemicals).

The key issues affecting the groundwater resources in the area, and those anticipated in the future include:

- *Saline intrusion* although some parts of the South Downs aquifer are afforded protection from saline intrusion by structural and geological controls, large parts of the aquifer remain vulnerable. Groundwater management policies have played a significant role in reducing the occurrence of saline intrusion. However, considerable sections of the productive aquifer are at risk, and this will constrain groundwater development at some point in the future.
- *Groundwater contamination* although not as intensively farmed as other Chalk regions, the South Downs has a significant area of land under arable cultivation. In spite of the Aquifer Protection Policy implemented by the Southern Water Authority in 1985 (see Chapter 7), nitrate concentrations in some boreholes are now increasing. In some areas, particularly near Eastbourne, a change in agricultural policy in the 1970s is reflected in rising nitrate concentrations in groundwater. Additional potential groundwater contamination problems include pesticides (from both agriculture and rail track application), leaking sewers, and point sources such as landfill sites and hydrocarbon spillages. The expansion of urban areas around existing sources may exacerbate these problems.
- *Drought management* throughout the prolonged drought between 1988 and 1992, the available water supply was matched with (reduced) demand. Resource management and careful operation of sources, demand management and leakage control are all contributory factors.

TOPOGRAPHY

The South Downs is divided naturally into five 'blocks' by the four rivers, the Arun, Adur, Ouse and Cuckmere, which rise in the Weald, to the north of the Chalk scarp. The South Downs attains an elevation greater than 50 m above OD over most of its length, with maximum elevations of over 240 m in the west but slightly lower (up to 215 m) in the east. The landscape of the Chalk has the characteristic form of rolling downland with convex slopes and steep valley sides, often with relatively wide valley floors. The chalk excarpment is breached by four windgaps: near Cocking, Washington, Pyecombe and Jevington.

High cliff-bound land abuts the coast in the east, but there is a distinct coastal plain to the west of Brighton, which is better developed to the west of Worthing.

CLIMATE

The coastal district of Sussex is one of the mildest and sunniest parts of Britain, with average summer and winter temperatures of 16.1°C and 5.5°C respectively; it receives an average of seven hours sunshine per day during the summer. Average annual rainfall is 844 mm,

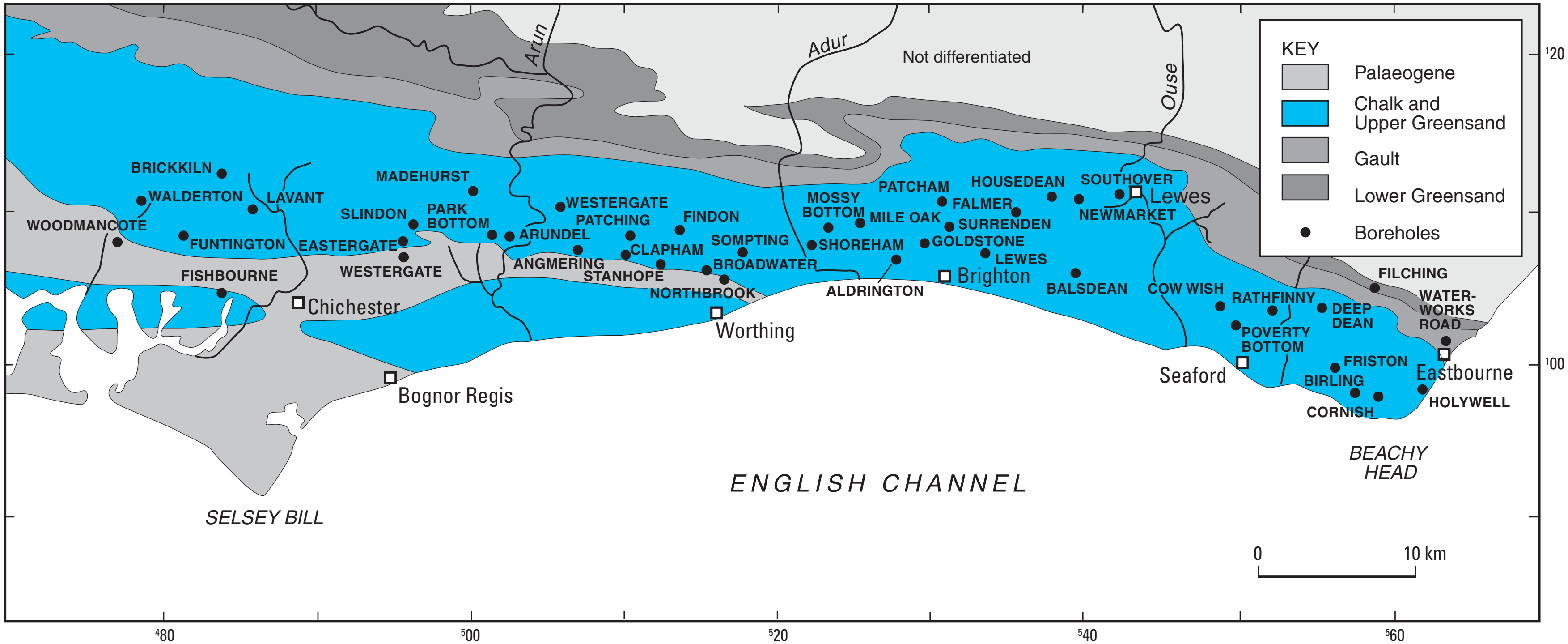


Figure 1 Location map, showing basic geology and public water supply boreholes.

Plate 1 The escarpment at Washington looking eastwards towards Chanctonbury Ring. [A1888].

but the distribution is strongly influenced by topography, with the higher Chichester and Brighton blocks receiving over 25% more precipitation than the coastal areas. Average evapotranspiration is 485 mm a^{-1}, and a broad figure for effective rainfall is, therefore, 359 mm a^{-1} (see Table 1).

The mean annual recharge of the Chalk of the five Chalk blocks ranges from over 475 mm in the Brighton and Chichester blocks to 373 mm in the Seaford Block, the variation being influenced by the topography. Recharge during a year of severe drought, such as 1975/76, is between 40 and 50% of the mean, except in the Chichester Block where it may be as low as 36%. During the extended drought between 1988 and 1992 the average recharge over the entire period was only 50 to 70% of the mean (Marsh and Monkhouse, 1993).

LAND USE

There are three broad land-use categories in the South Downs:

The scarp face is largely given over to pasture since much of it is too steep for arable farming. This land reverts

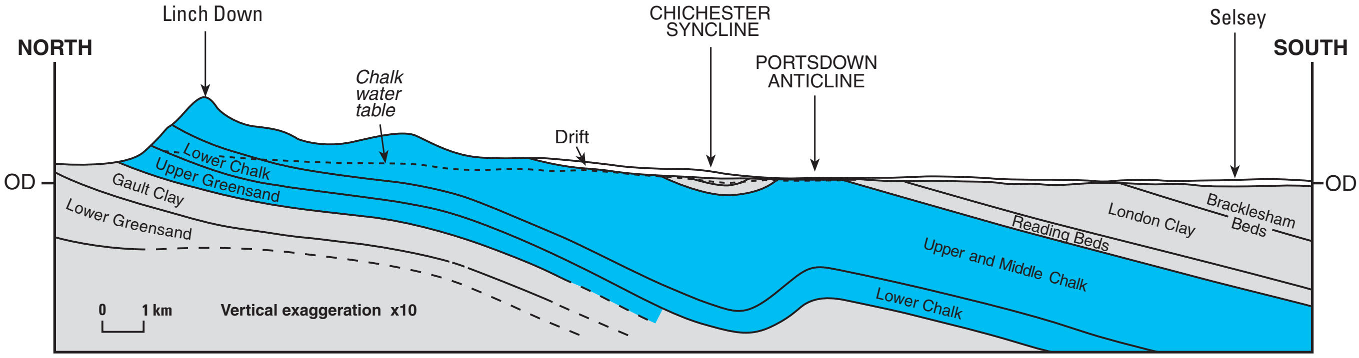


Figure 2 Cross-section through the Chichester Block of the South Downs (from Southern Water Authority, 1984).

Table 1 Resources of the Five Chalk Blocks (mm a^{-1}).

	Eastbourne	Seaford	Brighton	Worthing	Chichester
Chalk outcrop (km^2)	60	52	139	132	242
Mean annual rainfall	777	705	901	739	904
Mean annual recharge	411	373	477	391	476
1975/76 recharge	200	176	219	168	173
1975/76 recharge as % of average	48%	47%	46%	43%	36%

rapidly to scrub woodland if left ungrazed. Villages in this area are generally built along and below the spring line.

The coastal zone in which urbanisation has been most intense, has seen development spread from the river estuaries and harbours along the coast and inland. There is now a continuous built-up zone extending from Bognor Regis to Seaford which is only separated from the town of Eastbourne by the line of cliffs known as the Seven Sisters. This urban area extends well up onto the downland, particularly north of Brighton.

The Downs is the largest category and is occupied by a mixture of arable farming and grassland typical of the Chalk outcrop throughout southern England. The most important crops are winter cereals, together with some rotation with oil-seed rape and peas. The soils tend to be very thin and stony, precluding extensive cultivation of root crops. This area is dissected by several river valleys which have historically provided transport routes and are occupied by a line of small villages, major roads and railway lines.

USE OF GROUNDWATER

Groundwater is the traditional water source for the area. At Saddlecoombe Farm near Brighton a 73 m deep well is covered by a timber structure that contains a donkey-operated treadmill dating from the 16th century which was built by the Knights Templar. What is claimed to be the deepest hand-dug well in the world was completed in 1862 to a depth of 392 m at Woodingdean in Brighton, passing through the entire Cretaceous sequence (Green, 1955).

Groundwater in the Chalk provides the water supply for the major urban areas of Eastbourne, Brighton,

Plate 2 Looking west along the escarpment near Poynings. [A13378].

Plate 3 The donkey treadmill at Saddlecombe (GS 627).

Worthing, Chichester and Portsmouth and their surrounding districts, as well as small settlements and individual houses. Currently, the South Downs aquifer lies within the water supply areas of three water companies (Figure 3). The two most eastern Chalk blocks of Eastbourne and Seaford are within the supply area of South East Water plc, while Southern Water Services Ltd, the principal subsidiary of the Southern Water Group, covers all the Brighton and Worthing Chalk blocks, as well as the eastern end of the Chichester Block and a small part of the Seaford Block. Portsmouth Water Company supplies water to most of the Chichester

Figure 3 Water companies of the South Downs area.

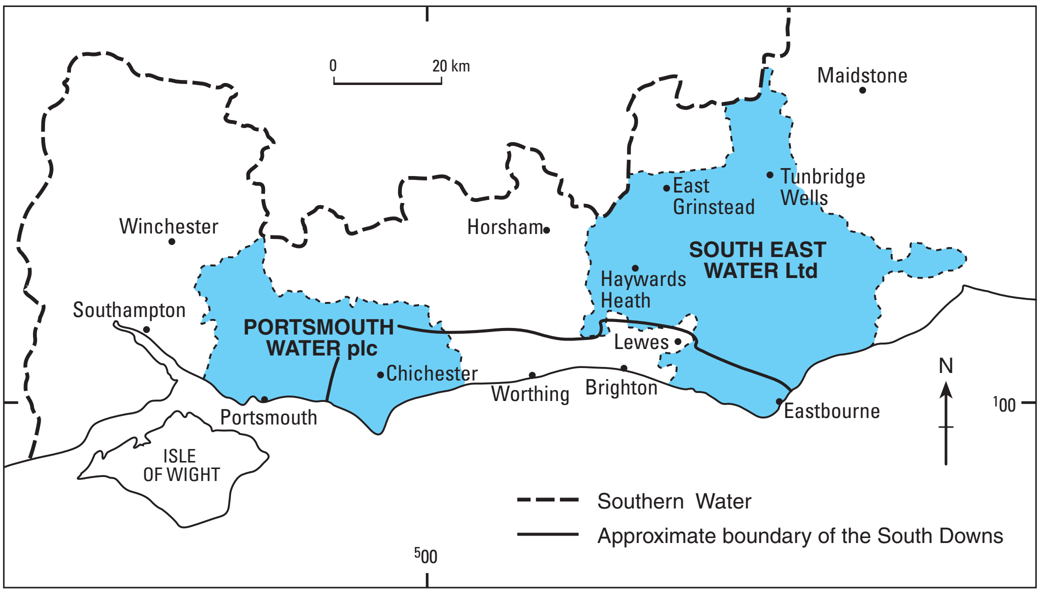


Table 2 Population served and water supplied by the water companies for the South Downs.

Company	Population served	Number of sources	Supply (Ml d^{-1})
South East Water	134 000	14	52
Southern Water	490 000	23	135
Portsmouth Water	40 430	9	52

Table 3 Use of the Chalk Blocks for public water supply (Ml d^{-1}).

	Eastbourne	Seaford	Brighton	Worthing	Chichester
Average recharge	67.7	53.2	312.9	141.4	315.6
Drought recharge	32.9	25.1	115.9	60.8	114.5
Licensed abstraction	31.1	20.5	108.5	60.5	125.6
1993 abstraction	23.5	11.6	80.1	55.1	52.1
Autumn drought yield	27.1	16.4	112.9	54.5	98.7

Block in the west. Until 1994, the Eastbourne Waterworks Company and the Mid Southern Water Company supplied water to the two smaller eastern blocks but this company is now incorporated within South East Water. The population served, the amount of water supplied within these blocks, and the number of public water supply groundwater sources operated are given in Table 2.

Industrial and private abstractions of groundwater are small, mainly limited to the processing of sand and gravel aggregate around Chichester, for which all but 0.3% of the quantity abstracted is estimated to be returned to the aquifer. Abstraction for agriculture (animal husbandry, spray irrigation and horticulture) although important, is again small by comparison to abstractions for public water supplies. Abstraction for public supply amounts to between 89 and 97% of the total from the five Chalk blocks.

The amount of groundwater used for public water supply can be examined in several ways. A comparison of licensed abstractions with average available resources (i.e. average annual recharge) shows that the commitment of resources for the five Chalk blocks is between 34 and 45%. It is prudent to base development potential on the resources available in a drought year, particularly when dealing with a coastal aquifer, subject to the threat of saline intrusion. The licensed commitment of resources for the single drought year 1975/76 (which had a return period in excess of 1 in 100 years), was between 81 and 90%, while the actual use of resources under these drought conditions was between 60 and 90%. In terms of the total autumn drought yields of the public water supply sources (compared with minimum reliable yields) the degree of licensed commitment amounts to between 80 and 94% of the available resources in a drought year (see Table 3).

Exploitation of the South Downs Chalk aquifer is highly developed and intense. Significant potential for further development by direct continuous abstraction remains only in the Chichester Block.

2 Geology and structure

GEOMORPHOLOGY

The landscape of the South Downs has been shaped by geomorphological processes. The five southward flowing rivers, the Arun, Adur, Ouse and Cuckmere, originated as northern tributaries of the ancient Solent River, one of the major west-to-east consequent rivers that developed initially on the Chalk and subsequently on the Palaeogene landscape (Reid, 1887; Linton, 1951). As the Palaeogene cover and the Chalk were eroded within the boundaries of the Weald, the original basic drainage pattern became more complex, and the characteristic scarp and vale scenery developed as erosion took advantage of variations in lithology. During the late Palaeogene and Pleistocene, river capture and diversion gradually led to the present mature drainage pattern. Four major wind gaps breach the crest of the South Downs, near Cocking, Washington, Pyecombe and Jevington, and these were developed by former rivers which breached the Chalk and which were subsequently captured and diverted.

The gradual but complex evolution of the South Downs, in the broader context of its position on the margin of the Wealden anticline, has been reviewed by Jones (1981) and Sparks (1986). A secondary escarpment, behind the primary Chalk escarpment, is caused by differential weathering and erosion. This reflects variations in the strength of the Chalk, and is linked to lithological controls over fracture patterns (Mortimore, 1993).

The plain has three principal erosion levels: 33–41 m, 20–25 m, and about 7.5 m above OD. These reflect significantly higher sea levels in the recent past, the middle level has been dated as Cromerian age and the 7.5 m level as Ipswichian. The coastal plain is covered by an extensive and thick spread of Combe Rock (now mapped as Head Gravel) and brickearth, the latter mainly a windblown deposit (Akeroyd, 1972). Outcropping Chalk in the Portsdown–Littlehampton anticline, has been planed off except for the small parts of the relic cliff line that forms Portsdown (120 m above OD) and Highdown (80 m above OD).

The coastal plain of the South Downs is drained by several small streams between Arundel and Chichester which are known as the Rifes. They are partly fed by Chalk groundwater but the main source is groundwater from the superficial deposits of the coastal plain (Harries, 1979).

A prominent feature of the landscape are dry valleys on the dip slope, and combes along the steep scarp. Most of the larger dry valleys have a general north–south alignment. There are two prominent transverse east–west dry valleys, one east of Singleton and the other between Falmer and Lewes. The valleys vary from shallow depressions to deep incursions up to 100 m below the adjacent interfluves. They do not generally intersect the present water table apart from the Winterbourne at Lewes and the Lavant at Chichester. The nature of the Chalk ensures rapid infiltration and percolation through the unsaturated zone; the infiltration capacity is rarely if ever exceeded, and runoff seldom occurs. Surface erosion is, therefore, unlikely under present-day conditions.

The formation of dry valleys was described by Goudie (1990). The South Downs valleys were probably developed by normal fluvial processes which took place when the water table, and the sea level, was higher (e.g. Fagg, 1923; Williams, 1980). During the Calabrian transgression of the Palaeogene, for example, the sea level was 180 m above its present level and groundwater levels onshore backed-up so that rivers and streams flowed over the chalk As the sea level receded during the Pleistocene, groundwater levels dropped beneath the valley bottoms diverting river flow underground through the chalk. Groundwater levels also fell as a result of the steady lowering and retreat of the escarpment (Chandler, 1909).

The development of the valleys was enhanced by permafrost conditions during the Pleistocene which rendered the near-surface chalk impermeable even during the summer snow-melt floods. Physical weathering, accentuated by freeze–thaw alternations, encouraged erosion. However, Jones (1980) suggested that the general form of the Chalk dip slope was the result of the modification of the surface by solution, albeit sculptured by conditions during the Quaternary, particularly the Pleistocene. Associated periglacial phenomena included solifluction spreads which produced the Combe Rock or Head Gravel (Reid, 1887; Bull, 1940).

The Chalk surface is gradually being lowered by solution. The rate has been estimated at between 17 and 50 mm per 1000 years (West and Dumbleton, 1972; Sperling et al., 1977) and this suggests between 35 and 100 m of chalk could have been removed during the Quaternary. Classical solution features, such as swallow holes, are not generally well developed on the South Downs although some are present.

GEOLOGICAL SEQUENCE IN SUSSEX

The geological succession represented in the South Downs and the surrounding area extends from the Purbeck Group to the Palaeogene (Figures 4 and 5). It includes several significant hydrogeological units: the Tunbridge Wells Sand, the Ashdown Formation, and the

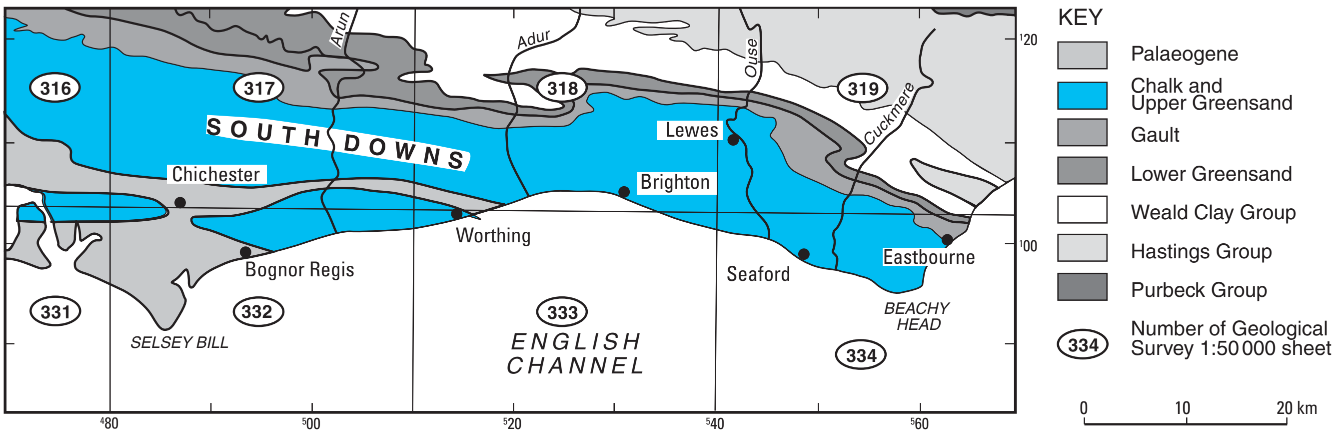


Figure 4 Outline solid geology of the South Downs and adjacent areas.

Lower Greensand Group, and the Chalk. Although each is usually considered for practical purposes to be a separate, distinct aquifer, the cover above the Hercynian basement actually represents a single hydraulic continuum with a regional flow system extending from the crest of the Weald to the coastal outlets (Downing and Penn, 1992, fig. 2).

Purbeck Group

These rocks, up to about 140 m thick, crop out only in a few small inliers in the core of the Wealden Anticline and are the oldest exposed rocks in Sussex. The dominant lithologies include blue-grey, often calcareous, mudstones, groups of thinly bedded or nodular argillaceous limestones, channel sandstones and a basal group with evaporites. This range of lithologies records the transition from the marine environments of the late Jurassic Portland Formation to the fluvial and lagoonal conditions in which the succeeding Wealden formations of early Cretaceous age were laid down. The Jurassic–Cretaceous boundary within the Purbeck Group of Sussex is, however, poorly defined (Casey, 1963).

The Purbeck Group is of little hydrogeological significance; the limestones contain small amounts of hard groundwater but have a very small outcrop area.

Wealden Super Group

These rocks of early Cretaceous age, comprise alternations of mainly arenaceous (sandstone and siltstone) and argillaceous (clay and mudstone) units, which were laid down in fluvial and lagoonal environments fed from contemporary source areas in the London Platform and Cornubian massifs.

Hastings Group

Formerly known as the Hastings Beds, this group comprises the basal arenaceous Ashdown Formation, which is overlain by the Wadhurst Clay and the Tunbridge Wells Sand. The latter is locally divided into Lower and Upper Tunbridge Wells Sand where the Grinstead Clay is developed.

Ashdown Formation

Laid down in fluvial and alluvial environments, the Ashdown Formation comprises major sandstone units, siltstones, mudstones and clays and attains a maximum thickness of approximately 200 m.

The Ashdown Formation (which includes, locally, the Fairlight Clays) shows considerable lithological variation, both laterally and vertically, by virtue of its deposition in mixed transient fluvial environments. Its outcrop in the High Weald is disturbed by east–west strike faulting. Goundwater is present in the massive, medium-grained sandstones usually developed in the top 15 to 50 m of the formation. Groundwater is soft and may be rich in iron and manganese.

Wadhurst Clay

This formation comprises up to 50 m of grey-green clays, often interlaminated with thin siltstone layers, and it includes beds of sandstone, thin shelly limestone and nodular clay ironstone.

The Wadhurst Clay acts as an important aquiclude between the Ashdown and Tunbridge Wells Sand formations. Locally small household supplies of groundwater have been obtained from the interbedded sandstones.

Tunbridge Wells Sand

The Tunbridge Wells Sand is 80 to 100 m thick, is lithologically similar to the Ashdown Formation and marks a return to fluvial environments after the lagoonal episode of the Wadhurst Clay (in the western Weald, the Grinstead Clay separates the Lower and Upper Tunbridge Wells Sand).

There many thin clay layers and it is difficult to extract useful quantities of groundwater from these strata.

Weald Clay Group

This major clay unit varies in thickness from about 60 m near Eastbourne to over 180 m west of the Arun. It comprises mainly grey-green clays, often with silty laminae, and with thin interbeds of 'Paludina' limestone, sandstone and clay ironstone, which were deposited in a lagoonal environment. In general, the Weald Clay is an aquiclude, although individual beds of sandstone, fractured limestone or siltstone within the clays are capable of transmitting some groundwater.

Lower Greensand Group

The transition from Wealden to Lower Greensand rocks marks a considerable stratigraphical break, and few of

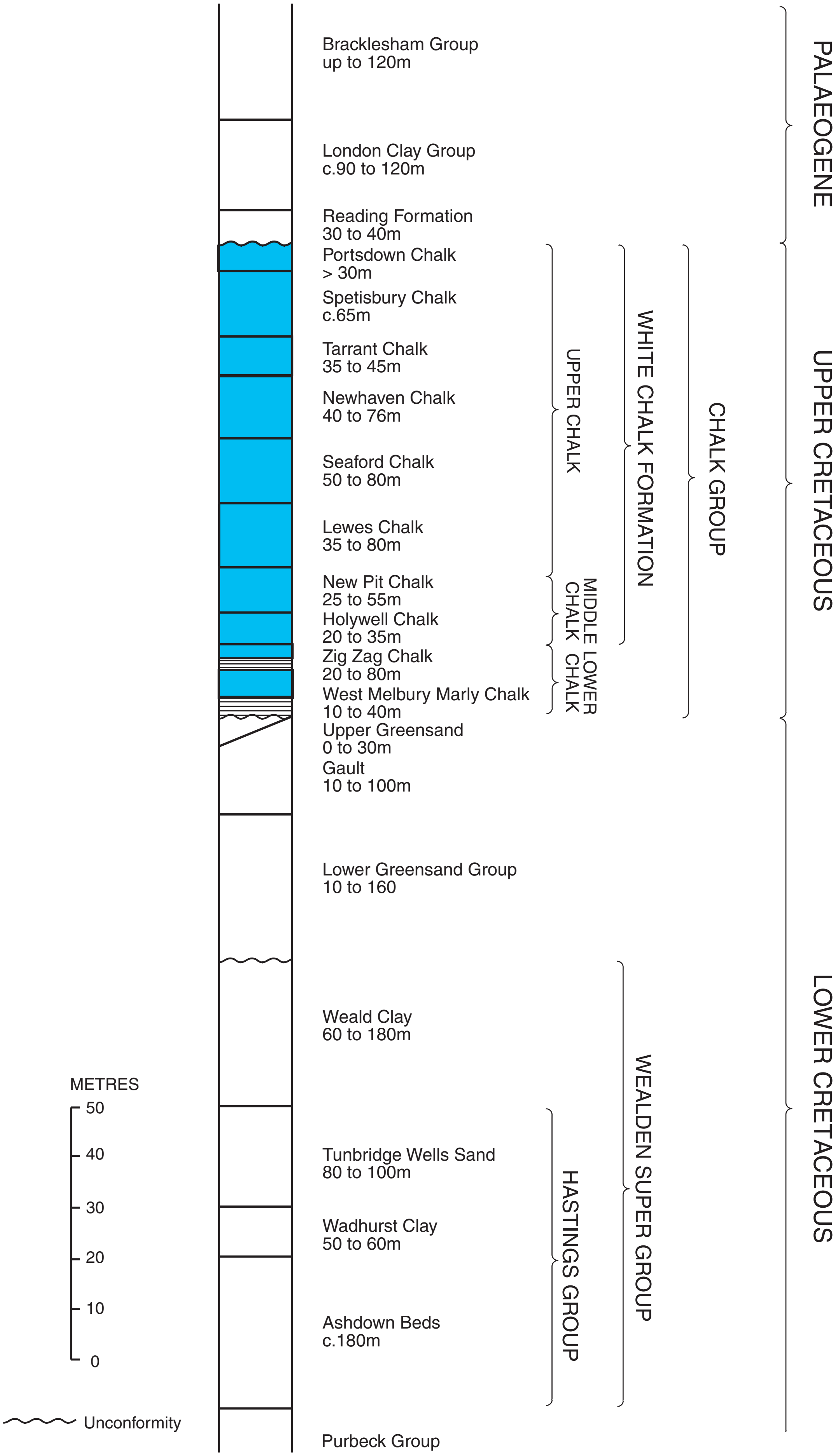


Figure 5 Geological sequence in Sussex and the South Downs.

the faults affecting the Wealden rocks extend up into the Lower Greensand.

The group is generally split into four formations in southern England: the Atherfield Clay, the Hythe Beds, the Sandgate Beds and uppermost the Folkestone Beds. These subdivisions can be recognised in the west of the area, where the total thickness reaches 160 m, but lose their identity as the outcrop is traced eastward towards Eastbourne, where the Lower Greensand Group is only a few metres thick. It also thins down dip beneath the Chalk cover, changes due to the proximity of the westerly extension of the South Downs–Paris-Plage basement feature (Young and Monkhouse, 1980).

Atherfield Clay

This basal formation is about 12 m thick and consists mainly of blue, grey or chocolate coloured clays containing marine shelly fossils.

It is an aquiclude like the underlying Weald Clay, and springs commonly occur at its junction with the Hythe Beds.

Hythe Beds

This mainly sandy formation shows considerable variation in lithology and thickness within the area. The Kentish 'rag and hassock' facies with hard calcareous sandstones alternating with softer sands is developed east of the River Arun. To the west, however, the formation is more uniformly sandy with minor lenticular developments of chert. The thickness exceeds 90 m in the western outcrops.

Occasional thin beds of clay or silt give rise to perched water tables locally, and moderate yields of groundwater are obtained from boreholes in the western outcrops.

Sandgate Beds

The Sandgate Beds include clays, sandy clays, sands and sandstones, which are often glauconitic. It is best developed in the west where it is up to 60 m thick.

The formation contains little groundwater and acts as an aquiclude separating the Hythe Beds and the Folkestone Beds.

Folkestone Beds

The Folkestone Beds consists of some 10 to 75 m of medium to coarse, poorly cemented sands, in places glauconitic, with occasional seams of pebbly sand and thin clay units. They are best developed to the west of the area. The sands typically show strong cross-bedding, reflecting their deposition in a shallow tidal sea. Secondary deposition of iron hydroxides commonly occurs in irregular anastomosing networks of 'carstone' or 'Liesegang' concentric iron-staining effects.

In West Sussex, the formation is a valuable aquifer with intergranular storage, providing useful supplies of groundwater. It has been extensively exploited for sand extraction, and some of the pits have subsequently been used for landfill.

Gault Formation

The Gault Formation was deposited in a marine environment and comprises pale- to dark-grey calcareous and silty mudstones, with thin seams of phosphatic nodules marking minor non-sequences. In the extreme east of the area it is only 15 m thick, but near Lewes the greatest recorded thickness of the formation in southern England of 104 m was proved by Lake et al. (1987).

The Gault is an aquiclude separating the Folkestone Beds and Upper Greensand/Chalk aquifers.

Upper Greensand Formation

The Upper Greensand Formation is 30 m thick at the foot of the Chalk escarpment near Midhurst but is absent at outcrop east of Ringmer, apart from a limited exposure at Beachy Head. It comprises variably indurated fine-grained glauconitic silty sands and sandstones. The Upper Greensand is the time equivalent of the highest beds of the Gault elsewhere in southern England. Its absence from parts of the area may reflect the original facies distribution to some degree, but it also marks a period of gentle folding and erosion prior to the deposition of the Chalk.

The Upper Greensand Formation is in hydraulic continuity with the succeeding Lower Chalk, but is of relatively minor importance as an aquifer because of its limited outcrop area.

CHALK GROUP

The Chalk Group attains a maximum thickness of almost 500 m in the South Downs (Figure 5). Approximately 60 to 70 m are classified as Lower Chalk, about 80 m are Middle Chalk and 320 m Upper Chalk. Reclassification of the Chalk in the Fareham and Chichester districts has identified ten members of more or less distinctive lithological character.

Variations in thickness and lithology occur within the formations and members of the Chalk Group, and the sequence is interrupted at frequent intervals by marls, hardgrounds, and flints. These relate to the controls exercised on sedimentation by basement structures and sea level change. Structural factors also impose regional and local fracture patterns on the Chalk.

The Chalk is a very pure limestone consisting almost entirely of calcium carbonate, with a small proportion of clay minerals and other minor constituents. It consists of a fine fraction comprising remains of algae, and a coarser fraction of foraminifera and other small shell debris. The finer fraction consists of coccolith debris, fragments of the 'coccosphere', the spherical calcite secretions made by algae of the order of Coccosphaerales. In the near absence of magnesium calcite, the Chalk is stable at low temperatures and pressures and has changed very little since it was deposited, remaining soft and friable. The constituent particles have a high porosity, but the pore sizes and the interconnecting pore-throats are small, typically 0.1 to 1 µm and the matrix of the rock has a very low permeability (Price, 1987; Price et al., 1993).

The Middle and Upper Chalk have the least detrital content, reflecting an absence of terrigenous input to the Chalk seas. The Lower Chalk does, however, contain appreciable proportions of clay minerals which vary in accordance with the small-scale sedimentary cycles that characterise this formation; the Lower Chalk also contains some silt grade quartz and authigenic pyrite, with glauconite abundant in the basal Glauconitic Marl bed. Reworked phosphatic nodules are locally common in the Glauconitic Marl.

Marls (calcareous clays) occur in the Middle and Upper Chalk as thin, but laterally persistent, seams that can be correlated over large distances. The seams are generally up to about 0.1 m thick and may be rich in smectite, possibly derived from contemporary airborne volcanic ash falls. They are impermeable relative to the fractured chalk and may cause local perching of groundwater. Recent geochemical studies (Wray and Gale, 1993) have shown that some marl seams have distinctive trace element signatures which facilitate their interregional correlation. The Plenus Marls, at the Lower–Middle Chalk boundary, mark a regressive interval of widespread significance (Jefferies, 1963; Jeans et al., 1991; Jenkyns et al., 1994). The cyclic marly chalks of the Lower Chalk are informally known as the Chalk Marl and are generally much less permeable than the overlying beds.

Hardgrounds are layers of hardened chalk, often mineralised or coated with calcium phosphate and glauconite. The development of hardgrounds, as well as harder nodular and griotte chalks, is related to synsedimentary diagenesis at or just below the sea bed. The hardgrounds represent an ecological change on the sea floor, reflected in the fossil types, with a predominance of hard-sediment borers over the more usual soft-sediment borers. Well-developed hardgrounds (such as Strahan's Hardground) contain phosphate and glauconitic coatings on surfaces (Mortimore, 1986b). Hardgrounds may pass laterally into nodular chalks, which are indicative of a lesser degree of synsedimentary lithification. The harder, more brittle, horizons commonly have higher permeability than softer chalks, due to more intense fracturing.

Flints, either nodular or tabular, are also well developed in some Chalk units. Some bands of nodular flint have a distinctive aspect, and are used as marker beds, e.g. Bedwell's Columnar Flint. Sheet or tabular flints may be parallel to the bedding or related to oblique tension fractures. They are usually of later origin than the nodular flints. The development of nodular flint in the Middle and Upper Chalk seems to have occurred during early diagenesis at some small distance below the sediment/sea water interface (Clayton, 1986). The flint may take the form of a burrow cast or an echinoid test. The flints show little or no sign of compressional deformation suggesting that they were emplaced soon after the deposition of the chalk.

Palaeogene

A major unconformity, representing a long period of uplift, flexuring and erosion separates the Chalk Group from the overlying Palaeogene. The tectonic movements began in late Cretaceous times and continued episodically throughout the Palaeogene.

The Palaeogene formations of the South Downs and adjacent areas lie within the present, structurally isolated, Hampshire–Dieppe basin which extends offshore beneath the English Channel (Curry and Smith, 1975). They are separated from similar deposits of the London–Southern North Sea basin by the Weald–Artois ridge or axis. It is now generally accepted that the two basins formed part of a single larger depositional area, the Anglo–Paris–Belgian basin, and were only separated by later tectonic movements (King, 1981).

The Palaeogene (Lower Tertiary) sequence includes the Reading Formation (formerly the Woolwich and Reading Beds of Palaeocene age) and the London Clay and Bracklesham groups (of Eocene age). The Thanet Formation, which is at the base of the Palaeogene sequence in Kent and East Anglia, is absent in Sussex. Here the Palaeogene is about 250 m thick and includes representatives of the Reading Formation, London Clay Group and Bracklesham Group (Figure 5). The greater part of these rocks is concealed by drift in the coastal plain of West Sussex, and details of these strata are only available from ephemeral shore platform exposures, a limited number of borehole sections and extrapolation from the coastal sections of the Isle of Wight.

Reading Formation

Ellison et al. (1994) have revised the lithostratigraphy of the early Palaeogene rocks of the London Basin so that the 'Woolwich' and 'Reading' types receive formation status within the new Lambeth Group. The new scheme has not yet been extended to Sussex, but it is considered appropriate to adopt the term Reading Formation.

The Reading Formation has a maximum thickness of 40 m, and has a continuous outcrop along the coastal plain eastwards to Worthing and Shoreham Harbour, beyond which it is represented by smaller outliers on the Chalk dip slope near Brighton, Newhaven and Seaford where it is only 8 m thick. It comprises mostly brightly mottled red, brown and greenish grey clays, which overlie a basal glauconitic sandy or loamy unit with flint pebbles and chalk clasts (analogous to the Bottom Bed or Upnor Formation of the London Basin). Other bodies of fine-grained sand occur locally within the clays, and lignite or fossil wood is found near the base of the formation.

The Reading Formation of Sussex generally behaves as an aquiclude, confining groundwater in the Chalk aquifer, although local sandy beds may give rise to chalk water springs. A common feature around the margins of the Reading Formation outcrop on the Chalk is the development of swallow holes, where acid runoff comes into contact with the chalk to create large solution features (see Chapter 3). The Reading Formation is also believed to be the in-situ parent material from which the clay-with-flints has developed on the Chalk dip slopes (Hodgson et al., 1967; Hodgson et al., 1974; Catt, 1986).

London Clay Group

The stratigraphy of the London Clay was reviewed by King (1981) who recognised five coarsening-upward cycles in the London Basin. In Sussex the group is dominated by argillaceous lithologies and consists mainly of grey, brown-weathering, pyritic, silty and sandy clays with some thin courses of calcareous cementstone nodules. Each cycle commences with a glauconitic sandy horizon, often with reworked flint pebbles, which mark a transgressive event. Silty clays gradually coarsen and become sandy upward in the cycle, which concludes with a sheet-like sandy body of fairly wide extent, truncated by the erosion surface at the base of the next cycle.

The London Clay is generally impermeable but some groundwater occurs in the sandy horizons. The small amounts of groundwater are generally of poor quality, with high concentrations of sulphate and iron in solution.

Bracklesham Group

The Bracklesham Group comprises 120 m of shelly glauconitic sands, silts and clays with sporadic flint pebble beds. The flint beds were deposited in three sedimentary cycles represented by the Wittering, Earnley and Selsey divisions (Figure 6). The Bracklesham Group outcrop is largely concealed by drift in the Selsey peninsula.

In the Chichester Syncline, the Palaeogene rocks are folded with the Chalk. They form a barrier to groundwater movement between the Chalk of the dip slope outcrops and that beneath the Selsey peninsula and the coastal plain, although there are several significant breaches. The rifes, which drain the coastal plain, originate from groundwater in the drift deposits overlying the planed-off Palaeogene rocks in the Chichester Syncline (Shephard-Thorn et al., 1982).

Quaternary

The Quaternary Era saw the final stages of the development of the landscape of the South Downs, against a background of alternating cold and temperate climatic regimes, with concomitant changes of sea and groundwater levels. Drift deposits were laid down in response to erosion of the land surface in fluvial, marine, periglacial and aeolian environments. Frost weathering and solution of the Chalk had significant effects on its aquifer properties.

Considerable progress has been made in linking the various glacial and interglacial deposits to the climatic curve of Shackleton and Opdyke (1973) in the last 20 years, but some uncertainty remains due to the incompleteness of the geological record and the scarcity of suitable dating evidence.

Several aspects of the Quaternary history of Sussex are directly relevant to the development of the prevailing hydrological and hydrogeological conditions (see Chapter 3). Most obviously the present landscape, rivers and coastline have evolved in response to the varying climatic regimes and sea levels throughout the Quaternary. In addition, various processes have contributed to the weathering of the surface rocks to significant depths. To some degree, evidence of palaeohydrogeology may be preserved as 'fossil' zones of enhanced permeability in the Chalk marking former bands of water table fluctuation. Furthermore, clay-with-flints may affect infiltration, and hence recharge to the aquifer.

Clay-with-flints

This is probably the oldest drift deposit of the South Downs. The deposits are stiff, yellowish and reddish brown clays with fresh and broken, weathered flint nodules resulting from the in-situ weathering of the Reading Formation over long periods. The latter rests on a sub-Palaeogene erosion surface cut on the Chalk dip slope of the South Downs and it has been demonstrated that the clay-with-flints rests on the extension of this surface beyond the present outcrops of unaltered Reading Formation (Hodgson et al., 1967). A thin basal part of the deposit, comprising fox-red clay with unworn corticed flint nodules, is believed to result from solution of the Chalk and translocation of clay minerals (Catt, 1986). The upper and major part of the deposit represents the altered residuum of the Reading Formation. Solution pipes in the Chalk occur beneath the clay-with-flints around the margins of its outcrops.

The tenacious nature of the clay component of the clay-with-flints suggests that it forms an impermeable capping to the Chalk. However, in practice, soil cracks, plant roots and the junctions of clay and flints provide pathways for the migration of water to depths of at least 2 m, and it is best to regard the clay-with-flints as semi-permeable rather than impermeable. The deposit is highly dissected and less than 5 m thick over much of the South Downs, and the small remaining patches have little effect on retarding infiltration. The age of the transformation from in-situ Reading Formation to clay-with-flints is obscure, but Catt (1986) suggests that it commenced no later than the Cromerian Complex of interglacials (approximately 500 000 years ago).

Head gravel

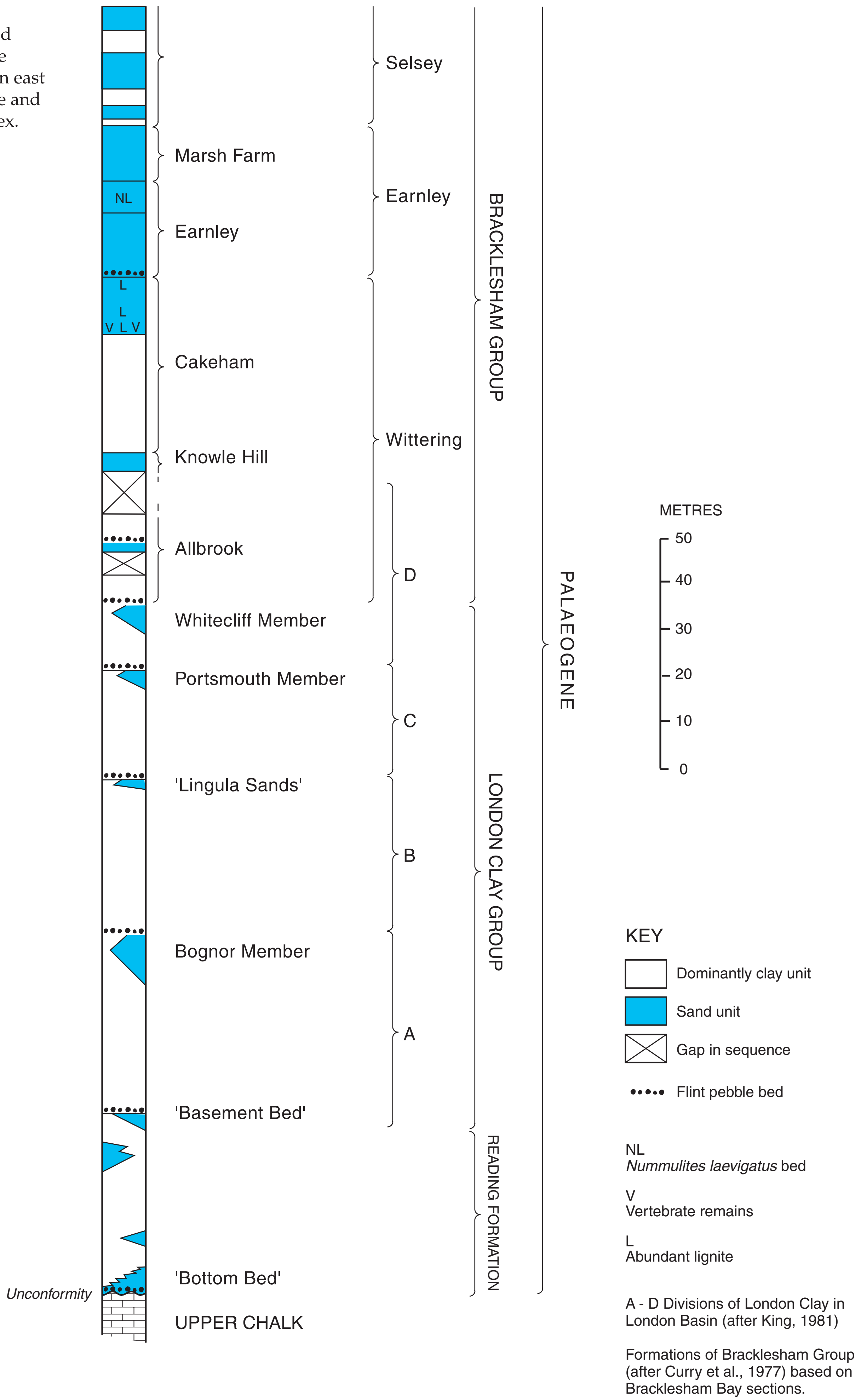
This term is applied to solifluction gravels which overlie and protect the deposits of the higher raised beach and, in part, those of the lower raised beach in West Sussex. The gravels may be up to 10 m thick near the cliff line of the higher raised beach but thin southwards. They comprise

Quaternary history

The Quaternary has been conventionally divided into Pleistocene and Recent. It extends back over the last 1.6 million years, of which the Pleistocene represents by far the greater part and the Recent (Flandrian or Holocene) only the 10 000 years since the retreat of the last ice sheets from north-west Europe. Palaeoclimatic studies, have shown that over 20 cold and temperate climatic oscillations occurred during the Quaternary (Shackleton and Opdyke, 1973). Northern Europe was covered by regional ice sheets during at least three of the more recent cold episodes (glacials). The growth of polar ice caps in these periods led to global sea level falls of 100 m or more. The intervening temperature periods (interglacials) saw the return of temperate vegetation and animal life, accompanied by sea level rises resulting from the melting and retreat of ice sheets and glaciers. There has been a long-term 'eustatic' element in relative land/sea level changes with an overall rise in land levels over most of southern England, so that older river terraces and raised beaches occur at higher elevations than the younger ones.

The alternating glacial and interglacial periods, and consequent falls and rises in sea level, significantly affected both surface drainage and groundwater flow in the South Downs. The effect on the development of aquifer properties is discussed further in Chapter 3.

Figure 6
Generalised Palaeogene sequence in east Hampshire and West Sussex.



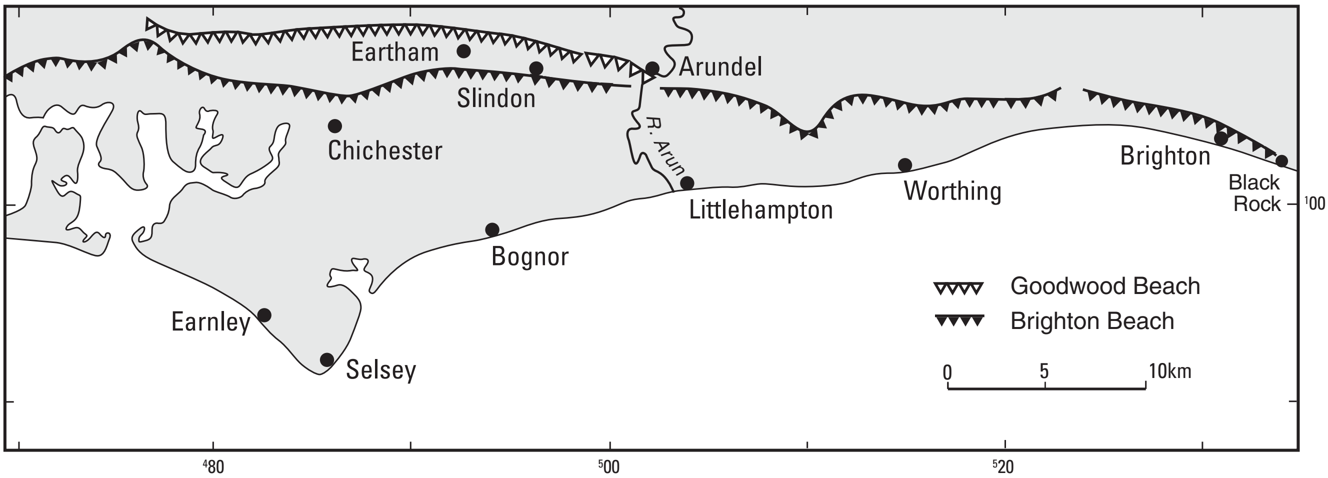


Figure 7 Cliff lines of the Sussex raised beaches (after Hodgson et al., 1967).

coarse angular flints in a reddish brown clay matrix and are generally non-calcareous. Patches of gravel with a chalky matrix are preserved locally, suggesting that all the gravels were originally calcareous. They have previously been known as Valley Gravels and Combe Rock.

Raised beach deposits

These deposits reflect higher sea levels associated with interglacials, and are developed on at least three levels along the coastline of Sussex. The deposits range in grain-size from fine intertidal sands and silty clays to large cobbles and are nowhere more than 5 m thick. They rest on erosion surfaces cut in Chalk or Palaeogene strata, and are associated with 'fossil' cliff lines (Figures 7 and 8). The elevations of the beach platforms range from 5 to over 40 m above OD. They are commonly concealed decalcified head gravel or brickearth, which has no doubt helped to preserve them from erosion.

At Boxgrove, near Chichester, older raised beach deposits are more or less permeable and in hydrogeological continuity with the Chalk, although they are above the present water table. Several major solution

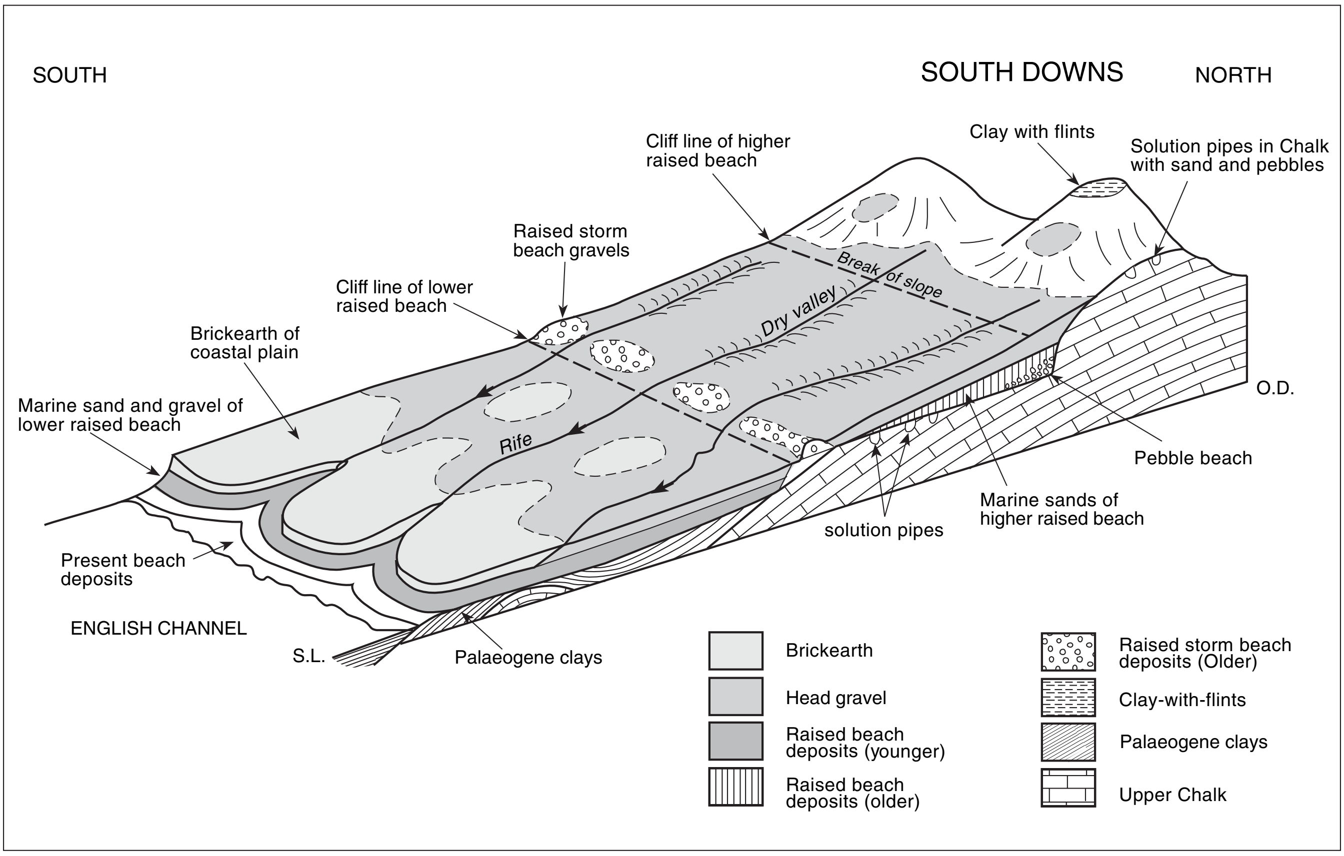


Figure 8 Schematic block diagram illustrating the drift sequence of the coastal plane of West Sussex.

collapse features occur in the Chalk below the raised beach deposits and their cover of head gravel, similar to those associated with the clay-with-flints (Shephard-Thorn et al., 1982).

Younger raised beach deposits (known as the Brighton Raised Beach) extend for about 30 km along the Sussex coast between the Hampshire border and the fossil cliff exposed at Black Rock, Brighton (Figure 7). These deposits and overlying drifts are permeable and can store and transmit groundwater.

River terrace deposits

Sand and gravels forming river terraces are preserved at up to six levels in the valleys of the Lavant, Arun, Adur, Ouse and Cuckmere rivers at heights up to 40 m above the present flood plain. All these rivers, except the Lavant, rise on Wealden strata in the Central Weald and reach the sea via gaps in the South Downs. In the headwaters of the rivers, the gravel clasts are dominated by Wealden lithologies such as ferruginous sandstone and siltstone, but flint and chert (from the Lower Greensand) become more important southward as the rivers pass over the Chalk gaps (Lake et al., 1987; Young and Lake, 1988; Bristow and Wyatt, 1983; and Shephard-Thorn et al., 1982). The terrace deposits are relatively thin and of small extent and though highly permeable are of little value as aquifers.

Other deposits

Other minor Quaternary deposits include fan gravels which are subangular, chalky-flinty gravels on the floodplain of the River Lavant at Chichester (Shephard-Thorn et al., 1982), alluvium, and brickearth (yellowish brown, silty-clayey loam).

CLASSIFICATION OF THE CHALK GROUP

Schemes to subdivide the Chalk Group have been based alternately on its lithological characters (lithostratigraphy) or its contained fossil faunas (biostratigraphy). Neither can be used on their own for long-distance correlation and current practice is to use a combination of faunal and lithostratigraphical observations supported, where possible, by geophysical data, to make detailed correlations.

Early descriptions of the English Chalk, such as those of the Dover cliff sections by Phillips (1821), relied largely on the lithological characteristics of the chalk, such as colour, clay content and the presence or absence of flints. This method fails when applied to areas affected by lateral changes in lithology.

Towards the end of the 19th century, palaeontological studies had advanced sufficiently to allow a zonal scheme, based on the ranges of certain index fossils, to be introduced by Barrois (1876) in France, and subsequently refined in England by Rowe (1900, 1908). The zonal scheme itself proved inadequate for detailed interregional correlation because many of the index fossils were rare, and their full ranges could not always be easily determined.

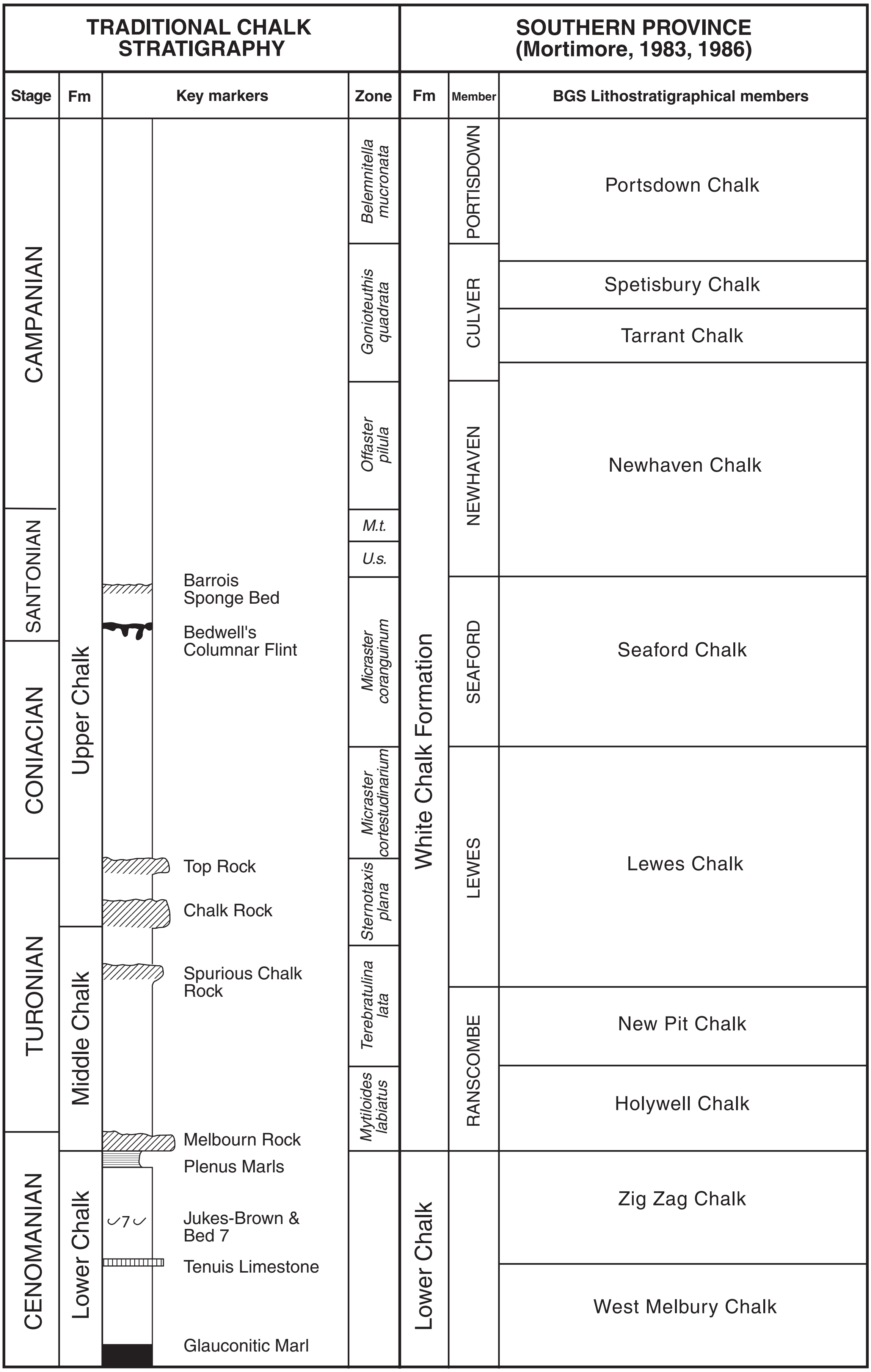
Some workers attempted to map zonal boundaries, based on the collection of fossils from the numerous small chalk-pits dotted over the Chalk landscape. Brydone (1912, 1914, 1915) in Hampshire and Gaster (1924, 1929, 1937, 1939, 1944, 1951) in Sussex were the main exponents of this method, which revealed very useful data on structure and variations in thickness.

The British Geological Survey adopted a three-fold division of the Chalk into Lower, Middle and Upper units for its Old Series 'one-inch' geological maps (issued in the 19th century) based on the occurrence of mappable lithological marker beds. These were the Glauconitic Marl (originally Chloritic Marl) at the base of the Lower Chalk, the Plenus Marls/Melbourn Rock at the Lower–Middle Chalk boundary and the Chalk Rock at the base of the Upper Chalk. The zonal scheme overlapped with this three-fold division and worked well in the Cambridge (Penning and Jukes-Browne, 1881), Chilterns and North Downs areas. Problems arose in Sussex, Hampshire and Wessex where the marker beds were weakly developed or were liable to be confused with other similar beds.

In Sussex, the Geological Survey mapped Lower, Middle and Upper Chalk on the Old Series 'one-inch' maps, which were subsequently reissued as New Series sheets in the 1920s with only minor modification. However, when the Lewes (319) and Brighton (318) sheets were resurveyed in the 1970s, it was found impracticable to divide the Middle and Upper Chalk in the field because the topographic feature and soil brash normally associated with the Chalk Rock were not clearly developed. Furthermore, it was becoming clear that the traditional tripartite division of the Chalk was inadequate.

Mortimore (1986b) used a combination of the above approaches and divided the White Chalk Formation in Sussex (Middle and Upper Chalk undivided) into six lithostratigraphical members, made up of a number of distinctive beds and defined by marker horizons. The key to developing this lithostratigraphical classification system was the recognition of numerous laterally continuous marker horizons such as marl seams, flint courses, layers of nodular chalk and well-defined horizons of trace fossils. The division was based on the careful recording of quarry and coast sections of Sussex, with additional input from geophysical logs and biostratigraphical data. Mortimore recognised the importance of thin persistent marl seams for correlation purposes, as they could be detected and correlated by wireline geophysical logging (Gray, 1958; 1965; Murray, 1986). In southern England recent research and mapping has resulted in the recognition of at least ten mappable subdivisions of the conventional Lower, Middle and Upper Chalk (Bristow et al., 1998) (Figure 9).

The refined stratigraphy allows resolution of units of chalk less than 1 m thick in boreholes and field sections. With such a detailed stratigraphical framework it is possible to demonstrate lateral variations in thickness and sediment type, and therefore also the concomitant changes in fracture style and frequency. It is also possible to examine the distribution of matrix properties (porosity and density) and rock mass characters (fracture style, frequency and weathering). In addition, lateral changes in sedimentation influenced by deep-level Variscan basement structures can be identified (Mortimore, 1979, 1983, 1986a, b, 1993; Lake et al., 1987; Young and Lake, 1988). Furthermore, faults and fracture



U.s. - Uintacrinus socialis Zone
M.t. - Marsupites testudinarius Zone

(Not to scale)

Figure 9 Comparison of 'traditional' and R N Mortimore's classifications of the Chalk of Sussex, with lithostratigraphical mapping units adopted by BGS.

zones may be more accurately identified (Mortimore, 1986a; Mortimore and Pomerol, 1991; Mortimore and Lamont-Black, 1996).

Mortimore made contributions to the Lewes (319) (Lake et al., 1987) and Brighton and Worthing (318 and 333) (Young and Lake, 1988) sheet memoirs on the basis of his research. At the time these members were not mapped, but more recently the British Geological Survey has adopted a modified version of his scheme based on the lithological character of the members and their feature-forming propensities in the Shaftesbury–Dorchester area of Dorset and in the Fareham–Chichester area of Sussex. In Sussex, the new mapping shows generally close parallelism with the zonal maps of Gaster (1944) although the zonal and member boundaries do not usually coincide. The mapping team has also employed Landsat TM satellite imagery and conventional air photographs as an aid to rapid mapping (Marsh, 1993). The topographic expression of the members of the Chalk Group in West Sussex is shown in schematic cross-section in Figure 10 (based on a drawing by Dr D T Aldiss).

Remote sensing: an aid to mapping the Chalk

Satellite images may provide detail of regional fracture patterns and other major positive features, as expressed in surface topography, which may be of use to the field geologist. Recent work by the Remote Sensing Group of BGS (Marsh, 1993) has aided large-scale geological mapping near the western edge of the South Downs (Fareham and Chichester sheets). Landsat Thematic Mapper data were acquired for the winter months, when low sun angles emphasised topography. Data were processed to emphasise further the topographic attributes, and the detailed information used to map several features, including the main Chalk escarpment and several lesser escarpments, and lineaments. The lineaments were mainly identified as straight, deep dry valleys on the Chalk, and stream sections in the Lower Greensand.

The above work was carried out in order to expedite the field mapping process, and identified several points requiring further clarification in the field:

- Although, in places, scarps corresponded to a geological boundary, there were exceptions. The reasons for these anomalies needed to be identified.
- Relationship of the internal stratigraphy of the Upper Chalk to the scarps seen on the Landsat data.
- The cause of the lineament pattern observed.
- The relationship between apparent offsets in the scarps and known faults.

The following summarises the main characteristics of the defined lithostratigraphical members of the Chalk Group (Bristow et al, 1998).

Lower Chalk

GLAUCONITIC MARL (c.2 to c.4 m)

This thin member of green glauconitic clayey fine sands or silts marks the base of the Chalk in Sussex. Dark grey, phosphatic nodules are common, and the bed is extensively bioturbated (Young and Lake, 1988). Locally it rests on a burrowed surface of the Upper Greensand siltstone. The upper contact is gradational, with a progressive reduction in glauconite content. Where of sufficient thickness it has been mapped separately, but where very thin it has been included with the overlying West Melbury Marly Chalk.

WEST MELBURY MARLY CHALK (c.10 to c.40 m)

This lower part of the Lower Chalk comprises the Glauconitic Marl at the base and that part of the overlying 'Chalk Marl', up to the base of the Tenuis Limestone. Above the base, the member consists of typically rhythmically layered alternations of off-white to creamy marls, greyish chalks and pale grey to brown limestones. The West Melbury Marly Chalk generally gives rise to muddy soils with limestone brash locally present in favourable situations.

ZIG ZAG CHALK (c.20 to c.80 m)

This member includes the Tenuis Limestone at its base and the Plenus Marls at the top, and encompasses the upper part of the Chalk Marl and the Grey Chalk. The thin Tenuis Limestone consists of hard grey fossiliferous chalk with ammonites and the bivalve *Inoceramus tenuis*, after which it is named. Rhythmically bedded marls and limestones (some fossiliferous) continue up to Jukes-Browne Bed 7, a hard gritty chalk, about 2 m thick, marking the base of the Grey Chalk.

The Grey Chalk comprises rather uniform, massive, greyish blocky chalk, with a few thin marls. It is more massively bedded than the Chalk Marl. The Plenus Marls (2 to 4 m thick) at the top include alternations of olive-grey marls and yellowish grey limestones making up the 8 numbered beds of Jefferies (1963).

Sussex White Chalk

HOLYWELL CHALK MEMBER (c.20 to 35 m)

The Holywell Chalk member includes the beds between the Melbourn Rock to immediately below the Glyndebourne Flint. It comprises hard gritty nodular chalk with abundant shell debris and with greyish green wispy (or flaser) marl seams separating the nodules. In East Sussex the Melbourn Rock is about 2.7 to 4.0 m thick, comprising seven to nine nodular beds separated by more marl-rich layers. The Melbourn Rock conventionally marks the base of the Middle Chalk, and usually forms a prominent feature on the primary escarpment of the South Downs (see Figure 10) (Young and Lake, 1988). It and the remainder of the Holywell Chalk give rise to typical soil brash of rough nodular appearance.

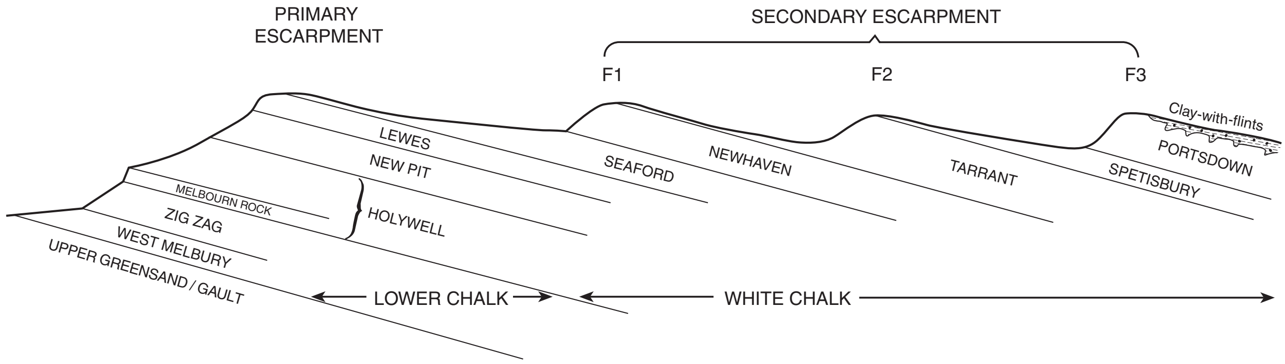


Figure 10 Schematic cross-section showing relationship of lithostratigraphical members of the Chalk Group to topographic features (after D T Aldiss).

The nodular beds are surprisingly impersistent, often cutting out within a few metres laterally only to reappear a few metres distant. This is displayed well in cliff sections at Beachy Head. The nodular chalk of the Melbourn Rock is quite different from the hardgrounds of the Lewes Chalk, both in texture and in the degree or depth to which synsedimentary hardening has occurred. This is probably due to the activity of a specific range of benthonic organisms which in turn may be related to depth and rate of sedimentation. It is the welding together of the nodular chalk and hardground surfaces of the Melbourn Rock that resulted in the formation of this rock band, sometimes of exceptional hardness. As a consequence, fractures tend to be open, giving the Melbourn Rock its character and value as an important aquifer horizon in the Chalk.

New Pit Chalk Member (25 to 55 m)

The New Pit Chalk Member comprises the beds from the Glyndebourne Flint to the Glynde Marls. The Member consists of fairly pure, massively bedded white chalks with pairs or groups of thin but conspicuous marl seams. The chalk is medium hard and gives rise to a blocky or slabby soil brash. Flints occur commonly from within a few metres of the base, but not in great abundance or strong bands. Shell debris is sparser than in the Holywell Chalk.

The Holywell and New Pit Chalk Members were originally described by Mortimore (1986b) as Ranscombe Chalk; in other areas, they are equivalent to most of the Middle Chalk. The outcrops of the Holywell and New Pit Chalk Members, and also the lower part of the Lewes Member, are largely confined to the primary escarpment of the South Downs (Young and Lake, 1988).

Lewes Chalk Member (c.35 to 80 m)

The Lewes Chalk contains many more cyclic rhythms than the New Pit Chalk, each comprising a series of alternations of soft to nodular chalks culminating in a major sedimentary discontinuity such as a hardground. The hardground known as the Chalk Rock, which is taken to mark the base of the Upper Chalk in the Chilterns and Kent, is not clearly developed in Sussex, being replaced by coarse, gritty, nodular chalks. The termination of the Glynde Marls provides the marker for the major change in sedimentation that occurred at the base of the Lewes Chalk; above this horizon regular seams of nodular chalk and flint are found, and the junction between the New Pit and Lewes Chalk Members is taken as the incoming of hard nodular chalks. The junction with the overlying Seaford Chalk is taken as the top of the Shoreham Marls.

The Lewes Chalk is resistant to weathering and underlies the steepest slopes at the top of the primary Chalk escarpment (Figure 10), giving rise to a rough rubbly soil brash.

Seaford Chalk Member (50 to 80 m)

There is a marked change in lithology from the nodular and flinty Lewes Chalk to the purer and softer Seaford Chalk. Its base is taken above the upper Shoreham Marl, and the top at the base of the lowest of the Buckle Marls. Named from the cliff sections at Seaford Head, this member comprises soft chalk with frequent regular courses of large flint nodules, some of which are so closely spaced as to form conspicuous ‘semi-tabular’ bands. Some marl seams and nodular chalks occur in the lower part. It approximates to the *Micraster coranguinum* Zone chalk of the older literature.

Newhaven Chalk Member (40 to 76 m)

Geophysical logs and lithological sections indicate a marked change from the relatively simple and featureless Seaford Chalk to the Newhaven Chalk with its numerous marl seams. The base of the member is taken at the base of the lowest Buckle Marl, and the top above the upper Castle Hill Marl. The Newhaven Chalk is characterised by nodular chalks and sponge beds, with well-developed nodular flint courses also present. It shows considerable variation in thickness and lithology, with marl seams most strongly developed in the thicker sequences. The secondary escarpment of the South Downs west of the Adur is related to the change in lithology between the Seaford and Newhaven Chalks.

Tarrant Chalk Member (35 to 45 m)

The base of the Tarrant Chalk Member is marked by the upper Castle Hill Marl. The Member comprises soft, white homogeneous chalks with nodular flint courses; marl seams are absent except in the basal few metres. Locally channels with hardgrounds and phosphatic chalks may occur.

Spetisbury Chalk Member

This member includes soft white chalks with flint courses, generally similar to the Tarrant Chalk. Its upper boundary is marked by the base of the Portsdown Marl. Together the Tarrant and Spetisbury Chalk members approximate to the Culver Chalk member of Mortimore (1986b).

PORTSDOWN CHALK MEMBER (over 30 m)

This is the highest member of the Sussex Chalk sequence and has been largely removed by pre-Palaeogene erosion. Its base is marked by the Portsdown Marl. It comprises white chalks with marl seams and sporadic flint courses. Locally it may be overlain by clay-with-flints, a residual deposit of the earliest Palaeogene rocks.

GEOPHYSICAL LOGGING OF THE CHALK

Geophysical logs have been run in most of the Chalk boreholes in the South Downs mainly by Southern Water and Southern Science, but with a small number by the British Geological Survey and the WRC. Records of the geophysical logs are kept by the Environment Agency Southern Region, and the British Geological Survey.

Several boreholes are relatively deep and have saturated thicknesses of Chalk in excess of 200 m, so that resistivity logs of much of the Chalk sequence have been recorded, e.g. at Climping, Goldstone, Hammerpot, Kingston Middle Road, Kingston Stony Lane, Portslade, Shripney, St Peters Church and Victoria Gardens boreholes. The logs of these boreholes and several newly acquired boreholes logs are listed in Appendix 2. Some of the boreholes logged for this study proved to be unexpectedly shallow compared with the original drilled depth; for example boreholes at Stoughton, Bow Hill at 121.1 m (drilled 186 m), Clapham 2 observation borehole at 118 m (drilled 152.4 m), and the East Dean Oxen Down borehole at 111.5 m (drilled 164 m). In each borehole, the obstructions were soft, and were assumed to be marls which had squeezed into the borehole.

Resistivity, gamma ray, and caliper measurements were made in selected boreholes spanning the whole of the Chalk Group, and are illustrated in Figure 11.

Geophysical log correlation

Gray (1958, 1965) was the first recognised that the distinctive profiles of electrical resistivity logs of the Chalk could be used for correlation purposes, and could also be used to define stratigraphic 'marker bands' for the Chalk of southern England. He used them to identify the Glauconite Marl, the Melbourn Rock and the Chalk Rock, and to classify the borehole sections into the traditional Lower, Middle and Upper Chalk. In the absence of named lithology, other distinctive and consistent resistivity marker peaks and lows were identified by a letter code. During the period 1950–1982 the British Geological Survey undertook resistivity logging (much with point reading equipment) and gamma ray logging of many Chalk boreholes in the London Basin and southern England, which demonstrated that the logs could be used to correlate the Chalk over long distances (Murray, 1982). Subsequent logging in Norfolk, Lincolnshire and Yorkshire extended the correlation as far north as Flamborough Head (Murray, 1986).

Resistivity logs of the Chalk show a surprising consistency of response over long distances. Similar profiles can be recognised in boreholes tens and hundreds of kilometres apart, from Humberside to the south coast, and into the Paris Basin, and allow the lithostratigraphic units to be mapped. The uniformity of the profiles is due to the fact that the Chalk is a marine deposit, is of biogenic origin, is relatively monomineralic, and has laterally extensive hard bands of distinctive high resistivity and marl seams of low resistivity. Correlation of the Chalk log profiles is largely simple pattern recognition. However, detailed examination of logs reveals that individual units change thickness and character laterally. Particular differences are evident in logs from shelf and basin areas, where sequences may be condensed. Furthermore, there is a risk of mis-correlation with many thin and similar beds. In this respect, resistivity logs are not always the optimum measurement, and correlation is more reliable when several different log measurements are used. It is important for log comparison that the log start datum is clearly referenced.

An example is given in Figure 11, which shows focused resistivity, gamma ray and caliper logs in the Zig Zag to Seaford Chalk in St Peters Church (TQ 3150 0490) and Victoria Gardens (TQ 3140 0460) boreholes in Brighton, together with the lithostratigraphy given by Mortimore (1986). The Plenus marl is an obvious key marker at 182 and 190 m depth respectively and it is evident the log profiles are similar in both boreholes. The Chalk Rock sequence is 30 m thick and comprises a series of distinctive marls (Glynde, Caburn, Southerham, Bridgewick and Lewes) with thin hard rock bands.

Gamma ray logs pick out the thicker marl seams in the chark such as the Plenus Marl and the Glauconitic Marl, but not the very thin seams. Increased gamma activity is seen at hardgrounds because of associated glauconite and frankolite.

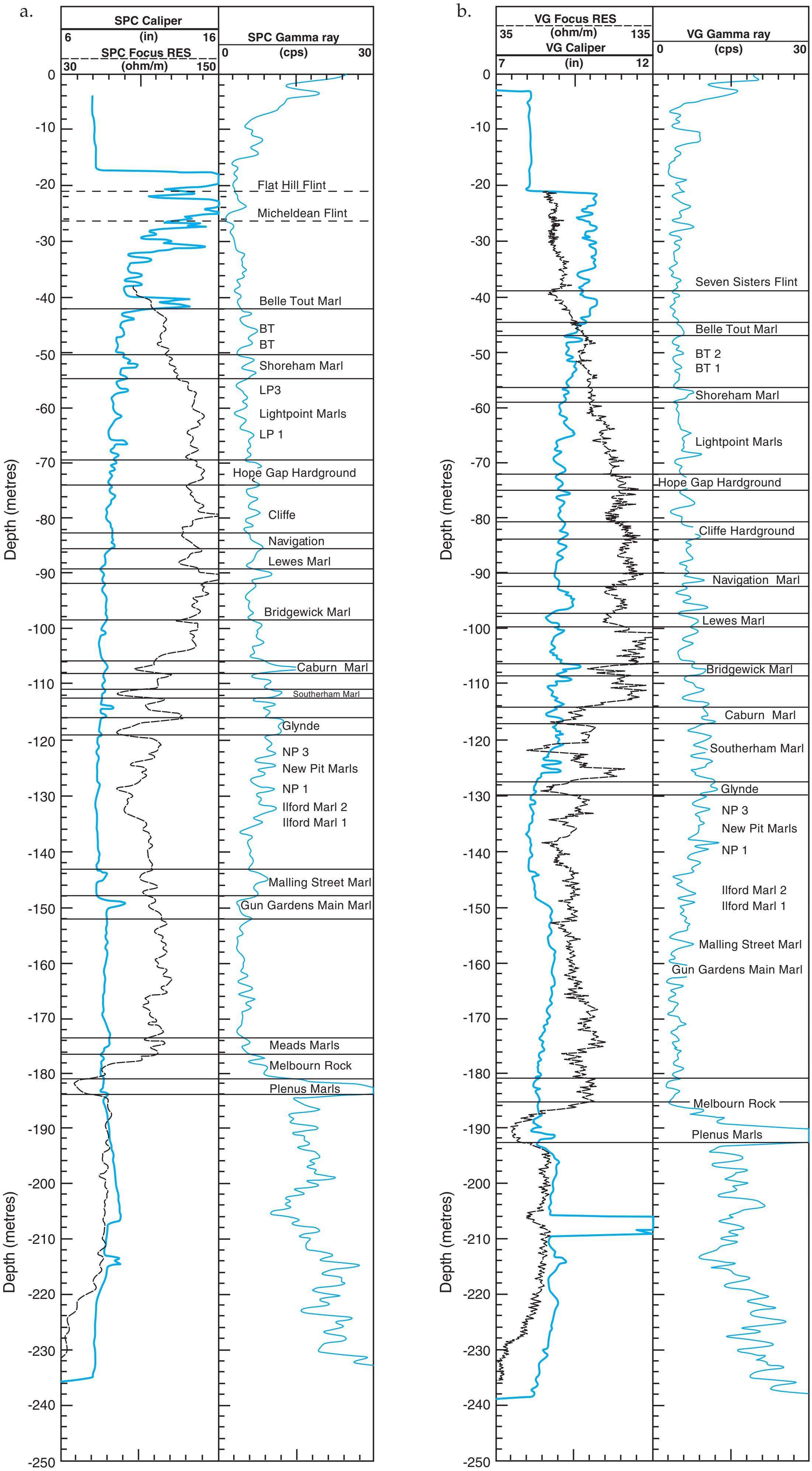
STRUCTURAL SETTING

The Chalk is intersected by a complex system of fractures that formed as a result of movements taking place from intra-Cretaceous to Quaternary times, with later joint development frequently exploiting earlier joint systems.

The Chalk sequence of southern England extends from Sussex into Wessex, dipping gently to the south, and thickening generally towards the south-east. To the north on the London Platform and to the south-west, in south-east Hampshire and Dorset, the sequence is attenuated. The broad form of the Anglo-Paris basin is indicated by contours on the Variscan basement (Mortimore and Pomerol, 1987, fig. 22), showing that the main trough occupies the Sussex–Dieppe area. The subsidence history of the basin is complex, with fairly continuous, rather than episodic, tectonic activity.

The stress pattern affecting the Chalk during deposition and during the Palaeogene, was the outcome of the north-westerly pressure of the African plate against Europe and the south-easterly pressure of the North Atlantic spreading ridge. Non-parallel shear in the local

Figure 11 Resistivity, gamma ray, and caliper logs for a. St Peter's Church and b. Victoria Gardens boreholes.



stress field was induced by basement fractures. These were either compressional or tensional, depending on geographical location. Hence, each part of the Chalk aquifer had an individual stress regime, which changed with time. The main uplift in south-east England produced the Wealden Anticline but numerous subsidiary folds developed including the Chichester Syncline and its associated anticline (the Portsdown Anticline in the west, becoming the Littlehampton Anticline in the east). The Chichester Syncline extends from Worthing to Chichester (Figure 12) and shows the same asymmetry as the Wealden structures with a gently dipping south limb (2–3°) and a steeply dipping north limb.

Much of the fracture pattern was imposed on the Chalk during the Palaeogene and Neogene. Two systems of mesofractures are related to the folds and flexures of early Oligocene to early Miocene times. The oldest of these strike east–west and are linked to an episode of north–south compression. The youngest strike mainly north–south or east–west but include some that strike obliquely to these directions. These are related to both east–west and north–south extension (Bevan and Hancock, 1986)

A later prominent system is a series of north-west-trending meso-fractures of Neogene age. The principal form of these fractures is a single set of vertical extension joints, but other types occur including conjugate sets of shear joints and normal meso-faults. They are considered to have formed as a consequence of north-east to south-west regional tension during the late Neogene phase of the north-west to south-east Alpine convergence. A system of orthogonal north-east-striking, vertical or steeply dipping cross-joints were formed after the north-west system during a phase of stress relaxation.

In the exposed Chalk of the South Downs, the regional gentle southerly dip is interrupted by east-west folds related to basement structures and the inversion of the Weald. The surface structures are related to a regional pattern of joints and fractures (Cawsey, 1977), which are significant to groundwater movement in the aquifer. There are six main fracture sets in the Chalk of the South Downs oriented at 012°, 038°, 058°, 112°, 138° and 158° to true north. Marsh (1993) concurred with these observations using satellite imagery. The fractures are shear and tensional sets on the main Wealden fold, with additional shear fractures on the secondary folds (Price, 1966).

En échelon folding in the South Downs, reflects the reactivation of basement structures, and preserves progressively higher stratigraphic sections in the Chalk beneath the Palaeogene erosion surface (Mortimore and Pomerol, 1991). Consequently the stratigraphical level of the Palaeogene erosion surface, from north-east to south-west, is:

1. in the base of the Culver (base Tarrant) Chalk in the Caburn Syncline at Falmer;
2. at the boundary between the Sompting and Whitecliff Beds in the Culver Chalk (probably Tarrant–Spetisbury boundary) in the Brighton Syncline at Shoreham Harbour;
3. in the high Culver Chalk east of the Adur in the Chichester Syncline but west of the Adur it is in the Portsdown Chalk or higher;
4. in the Portsdown Chalk or above to the west of Worthing in the Solent Syncline.

This structural arrangement results in the preservation of a thicker prism of chalk in West Sussex and south Hampshire than in East Sussex. It also results in different types of chalk, in terms of matrix porosity and fracture style, intersecting the ground surface. There is very limited information on the highest chalks in West Sussex and no complete field section or borehole through this chalk.

The structure also influenced Palaeogene sedimentation with sandy and lignitic deposits (Woolwich Formation) at the base of the Palaeogene east of Worthing, but clays (Reading Formation) west of Worthing. These differences are reflected in dissolution pipe-fills and may have had an influence on development of karst in the Chalk. For example, the lignitic and pyrite-bearing deposits at Newhaven and Shoreham Harbour have weathered yielding sulphuric acid which, combined with calcium carbonate in the shelly beds of the Palaeogene, has produced gypsum which can also be found in the underlying chalk (Mortimore, 1979). The

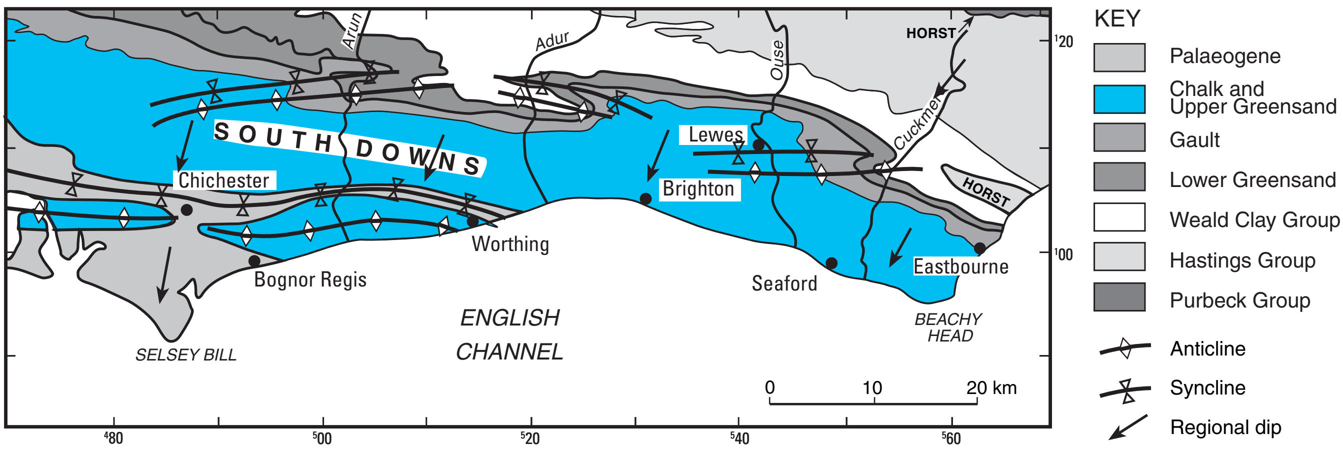


Figure 12 Main structural elements of the South Downs area.

karst processes are most active along the margins of the preserved Palaeogene deposits, particularly in the synclines, for example at Fontwell near Chichester.

SEDIMENTOLOGICAL VARIATION IN THE CHALK OF THE SOUTH DOWNS

The Chalk was deposited in a range of depositional environments, which produce both lateral and vertical variations in the sedimentary sequence. The different environments reflect the interplay between the major transgressive and regressive phases in the Upper Cretaceous and the local tectonic uplift and subsidence (Hancock, 1975; Mortimore, 1986a; Mortimore and Pomerol, 1987; Mortimore and Pomerol, 1991; Gale 1980). Chalk sedimentation, in the southern England depositional province, took place in a broad basin with an axial trough running close to the northern margin of the South Downs of East Sussex and through Winchester and Salisbury to the west (Mortimore, 1983). East Sussex was the scene of maximum variation in depositional thickness. Isopachyte maps prepared by Mortimore (1983, fig. 3) demonstrate the presence of broad swells or shoals on the western and northern margins of the basin, and also, on a smaller scale, the presence of periclinal and trough-like structures in the South Downs area to which thickness and lithological variations are linked (Mortimore, 1986a, fig. 3.20). For example, thinner sequences are found along the East Sussex coast and two areas of thicker chalk occur in the Palaeogene Neville trough and in the axis of the Caburn Syncline (Figure 13).

Seismic profiles carried out in the search for hydrocarbons reveal a close relationship between these structures and those in the basement rocks (Mortimore and Pomerol, 1991, fig. 5). The major tectonic axes that originated as the Variscan structures, and were reactivated in Upper Cretaceous (and, later, in Palaeogene times), have had a profound influence on sediment thickness and type, both locally and basin-wide. The major movements of basement fractures are reflected in *en échelon* fold lines in the cover rocks, including the Chalk, and the tectonic axes are the locus of unusual chalk sediments. The resulting sedimentary bodies are often lozenge-shaped reflecting the nature of the fold belts overlying the Variscan fault systems (Figure 13). Sections across these sedimentary bodies show marginal wedges of sediment offlapping against a tectonic high. These changes in sediment thickness and type can be identified in the geophysical log responses, and in fracture styles (Mortimore et al., 1990).

Peaks of regressive phases are closely associated with the development of rock beds, such as the Melbourn Rock, the lower part of the Lewes Chalk and the hardgrounds in the Newhaven Chalk. Where shallow-water conditions existed, cementation at depths of 0.35 to 1 m below the sediment–water interface led to the formation of hardgrounds which in due course became a more-or-less continuous bed of lithified chalk. Sea-bed erosion reduced these beds to rocky hardground or conglomerate (Hancock, 1993) which was commonly glauconised and/or phosphatised (Bromley, 1967; 1975).

Marl seams generally persist over wide areas and appear to represent major events, reflecting the overall stability of pelagic sedimentation during the Upper Cretaceous. However, on a local scale, they are frequently absent over synsedimentary highs. They have been attributed to early dissolution of calcium bicarbonate

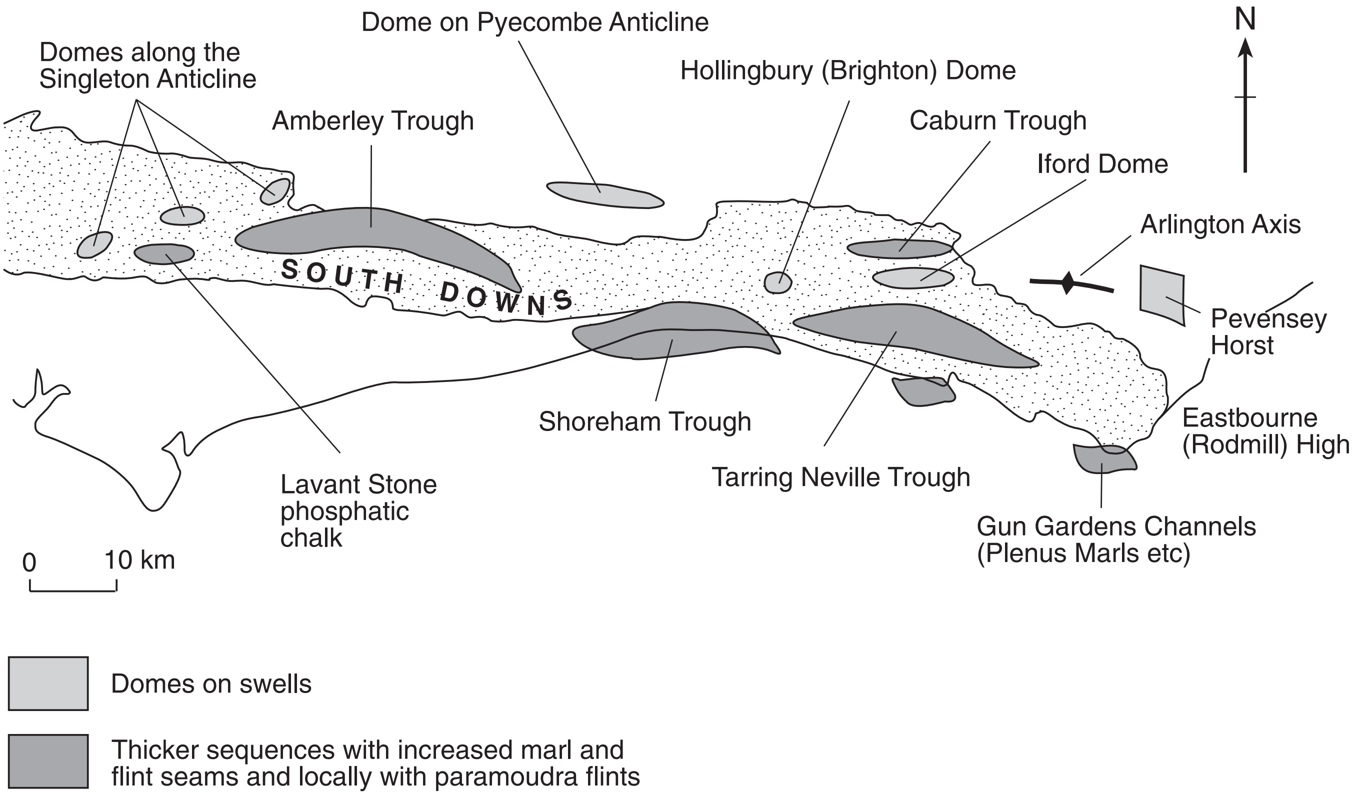


Figure 13 Shape of sedimentary bodies in the South Downs Chalk.

(Curry, 1982), although other workers (Pacey, 1984) attribute marls to airfall ash deposition. Their absence in Chalk units deposited under shallow-water conditions is believed to be due to the reworking of the sediment.

For example, tectonic axes such as the Kingston Anticline and Hollingbury Dome, Brighton, are the locus of maximum changes in thickness and sediment type; up to 50% thinning of the Newhaven Chalk occurs across the Hollingbury Dome, but the marl seams are locally absent. Hard grounds are well developed on these structural highs, reflecting the shallow-water depositional conditions and reworking of the sediment.

Periods of sea-level rise led to a blanket cover of the region by chalk units such as the Portsdown Member, which was deposited across the South Downs. In contrast regressions led to scouring or channel formation over structural highs such as at the base of the Lewes Chalk, the Melbourn Rock, and the Southerham Grey Pit Channel at Lewes, Sussex.

Mortimore and Pomerol (1991) drew attention to a number of sedimentary anomalies which can be interpreted as evidence for synsedimentary tectonic activity. The anomalies include channelling and other erosional features, the local development of hardgrounds over positive features with condensed sequences, intraclastic conglomerates, slumping, and the shattering of flints soon after their diagenetic formation. Without the grain-binding characteristics of silicate sediments, the chalk is relatively unstable and 'mounds', slumps, calciturbidites and related scour channels are easily generated. Examples include the rafted slump sequence on the flank of the dome in the Wallington Syncline (Gale, 1980), but conglomeratic layers and 'powdery' chalks are also common, for example those at Pankgrove and Bedhampton. Slump scars and shatter beds occur in the basal Coniacian at Seaford Head and major scour channels can be recognised along the Kingston Anticline, in the Cenomanian and Turonian at Southerham, Lewes.

The local and regional patterns in chalk sedimentation greatly influence the hydrogeology of the Chalk. This significance has only recently been appreciated, and is, as yet, not fully understood.

MATRIX POROSITY, INTACT DRY DENSITY AND STRATIGRAPHY

It is generally accepted that chalk porosity varies with stratigraphy (Price, 1987, table 1). For example, the Lower Chalk typically has a porosity of 20 to 40%, the Middle Chalk 30 to 40% and the Upper Chalk typically has a porosity of 28 to 48%. In the purer chalks low porosity values are associated with nodular and hardground bands, for example the Melbourn Rock is typically between 16 and 18% and the cemented calcisphere rocks of the Lower Chalk are between 14 and 18%. Lower porosity values of <15% are representative of the clay rich, marly chalks in the West Melbury and Zig Zag Chalk Members of the traditional Lower Chalk. Table 4 shows that chalks with similar porosity and density (intact dry density) can have quite different values of hydraulic conductivity and intrinsic permeability (Mortimore, 1979).

Intact dry density can be used to subdivide chalk samples into soft, medium hard and very hard, categories which in turn relate to pore throat diameter. Table 5 shows that median pore throat diameter may not be the most useful parameter to illustrate variation with intact dry density. The 10 to 90% range shows that the majority of the pore throat diameters of the softer chalks fall within a much narrower range than for the harder chalks. The data also show that pore throat diameters have the greatest range in harder, better cemented, chalks possibly because they have a stronger skeletal framework.

The apparent relationship between chalk porosity and intact dry density does not hold for chalk samples from other areas. Masson (1973) provided values for samples collected in France (Table 6). However, the values for porosity and the range of pore sizes do not easily relate to the density scale or other data for the South Downs Chalk, and more information is required on the types of chalk and their textures in the French examples before direct comparisons and contrasts can be made.

The difference in density (hardness) between chalks of the North and South Downs is illustrated in Figure 14 using intact dry density as a classification scale. These differences are significant to the contribution made by various layers of chalk to groundwater flow and the salinity of pore-water as they influence the contribution of groundwater movement in the matrix. The differences in hardness not only have an influence on the mechanical properties of the Chalk but also influence fracturing and dissolution. Consequently the aquifer properties of the South Downs Chalk relate strongly to the stratigraphical and lateral variations in intact dry density and porosity.

FRACTURING

Several factors influence fracturing in the Chalk including tectonic effects and lithological controls (for example, the presence or absence of marls, and alternations of hard and soft chalk).

Tectonic setting

Fracture styles are partly determined by tectonic setting (e.g. Middlemiss, 1983). These can be classified in the South Downs as follows:

1. Belts of intense vertical fracturing (e.g. Seaford Chalk in the Seven Sisters coast section and the A27 Patcham Cuttings, Brighton Bypass (Mortimore, 1993));

2. Low angle thrust joints in folds (e.g. New Pit and Lewes Chalks at Cliffe Industrial Estate, Southerham Lewes);

3. Steeply angled (dipping 60°–70°) shear joints with a zone of intense fracturing between the fracture planes. This fracture style has only been observed on the Portsdown Anticline in the South Downs, although it has also been observed on the Windsor Anticline.

Lithological controls

There is a significant difference in fracture style between chalks with marl seams (e.g. New Pit and Newhaven

Table 4 Porosity and permeability characteristics of the matrix of the White Chalk.

Hardness	Dry density (Mg m^{-3})	Specific gravity	Hydraulic conductivity (md^{-1})	Intrinsic permeability (mD)	Effective porosity %
Soft	1.61	2.71	0.27	4.26	40.40
	1.61	2.70	0.45	7.04	40.33
	1.64	2.71	0.33	5.19	39.32
	1.65	2.71	0.44	6.87	38.86
	1.66	2.71	0.46	7.08	38.66
	1.68	2.70	0.26	3.31	37.93
Medium	1.72	2.71	0.30	4.65	36.55
	1.73	2.71	0.21	3.25	36.15
	1.76	2.70	0.15	2.40	35.06
Hard	1.96	2.71	0.46	7.10	27.62
	2.10	2.71	0.17	2.59	22.36
Very hard	2.28	2.67	0.67	10.46	14.63
	2.32	2.68	0.42	6.46	13.27
Hardground + burrows, Hope Gap Beds (Early Coniacian)				7.47	36.75
Less burrowed Chalk in Hope Gap Beds				5.41	36.58

K = Hydraulic conductivity (pure water, 10° C) m d^{-1}

k = Intrinsic permeability to a non-reactive liquid, millidarcys mD

SG = Specific gravity

Table 5 Mercury-intrusion pore-throat size distribution compared with hardness and intact dry density.

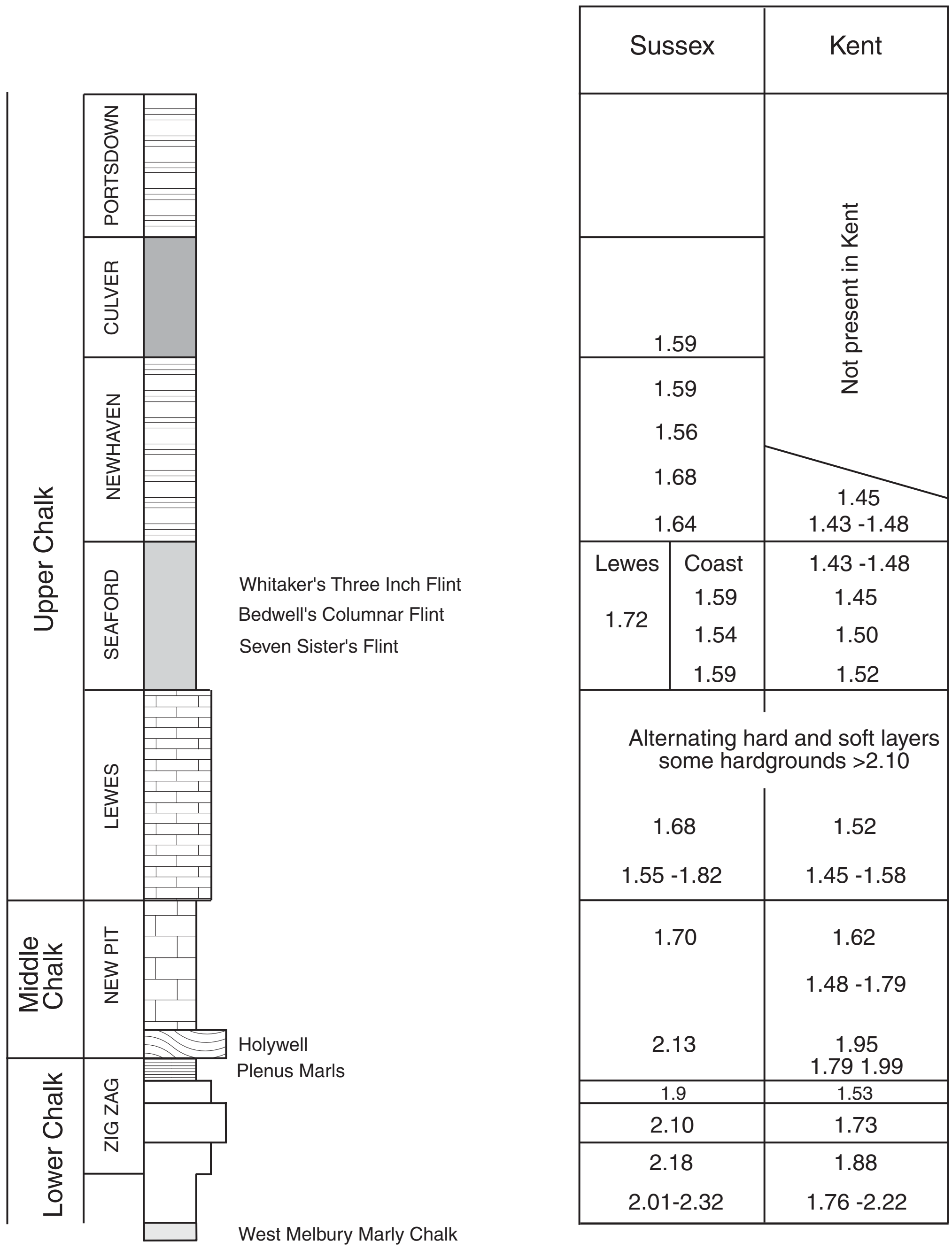
Hardness	Density (Mg m^{-3})	Median pore diameter (µm)	Pore throat diameter (µm) 10–90% range	Total range of pore diameter (µm)
Soft	1.61	0.61	0.34–0.80	0.012–98
	1.61	0.69	0.36–0.80	0.012–98
	1.64	0.68	0.35–0.84	0.012–98
	1.65	0.70	0.35–1.0	0.012–98
	1.66	0.60	0.32–0.78	0.012–105
	1.68	0.70	0.31–1.1	0.012–104
Medium	1.72	0.64	0.30–0.79	0.012–100
	1.73	0.59	0.31–0.79	0.012–98
	1.76	0.58	0.21–0.80	0.012–100
Hard	1.96	0.49	0.19–0.95	0.012–99
	2.10	0.30	0.15–0.39	0.012–98
Very hard	2.28	0.54	0.13–1.7	0.01–98
	2.28	0.84	0.21–1.8	0.012–100
	2.32	0.76	0.18–1.8	0.012–100

Table 6 Chalk porosity and intact dry density for earthworks performance (after Masson, 1973).

Hardness	Density (Mg m^{-3})	Porosity (%)	Median pore diameter (µm)	10–90% pore-size range (µm)	Location	Earthworks performance	Stratigraphical position
Extremely soft	1.50	39.1	0.75	0.38–1.60	Sauqueville	Very bad	C/E
	1.51	43.8	0.45	0.24–0.58	Le Catouillage	Very bad	C/M
	1.52	42.5	0.55	0.35–0.85	Pacy-sur-Eure	Very bad	S/L
Very soft	1.57	40.9	0.73	0.38–1.40	Rouvray		
	1.57	42	0.33	0.15–0.42	Saint-Cloud	Very bad	Ca/L
	1.59	41	0.61	0.36–1.50	Incarville	Bad	Ca/E
	1.59	40.3	0.45	0.25–0.70	Morval	Bad	C/M
Soft	1.60	23.6	0.32	0.08–0.70	Belbeuf	Good	T
	1.64	41.5	0.38	0.18–0.62	Combles	Bad	C/M
	1.69	35.2	0.28	0.07–0.40	Trith-St-Leger	Good	T/L
Hard	1.82	30.2	0.22	0.07–0.33	Feuilleres	Very good	S/M

Stratigraphical position of road contract: T = Turonian, C = Coniacian, S = Santonian, Ca = Campanian
E = Early, M = Middle, L = Late

Figure 14 Comparative intact dry density profiles for the Chalk of Kent (North Downs) and Sussex (South Downs).



Chalks) and pure white chalks without marl seams (e.g. Seaford and Culver Chalks) (Mortimore, 1993). This difference in fracture style is illustrated by the change in lithology and fracturing across the Hollingbury Dome (Figure 15), where the marls of the Newhaven Chalk are absent across the Dome, although they are present on either side of the structure. Across the crest of the high, the homogenous, white chalk exhibits two nearly orthogonal sets of vertical fractures, whilst on the flanks, more frequent, steeply inclined, conjugate fracture sets are present. The lithological control on fracture styles is further illustrated by fracture data collected from excavations across interfluves in the Sussex and Hampshire Downs. Fracture style changes from predominantly steeply inclined conjugate sets in the Old Nore Beds of the Newhaven Chalk to predominantly vertical sets in the Bastion Steps and Haven Brow Beds (Mortimore, 1993).

Chalk lithology also influences the predominance of horizontal or vertical fracture sets. Usually horizontal joint sets are dominant over vertical sets. However, some medium hard chalks have vertical fracture sets more closely spaced and prominent than horizontal sets (Mortimore, 1993). Mortimore observed that subhorizontal joints are common in marly chalks, whereas vertical joint sets are more frequently observed in limestone bands. Both styles of fracturing occur in the weathered zone in the South Downs and exert very different controls on the rate and direction of water infiltrating into the Chalk.

Many hardgrounds and well-developed nodular chalk seams are sandwiched between extremely soft to very soft chalks. These hardgrounds occur either at the bottom of channels (e.g. the Grey Pit Channel and Strahan's Hardground at Southerham, Lewes) or have formed on the crests of mounds. Because of differential

Plate 4 Relatively unfractured Culver Chalk beneath a capping of Palaeogene at Castle Hill, Newhaven. Bypass flow in the Chalk has followed the primary fractures which have been widened by dissolution and are sediment filled (GS 628).

Plate 5 Newhaven Chalk subjected to Quaternary climate weathering near Black Rock, Brighton. The top chalk layers are intensely fragmented and cryoturbated. [A13408].

Plate 6 Seaford Chalk on the east side of the Coldean Road Bridge on the A27 Brighton bypass. Typical 'ice coated' chalk blocks with subhorizontal joints up to 3 mm wide (GS 629).

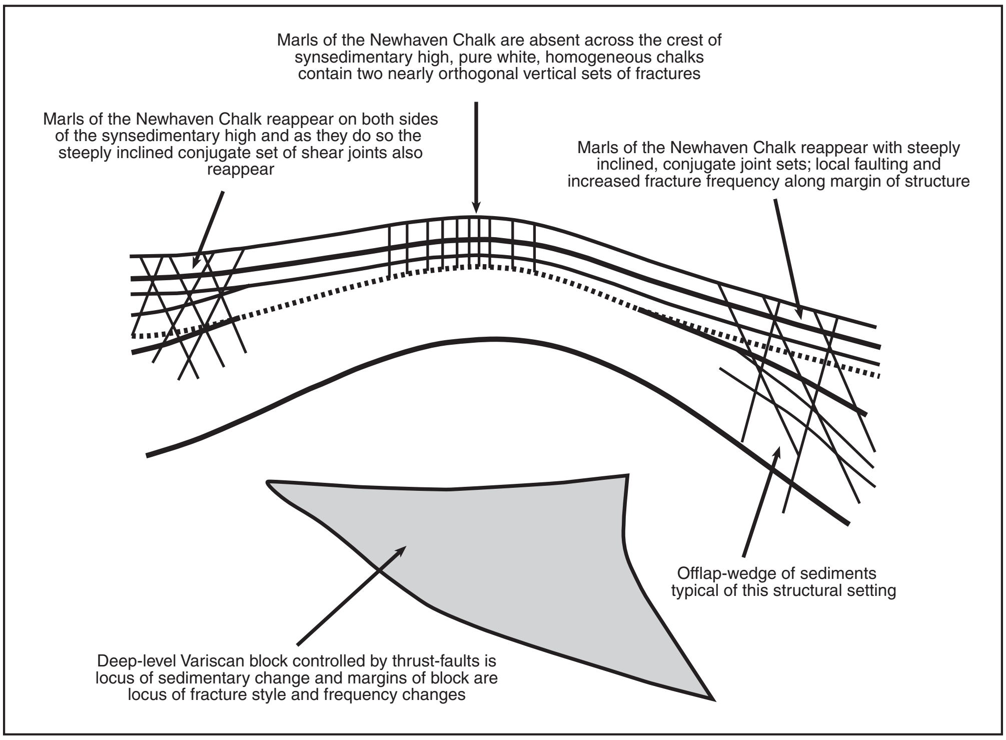
compaction of non-flat lying beds and the variations of competency between layers, the more brittle hardgrounds tend to be more densely fractured (Mortimore, 1979). An obvious example is the Melbourn Rock at Eastbourne, which has fractured rock beds overlying the relatively unfractured Plenus Marls. At this location, adits have been constructed along the fractured Melbourn Rock horizon and Lower Holywell Beds, to exploit this more-permeable, water-bearing horizon.

This is an example of the way in which marls dissipate stresses subhorizontally and fractures have opened in the overlying hardground because of tension. The reaction of the interbedded hard and soft chalks to differential movement throughout the sequence has a significant bearing on the formation of fractures and hydraulic conductivity of the Chalk. An example of intense conjugate fracturing occurs at the boundary between the upper New Pit Beds and the Lewes Chalk. This fracturing not only causes instability in the cliff at the north portal of the Lewes Tunnel but is the cause of a marked break of slope in the Beachy Head Cliffs.

Inland the purer, more homogeneous Seaford and Culver Chalk Members, which do not have marl seams, tend to be more intensely fractured by orthogonal, regular joint sets than the heterogeneous nodular chalks with marl seams of the Lewes and Newhaven Chalks (e.g. Mortimore, 1979; Mortimore, 1990, plate IId). This difference in fracture type and intensity is illustrated between the Lewes and Seaford Chalks in Shoreham Cement Works near Brighton (Mortimore, 1986b).

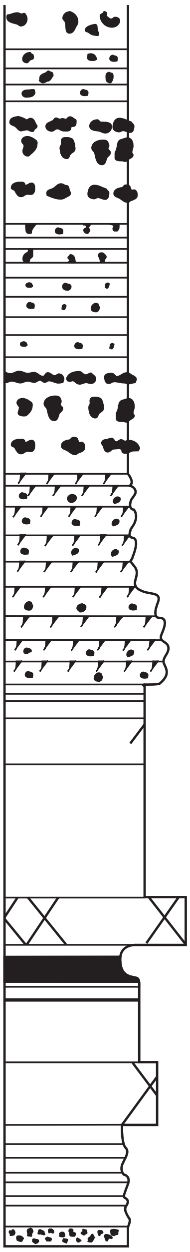
The intensity of fracturing in the different units of the Chalk significantly influences water storage capacity and yield potential (Figure 16). Units of the Chalk with high permeabilities resulting from intense fracturing also have a marked influence on tunnelling operations and slope stability. For example, those parts of the Lower Chalk (Chalk Marl–Grey Chalk) with increased

Figure 15 Schematic profile across the Hollingbury Dome, Brighton, showing lateral changes in the Newhaven Chalk (modified from Mortimore, 1977, 1979, 1983).



numbers of limestone bands and, therefore, relatively increased fracturing (higher permeabilities) have a greater potential for water inflow in tunnelling operations than the relatively less fractured thicker marl units.

The presence of thick layers of highly weathered 'putty' chalk, surrounding intact blocks, or the presence of extensive solution pipes, can have a marked influence on weathering of the Chalk. Dry valleys are frequently infilled with Combe Deposits resting on a deeply weathered, and extensively fractured, profile. In contrast the Chalk along many of the interfluves is tight, for example in quarries at Mile Oak, near Brighton, where inclined conjugate fractures are tight or annealed with sheet flints.



	HARDNESS	FRACTURE FREQUENCY	AQUIFER POTENTIAL
PORTSDOWN	very soft to medium hard		
CULVER	extremely soft to soft	medium spaced regular joints	high
NEWHAVEN	soft to medium hard except on highs where it is extremely soft	medium to widely spaced conjugate sets of joints with sheet flint	karstic features on marls, local flows
SEAFORD	very soft to medium hard	medium spaced regular joints	high
LEWES	alternating from very soft to very hard, some massive bands	nodular chalk fracturing and widely spaced conjugate joints	mixed; low except on faults
RANSCOMBE	medium hard	medium to widely spaced conjugate joints, Holywell Beds more jointed	locally good where well fractured
MELBOURN ROCK	hard	medium spaced conjugate sets	high
PLENUS MARLS	medium hard	poorly fractured	low
GREY CHALK	hard	conjugate sets	low
CHALK MARL	alternating medium to very hard	poorly fractured	low

Figure 16 Fracturing and aquifer potential in the Chalk of Sussex (after Mortimore, et al., 1990).

Plate 7 Disintegrated chalk beneath a dry valley at Saltdean. The original bedding is defined by harder blocky chalk layers and softer higher porosity layers (GS 630).

3 Hydrogeology

INTRODUCTION

There are many inhomogeneities within the Chalk which control both the distribution of primary fractures, and the extent of dissolution and consequent enlargement of the fractures (Price, 1987; Mortimore, 1993). In addition, small faults, which formed as a result of penecontemporaneous compaction and shearing (Hancock, 1975), have created incipient lines of weakness in the rock. Later diagnetic changes caused by burial, heat and tectonic pressures, accompanied by compaction and solution, have tended to harden the chalk and reduce the porosity of the matrix. As a result of these changes the matrix porosity of the Chalk of the South Downs is in the range 15 to 45% and the hydraulic conductivity is typically 10^{-4} to 10^{-2} m d^{-1}.

The terminology used to describe discontinuities in the Chalk has been discussed at length in the technical literature. Price (1987) recognised two types of fissures—undeveloped, closed discontinuities (primary fissures) and more open, solution-enhanced ones (secondary fissures). There is a range of fracture apertures and discontinuities, and Bloomfield (1994) has rigorously defined these. It is his definitions that are used throughout this report (see Glossary).

Groundwater flow is generally north to south in the South Downs, reflecting the surface topography, the geometry of the various formations, and variations in permeability. The geological structure of the area also has a marked impact on the hydrogeology and hydrogeochemistry. For example, the Chichester Syncline restricts southward-flowing groundwater and diverts it to the east, and the Palaeogene sediments infilling the syncline confine the Chalk groundwater in this area.

There is a perennial spring line to the north of the scarp slope just above the base of the Lower Chalk (Headworth and Fox, 1986). However, the location of springs on the gentler dip slope varies seasonally, giving rise to intermittent streams or bournes. Spring discharges also occur along the coastal margin; a thermal infra-red linescan survey carried out in 1971 identified numerous spring seepages around the low water mark (Headworth and Fox, 1986), particularly on the wave-cut platform to the east of Brighton, and through overlying superficial deposits to the west of the River Adur. Near the coast, and possibly offshore, some upward leakage from deeper and older formations occurs through the Chalk and ultimately to the sea.

The Gault Formation exerts a major influence on flow as it forms the lower, relatively impermeable boundary to the Chalk. The Reading Formation forms an upper boundary in the coastal plain of West Sussex where it acts to confine groundwater in the Chalk. The Quaternary deposits control infiltration to the Chalk and modify shallow flow paths in the aquifer, particularly beneath the Sussex coastal plain. The Quaternary deposits are also a local source of groundwater, which probably provides an important component of the flow to the streams known as the Chichester rifes (see Chapter 7).

UNSATURATED ZONE AND RECHARGE

As the form of the water table is generally a subdued reflection of the surface topography, the thickness of the unsaturated zone beneath the South Downs varies greatly in thickness. Beneath valleys, the water table is shallow and the unsaturated zone is thin (typically 0 to 20 m), whereas beneath the interfluves the water table tends to be deeper, and in some places is over 100 m (Figure 17).

The water table is the level within an aquifer, below which, the pores are fully saturated; the water table is at atmospheric pressure. However, due to the fine-grained nature of the Chalk matrix, and the small size of the pore throats, pore water suctions are high, and the pores cannot fully drain. Thus the chalk matrix remains largely saturated even above the water table. However, as pore water pressures are less than atmospheric pressure, the chalk above the water table is still described as unsaturated. Whilst the matrix cannot drain due to the small pore throat diameters, discontinuities and fractures with significantly greater apertures, are more readily drained.

Water transport through the unsaturated zone of the Chalk

Groundwater flow through the unsaturated zone of the Chalk is complex, comprising both a slow piston flow through the matrix and a more rapid bypass flow through the fractures (Smith et al., 1970; Foster, 1975; Downing et al., 1978; Gardner et al., 1990; Jones, 1992).

Observations and experiments have been undertaken at several sites on the outcrop of the Chalk, although only limited work has been carried out in the South Downs. Measurements of water content and matric potential (negative pressure potential in the unsaturated zone) at West Ilsley [SU 486 834] and Bridgets Farm [SU 517 337] indicated that at depths of greater than 1 m there is virtually no change in water content as potentials decrease from -3 to -70 kPa (Wellings and Bell, 1980; Gardner et al., 1990). Laboratory measurements (Price, 1987) have corroborated and expanded these findings, indicating that approximately 80% of the total porosity

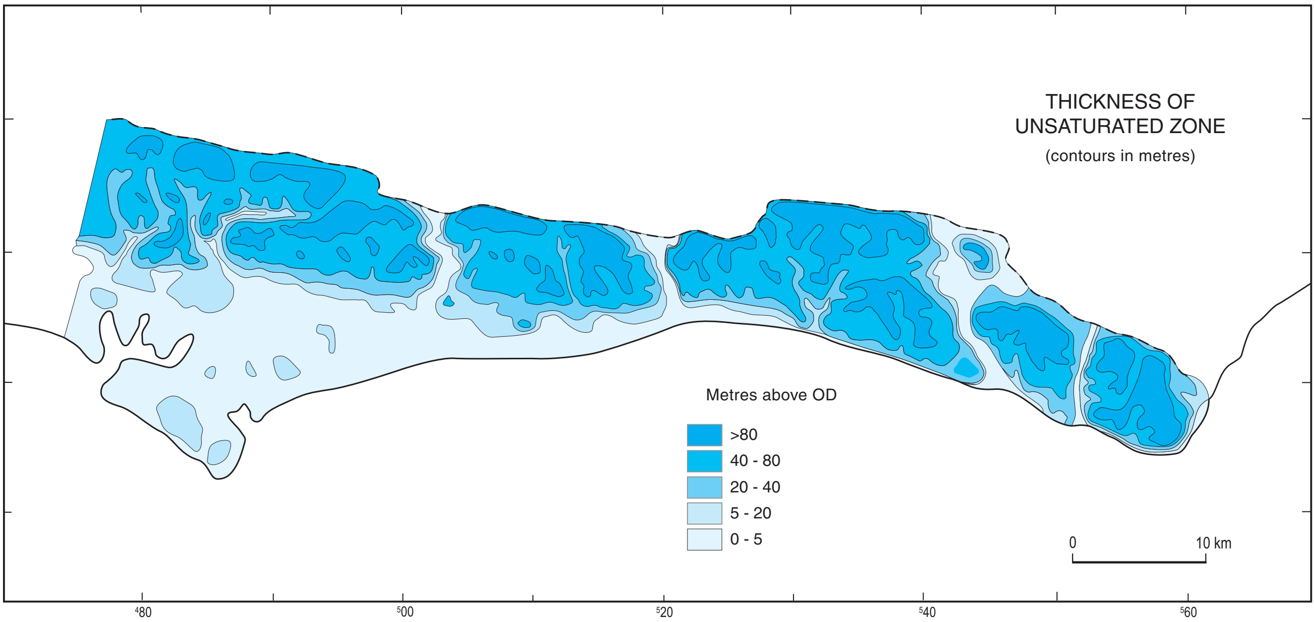


Figure 17 The thickness of the unsaturated zone over the South Downs, calculated using the water levels of March 1993.

can be attributed to pores with a narrow size range, which are interconnected by pore throats of between 0.05 and 1 µm, equivalent to pore water potentials of -300 to -6000 kPa. Water is therefore held very tightly within the chalk matrix.

The hydraulic conductivity of the unsaturated zone of the Chalk has been measured *in situ* at four sites throughout England (Gardner et al., 1990). At potentials of less than -5 kPa the hydraulic conductivity remains fairly constant, from 1 to 6 mm d^{-1}. As the potential rises above -5 kPa (i.e. pore water suction decreases), the hydraulic conductivity rapidly increases, with values several orders of magnitude higher in the range 100 to 1000 mm d^{-1} (see Figure 18). This rapid increase in hydraulic conductivity is caused by the increasing contribution to flow from the fracture network as it becomes saturated. Thus, at potentials less than approximately -5 kPa the fractures are not saturated and the conductivity is that of the chalk matrix, but above approximately -5 kPa, water can move through both the matrix and the fracture system, and the hydraulic conductivity is increased accordingly.

The frequency with which potentials exceed -5 kPa is an important variable which indicates whether rapid groundwater movement and recharge can take place within the unsaturated zone. Estimates of the relative proportion of recharge via fracture or bypass flow compared to the that in the matrix vary from 10 to 30% (Smith et al., 1970; Downing et al., 1978; Reeves, 1979; Foster and Smith-Carrington, 1980; Gardner et al., 1990; Jones, 1992). The Institute of Hydrology monitored potential profiles at various sites over a number of years to try to assess the contribution of fracture flow to recharge (Gardner et al., 1991). The work highlighted variations in recharge mechanisms between locations. Water potentials remained above -5 kPa throughout the majority of the winter months at some of the sites; at others the potential was generally lower than -5 kPa, although exceptional rainfall events increased potentials sufficiently for rapid bypass flow to occur. At sites that did not illustrate fracture flow it was assumed that the Chalk possessed sufficient permeability to enable overlying soils to drain freely throughout the winter without potentials ever having to increase above -5 kPa. In addition, soil, weathered chalk and drift were all thought to be important in buffering the effects of intense rainfall.

Recharge to the aquifer may also occur at any time of the year via large solution features, many of which occur close to the edge of, or beneath, the Palaeogene cover. Where rainfall is sufficient to activate the swallow holes on the Chalk outcrop, groundwater will flow rapidly to the water table.

The Chalk, therefore, appears to have three main components of flow through the unsaturated zone:

- slow 'piston flow' through the matrix
- rapid 'bypass flow' when potentials within the Chalk exceed -5 kPa
- extraordinary 'karst-like flow' which can occur if large solution features are activated.

Recharge studies within the South Downs

The unsaturated zone has been specifically investigated at various sites across the South Downs.

Wigden's Bottom

Work was carried out at Wigden's Bottom [TV 576 969] by the Institute of Hydrology from 1984 to 1986 to monitor quantities and modes of water flow through the unsaturated zone of the Upper Chalk. The site was at the bottom of a steep slope and comprised 0.03 ha, two-thirds of which was covered by Coombe deposits. The soil cover was removed from the site and replaced by 0.2 m of gravel (Gardner et al., 1990). Neutron probe access

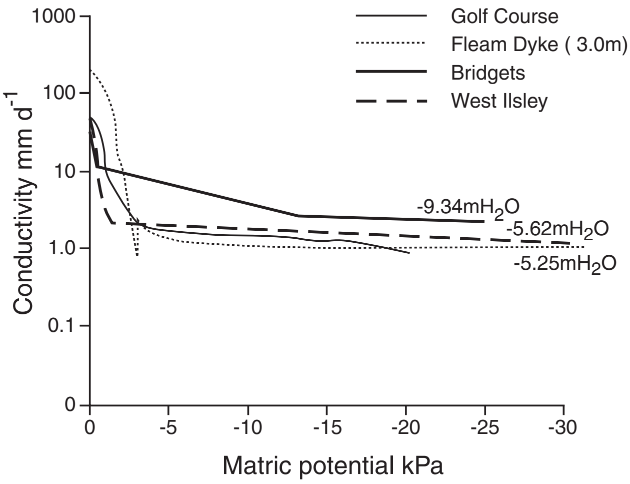


Figure 18 Variations in unsaturated hydraulic conductivity with matric potential measured at 2.1 m below ground surface (after Gardner, et al., 1990).

tubes, pressure transducer tensiometers, gypsum resistance blocks, a raingauge and gravel lysimeter were installed. However, the water balance of the site was severely affected by the removal of the soil cover, evaporation was reduced and drainage constituted 80% of rainfall, emphasising the importance of the soil cover in controlling recharge. The changes in water content in the Chalk suggested weathering of the profile to a depth of at least 2 m. During early 1985 fracture flow was thought to occur below 6.5 m depth, as potentials rose above -5 kPa. Measurements of matrix conductivity from the site ranged from 0.7 to 1.8 mm d^{-1}, increasing with depth. The generally increasing hydraulic conductivity with depth was thought to provide an explanation for the high matric potentials observed at 6.5 m in 1985.

There were two major limitations to work at this site, which should be noted when considering the results. Firstly, the site is located at the bottom of a valley, and run-off from the slope to the north of the site cannot be discounted; besides, considerable quantities of mud were washed onto the site after heavy rainfall. Secondly, the gravel cover over the site was likely to promote lower evaporation losses than would have occurred from a vegetated site. This would prolong the recharge period, and allow summer storms to wet up the profile and cause drainage.

Deep Dean

Hodnett and Bell (1990) undertook a study of water movement through the Coombe deposits at Deep Dean [TQ 536 023] in the Eastbourne Block using weekly measurements of rainfall, soil water content and soil water potential. The drainage flux was calculated using the water balance method in winter and the ZFP method after the appearance of the Zero Flux Plane. Unsaturated hydraulic conductivity was estimated using Darcy's Law and the measured potential gradient and weekly fluxes. There was almost continuous

Plate 8 Beneath the interfluves the chalk is strong enough to preserve Neolithic Flint Mines such as these at Harrow Hill which were re-opened in 1982 (GS 631).

drainage throughout the year below 3 m depth. Mean daily drainage at 2.85 m during the recharge period (October 10 to May 29) was 1.6 mm d^{-1}. Weekly mean rates of up to 3.7 mm d^{-1} were observed, although the profile responded very rapidly to rainfall, and peak short-term rates considerably exceeded this figure. Although the mean hydraulic conductivity was low and comparable to chalk, they found that much of the flux passed through a very small proportion of the wetted cross-section of the soil, giving rise to actual pore water velocities of up to 3 m d^{-1} at 2.85 m and 0.5 m d^{-1} between 0.5 m and 2.5 m depth. As the site was situated on a narrow strip of Coombe deposit, along a valley floor, the results were felt to be specific to this site.

The Water Research Centre monitored the movement of nitrate pulses from experimental farming plots at the same site during the late 1970s (Edwards, 1981). Soil and borehole sampling were used to prepare soil nitrogen mass balances and to study the distribution of nitrates in the unsaturated zone. Nitrate pulses from annual leaching losses were observed to be carried downward in the unsaturated zone predominantly by matrix flow at rates of 2.5–7 mm d^{-1}, and to a lesser extent by fracture flow, though at faster rates of possibly 20 mm d^{-1}. However, the extent to which the nitrate solutes were carried by the two different flow processes described above, and the degree to which exchange could occur between them is unknown. Nevertheless, it is evident that there is scope for rapid transport of solute through the Coombe deposit in such situations.

Brighton Block

Downing et al. (1978) studied tritium concentrations and water levels in three boreholes within the Brighton Block (Patcham, Lewes Road, and Aldrington), in order to study the age and composition of recharging water in relation to rainfall and water level data. Samples of pumped water were analysed routinely on a monthly basis, and after heavy rainfall also at weekly intervals. Figure 19 shows data gathered from one of the boreholes, Lewes Road pumping station [TQ 320 061] between 1973 and 1975. This borehole penetrates beds of the Sussex White Chalk Formation. Unsaturated zone thickness at the site fluctuated between 20 and 40 m bgl, although the unsaturated zone will thicken rapidly away from the borehole which is in the centre of a deep dry valley.

During the winter of 1973–74, tritium concentrations reached their maximum in February, about one month after the water level peak. The following winter showed a more complex pattern. Tritium concentrations increased rapidly during September from a base value of 10 TU to 28 TU, probably in response to eight days of heavy rainfall, and despite a recorded soil moisture deficit, the water levels then started to recover (Downing et al., 1978). The tritium concentrations reached a maximum in early January, again several weeks after the water level high, and remained high until June. Different responses were recorded in the other two boreholes monitored during the study which illustrates the complexity and variability of recharge to the Chalk. However, several conclusions can be drawn:

- The measured increase in tritium concentrations after heavy rainfall points to the existence of rapid flow through the unsaturated zone; Downing et al. (1978) suggested that this constituted 10% of the annual recharge.
- The majority of flow occurs through the larger pores of the matrix and 'micro' fractures. The flow rate is slow enough to allow tritium to diffuse into (and out of, if concentration gradients reverse) the smaller pores of the matrix.
- The tritium values measured in the boreholes during recharge events were higher than those measured in rainfall, implying that recharging water displaces older water lower in the profile by means of piston flow.
- There appear to be two components of groundwater flow: recent water recharged and discharged seasonally, and an older component which constitutes baseflow and contains only a limited amount of recent recharge. Downing et al. (1978) estimated in 1975 that 10% was derived from post-1953 rainfall, and represented rapid recharge through fractures.

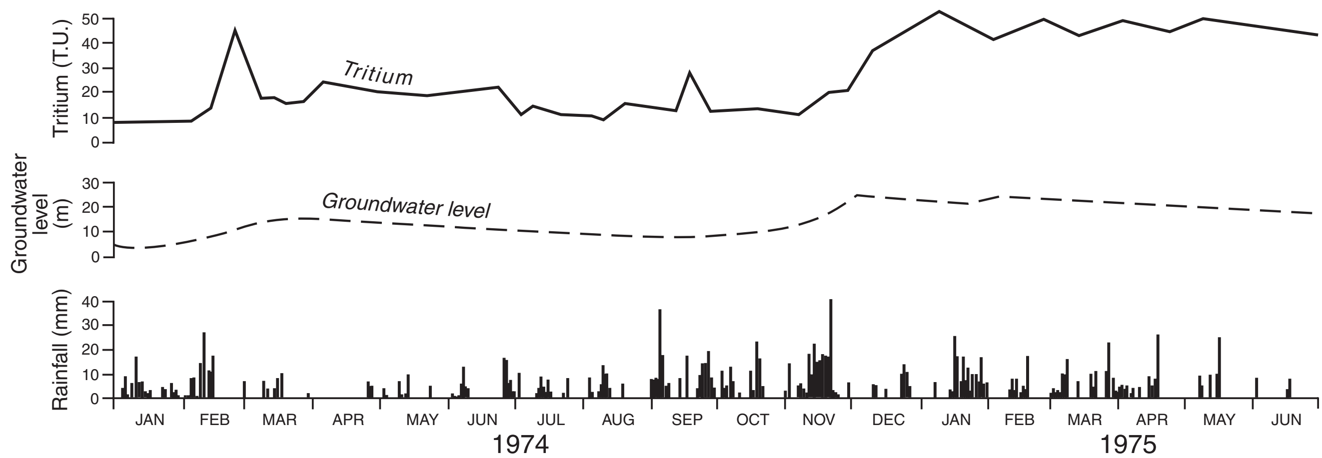


Figure 19 Tritium concentrations and water level data measured in the Lewes Road pumping station (after Downing et al, 1978).

This study also provided some evidence that recharge was occurring through large fractures and swallow holes in the area. In the Patcham Borehole [TQ 294 091], for example, bacteriological contamination is present less than 24 hours after heavy rainfall (Downing et al., 1978), and a tracer study carried out between a series of sinkholes and springs 5 km apart near the Bedhampton Springs proved a direct connection with turbulent flow through a discrete conduit system. The actual groundwater velocity was calculated at 2 km d^{-1}.

It is evident that recharge mechanisms vary considerably across the South Downs. These case studies illustrate the importance of investigating recharge processes through the Chalk and the overlying deposits, and highlight the possible dangers of extrapolating results from one area to another.

Water levels and climatological data

Water level data for the months March and September 1993 represent the highest and lowest water levels measured during the year (Figure 20). The water levels tend to a subdued version of the surface topography. Hydraulic gradients, and therefore groundwater flow,

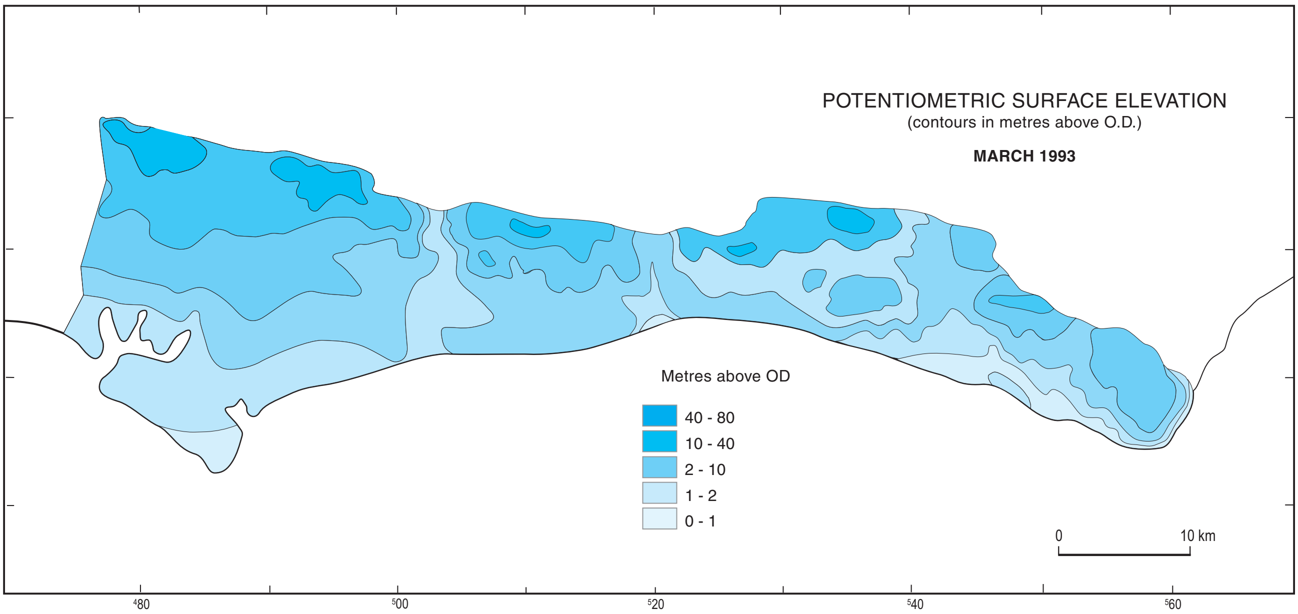


Figure 20a Potentiometric surface elevations within the Chalk of the South Downs: March 1993 (based on data provided by Southern Science).

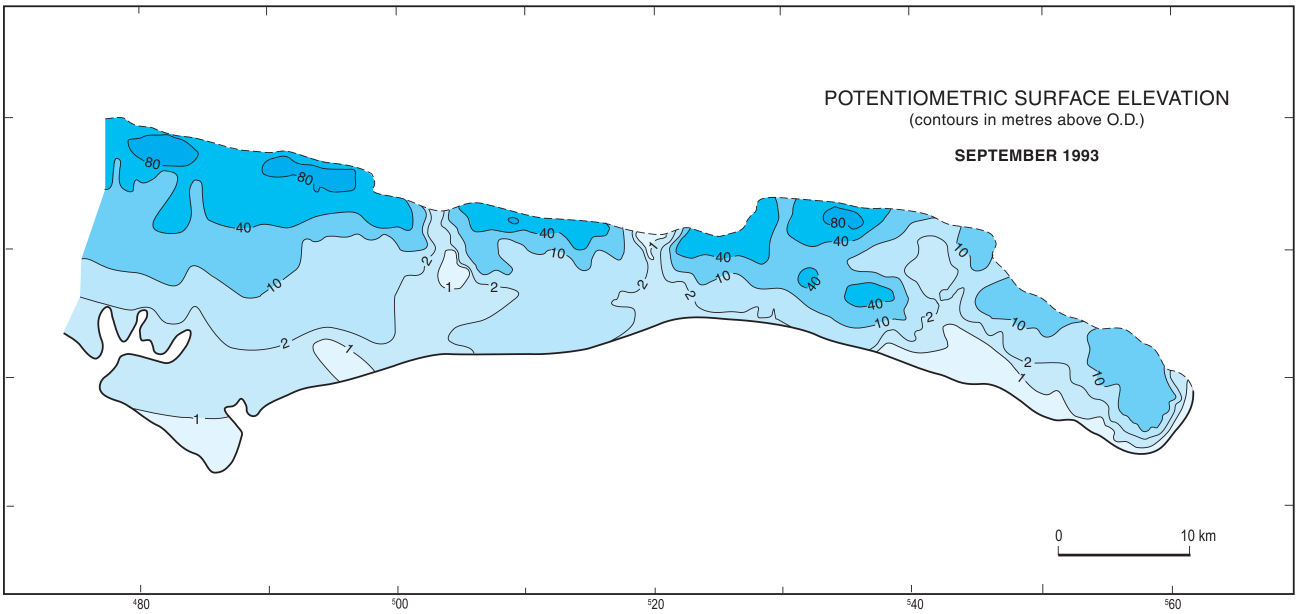


Figure 20b Potentiometric surface elevations within the Chalk of the South Downs: September 1993 (based on data provided by Southern Science).

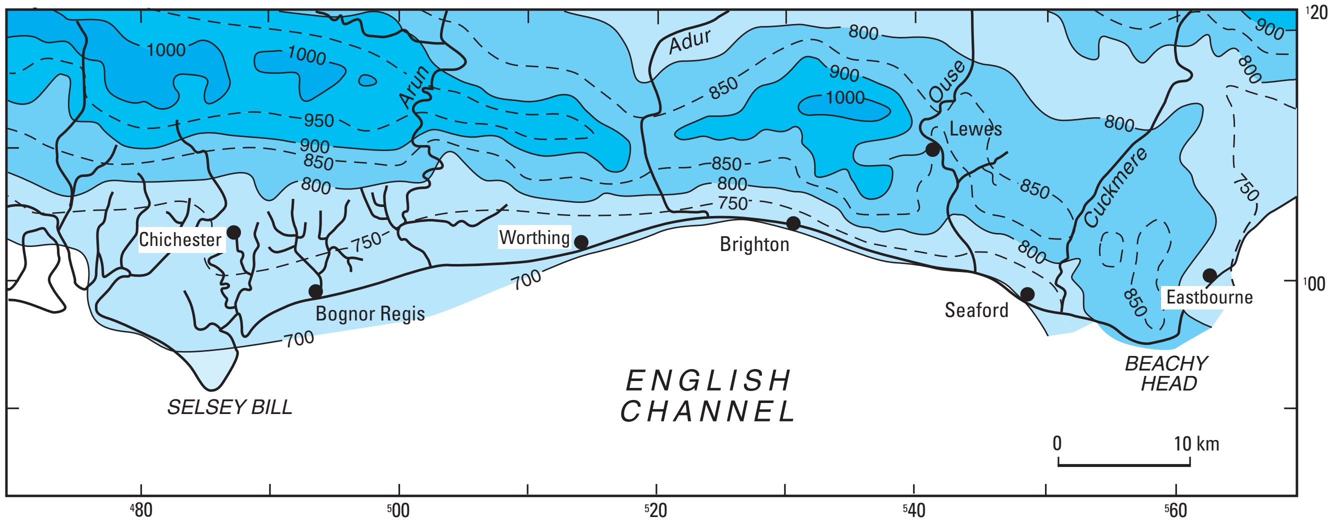


Figure 21 Average annual rainfall (mm) for the South Downs, 1941–70 (data from the Meteorological Office).

are generally towards the coast with subordinate flow towards individual rivers, although gradients are locally modified by topography, structure and pumping.

Comparison of the March and September water levels shows that there is little variation beneath the valleys and near the sea because groundwater levels are shallow. The greatest variation is towards the interfluves, especially within the Worthing and Brighton Blocks, where the water table can fluctuate by up to 21 m, reflecting the lower storage available in the Chalk in these areas, as even small amounts of recharge result in significant water level fluctuations. Other factors can also contribute to groundwater fluctuations, including the permeability of the unsaturated zone or drift deposits.

The rainfall distribution for the South Downs is shown in Figure 21. There is a significant variation across the area, with annual rainfall increasing from about 700 mm at the coast to over 1000 mm over higher ground. The wettest month is generally November with over 90 mm and the driest month July with less than 50 mm rainfall (Figure 22). Evapotranspiration and soil moisture data for the South Downs are shown in Figure 23. Potential evapotranspiration is highest in July when solar radiation is greatest; actual evapotranspiration, however, which takes into account the availability of moisture for evapotranspiration, is at a maximum in May.

The soil moisture deficit (SMD) provides a general guide on the potential for recharge to an aquifer. When the SMD is high, negligible recharge can occur except through extraordinary means, such as swallow holes or bypass flow through soils. Once the SMD has been overcome and the soil has attained field moisture capacity, rainfall my infiltrate the ground and drain towards the water table. From MORECS data (see Figure 22), the effective precipitation or recharge occurs generally between October and March and amounts to some 300 mm a^{-1}.

The Chilgrove House Hydrograph

The South Downs has the longest-standing record of groundwater levels in Europe and possibly the world.

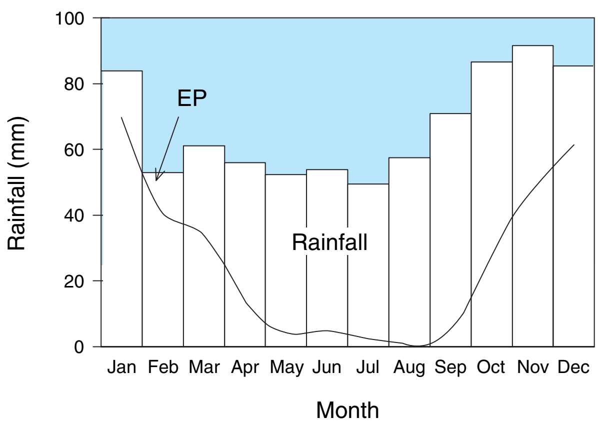


Figure 22 Average monthly rainfall and effective precipitation for the South Downs, 1961–94 (based on MORECS data).

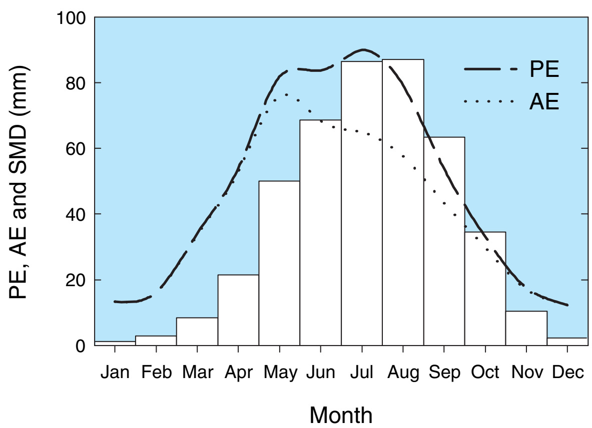


Figure 23 Average monthly potential evapotranspiration (PE), actual evapotranspiration (AE) and soil moisture deficits for the South Downs, 1961–94 (based on MORECS data).

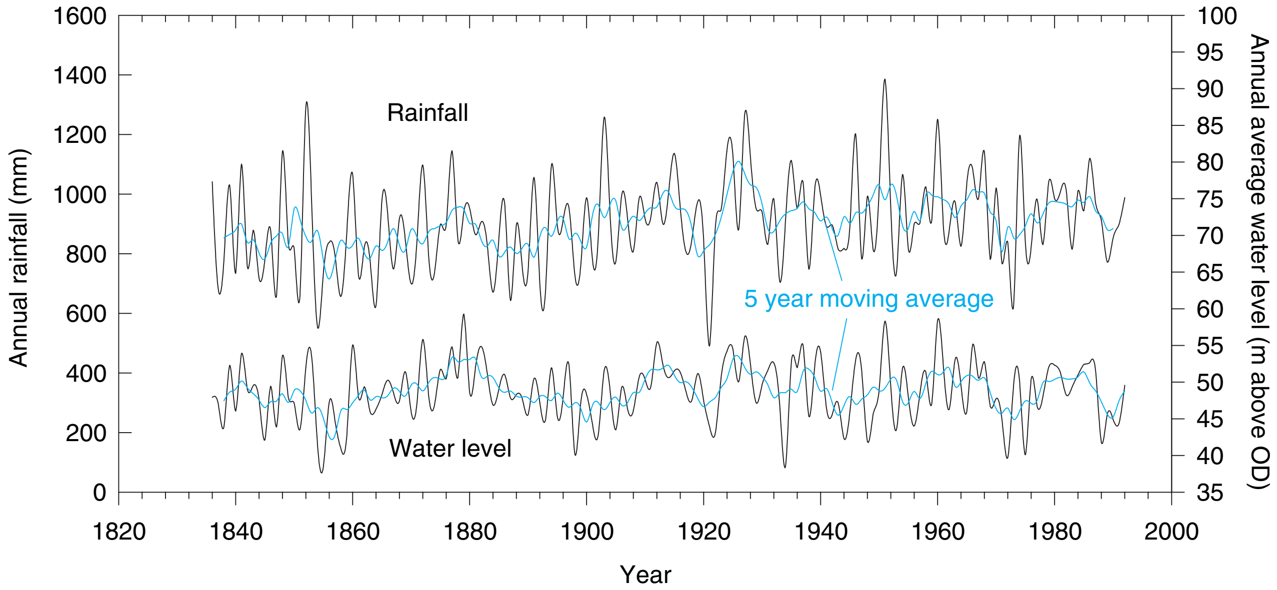


Figure 24 Annual average water level and rainfall data for the Chilgrove House well, 1836–1995.

Water levels have been measured in the Chilgrove House well since 1836 (Thomson, 1938; 1956; Monkhouse et al., 1990; Doorgakant, 1995). The well is situated in a dry valley which is connected with the River Lavant valley in the Chichester Block [SU 8356 1440]. Originally the well was a shaft, approximately 1 m in diameter and 41 m deep. In 1934 a 114 mm diameter borehole was drilled through the bottom of the well deepening it to 62 m. Groundwater levels have been measured almost continually from 1836 to the present day (Figure 24). The water level is not affected by pumping, and fluctuations reflect regional groundwater flow and recharge.

In general groundwater levels rise through the winter months with the highest levels occurring in January and February. Lowest levels are recorded near the end of the summer during August or September. Often multiple maxima are observed in the winter. This is largely a result of the uneven distribution of rainfall with several prolonged periods of rain giving rise to discrete recharge events, as, for example, in 1987 (see Figure 25). Occasionally (as in 1982) a double peak result from snow melt.

The Chilgrove House hydrograph illustrates the long-term trends, and puts present-day observations into a historical perspective. The main points are:

Plate 9 Dissolution openings expanding downwards in Lewes Nodular Chalk at Upper Beeding Quarry (GS 632).

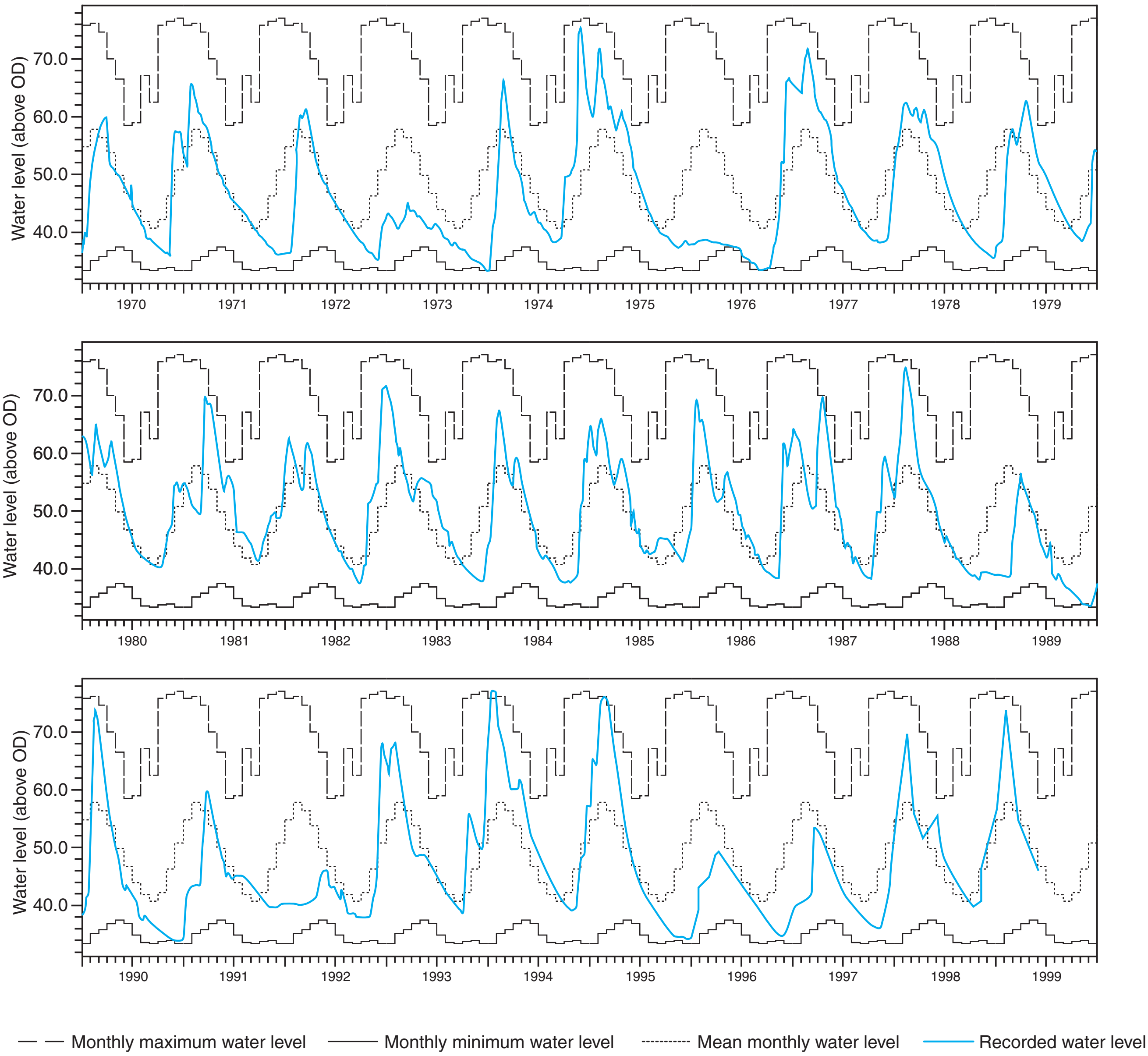


Figure 25 Monthly water levels for the Chilgrove House well, 1970–1999.

- The highest water level recorded to date was in January 1994 and the lowest level was in December 1973.
- The water levels closely follow changes in rainfall, especially when averaged over a five-year period.
- Average annual water levels were highest (59.3 m above OD) in 1879 and lowest (38.5 m above OD) in 1855. Annual rainfall was highest in 1951 (1386 mm) and lowest in 1921 (490 mm). The lowest and highest water levels averaged over a five-year period coincide with the high and low rainfall events: lowest water level and rainfall were from 1853 to 1858 (42.6 m above OD and 715 mm); the highest water levels over a five-year period coincide with highest rainfall, 1924 to 1928 (53.5 m above OD and 1110 mm).
- There have been five winter seasons when minimal winter recharge has occurred: 1854–55, 1897–98, 1933–34, 1975–76, 1991–92, and 1995–96. If there is little winter precipitation, then recharge does not occur and groundwater levels continue to decline throughout the winter and the following summer, resulting in significant depletion of the groundwater resource.
- Groundwater levels were very low during the 1850s. Throughout this decade groundwater levels did not rise significantly above the long-term average apart from 1852 to 1853 when they rose dramatically producing extremely high water levels for a period of a few months.
- From 1988 to 1992 water levels at Chilgrove House were generally depressed with sporadic and uncertain recharge.

Recent hydrological phenomenon

The long-term hydrographs reveal a cluster of unusual hydrological events over the last few years. This cluster is not unprecedented, there was the low water levels of the 1850s and high water levels of the 1912 to 1916 period, but it is nonetheless significant. Average

Plate 10 Collapsed cavern at Patcham Farm exposed in excavations for the A27 Bypass (GS 633).

monthly water levels for the period 1970 to 1995, together with the long-term monthly maxima, minima, and average, are illustrated in Figure 25.

The 1976 drought

The summer of 1976 was unusually hot with very little rainfall (Central Water Planning Unit, 1976; Hamblin and Wright, 1978), and there was a very high demand for water, especially in holiday areas such as the South Downs. There had been no significant recharge during the winter of 1975–76, resulting in minimal recovery of groundwater levels; consequently, at the beginning of the 1976 summer, water levels were approaching their minimum levels. This contributed significantly to the ensuing difficulties caused by the warm weather and high demand. However, despite the low groundwater levels, the aquifer managed to satisfy demand (although demand was reduced in response to appeals from the water authorities), and saline intrusion was controlled as best as possible.

The 1988–92 drought

The drought of 1988–92 was less intense than that of 1976, but was a protracted episode separated into a several phases of varying severity. (Management aspects of this drought are covered in Chapter 7). Rainfall was generally low in England and Wales, being only 81% of the long-term average in the NRA's Southern Region over the four-year period (Marsh et al., 1994). Evapotranspiration was also very high with the 1988–92 period constituting the warmest period in the 332 year history of the Central England Temperature Series. Runoff to rivers and recharge to the Chalk were severely limited throughout the four-year period, and there is apparently no parallel this century to such an extended period of low recharge. Nevertheless, groundwater levels recovered quickly during the latter half of 1992 when the drought ended.

A period of heavy rainfall interrupted the drought during the winter of 1989 to 1990, causing the water levels at Chilgrove House to rise sharply, almost to their long-term maximum, but then decline equally rapidly. This post-drought rapid response is common in Chalk boreholes. Protracted drought can create fractures within the soils which allow the first rains to infiltrate regardless of the soil moisture deficit. However, rapid rise and subsequent rapid decline in water levels would only be likely if the large fractures within the aquifer had been replenished during the recharge event (Price et al., 1993). With more prolonged recharge, water can penetrate the smaller fractures and some of the larger pores of the matrix, so that subsequent decline of the water level will take place more slowly. Air entrapment in the aquifer as a result of the rapidly moving recharge pulse may also contribute to this phenomenon (British Geological Survey, 1993).

The Chichester flood, 1993–94

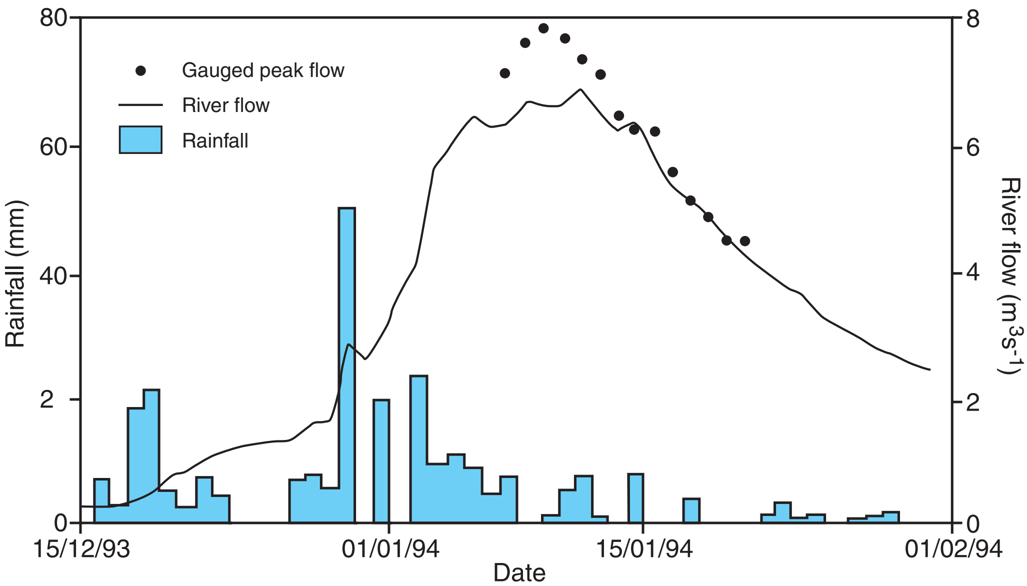
During the winter of 1993–94 severe flooding occurred in Chichester, lasting for nearly a month (Taylor, 1995; Midgley and Taylor, 1995; Posford Duvivier, 1994).

Plate 11 Continuous sheet flints 300 mm apart, acting as an aquiclude (GS 634).

Groundwater played a significant role in this event, which is highlighted by the hydrograph for the Chilgrove House well. Groundwater levels were fairly low in October 1993 at the start of the winter; however, subsequent rainfall was higher than the seasonal average and water levels in the aquifer quickly rose. From 28th November to mid January the area received 350 mm of rainfall, 40% of which fell in just six days (Taylor, 1995). Groundwater levels rose extremely rapidly and the Chilgrove House well became artesian on the 7th January for a period of 18 days, the longest recorded period of artesian overflow. As a result of the high water levels within the aquifer, springs appeared throughout the groundwater catchment and in the Upper Lavant. Consequently, flow within the River Lavant increased from 0.3 m^3 s^{-1} in mid-December to 1.7 m^3 s^{-1} on the 29th, peaking at 8.1 m^3 s^{-1} on the 10th January. The resulting flood caused much damage around the Lavant Valley and in Chichester in particular.

Figure 26 illustrates the rainfall, river flows and groundwater levels for the Lavant Catchment during this period. Groundwater levels and river flows in a Chalk catchment typically respond slowly to rainfall events; rainfall recharges the aquifer and groundwater provides baseflow to the river. The Lavant Catchment normally follows this pattern, but from mid-December to late January, the catchment underwent a significant change and became 'flashy' responding very rapidly to rainfall. The saturated nature of the Chalk played an important role in this change, and analysis by Posford Duvivier (1994) identified a critical water level within

Figure 26 River flow, groundwater levels and rainfall for the River Lavant at Graylingwell (after Taylor, 1995).



the Chilgrove House well (69.5 m above OD). Once this level was exceeded the catchment became much more responsive to rainfall, and water levels within the aquifer increased at a markedly slower rate than the river flows. At this point the capacity of the Chalk to store further recharge ceased. It has been suggested that this critical level corresponds to a zone of highly permeable chalk that acts as an overflow system providing a rapid flow path for groundwater to the discharge areas and springs within the valley. Similar high-permeability zones above the water table have been identified in the Chalk in other areas (Headworth et al., 1982; NRA, 1993; Allen et al., 1997) and may act as conduits for rapid water transport at times of high water levels.

The critical groundwater level (69.5 m above OD) has been frequently exceeded in the past and some, though not all, have resulted in flooding (e.g. winter of 1960 to 1961). Lack of long-term river flow records for the catchment prevents any further analysis, but it does appear that the Chichester flood was caused by the combination of intense rainfall at a time when water levels within the aquifer were already high.

The 1995 drought

The 1995 drought was a summer drought similar to that of 1976. In the south of the country, including the South Downs, the severity of the drought was mitigated by the availability of groundwater. Unlike the 1976 drought, groundwater levels had fully recovered during the previous winter and groundwater resources were in good condition at the onset of the drought. However, the high temperatures during the summer of 1995 coupled with the lack of significant precipitation during the autumn created a more serious problem for groundwater. By the end of the summer, soil moisture deficits were very high and the little rainfall that occurred during the early summer and autumn was insufficient to overcome the deficit. As a result, recharge did not occur and the groundwater levels recessed for an extended period of time. By the end of 1995, water levels in the coastal Chalk boreholes were 2.5 m below their 1989–90 levels (Anon, 1995), and the situation could have deteriorated by the summer of 1996 had not good winter rainfall followed.

SATURATED ZONE

Groundwater flow and storage

The Chalk is described as a dual porosity aquifer (Price, 1987; Barker, 1991; Price et al., 1993). In a classic dual porosity aquifer the matrix pores provide the storage and the fractures provides the permeable pathways that allow flow to take place. Groundwater movement within the Chalk is more complex: the high porosity is not readily drained, due to the very small pore throats (Price et al., 1976), and the *effective* groundwater storage depends largely on the fracture network and the larger pores. This effective storage probably only constitutes about 1% of the total saturated Chalk volume. Initially, groundwater drains from the larger fractures, but as these are dewatered, the head difference between the larger fractures and the matrix increases, and water drains from increasingly smaller fractures and macro pores. This 'delayed drainage' effect may be seen in pumping tests, where the drawdown curve implies a high degree of leakage.

The Chalk aquifer is also described as having *dual permeability*. Most of the flow tends to be concentrated in a few dilated fractures, often occurring at or within a few tens of metres of the water table. Flow velocities through these fractures are of the order of tens to hundreds of metres per day. At deeper levels within the Chalk the frequency and aperture of fractures decline due to the increasing pressure of overburden, and the reduction in circulating groundwater and hence dissolution. Groundwater tends to flow away from the recharge areas, to discharge through springs, or as baseflow in the valleys or directly to the sea. As in all chalk areas, a characteristic feature in the South Downs is the association of zones of high permeability with the dry valley systems.

Fracture spacing and enlargement due to dissolution is complex in the Chalk. The form of the fractures is very closely linked to the lithology, as well as to the structural history (Chapter 2). Dissolution, resulting in enlargement of the original fractures and discontinuities, are partly controlled by lithology, and further influenced by other factors, such as groundwater flux and the geochemical 'aggression' of the water (see later in this Chapter).

The majority of groundwater flow generally occurs within 50 m of the water table, through dissolution-enhanced fractures. Some smaller flows, however, have been found at depth (down to 140 m), especially close to the coast. These deep flow horizons are often associated with marl layers, flints or hardgrounds, and were probably developed in the Pleistocene as a result of greater groundwater circulation, lower sea level, or possibly sub-permafrost flow. Whatever their origin, they contribute little to the over-all groundwater flow, but may be important in terms of the groundwater chemistry, especially where they are connected to the sea.

The dual porosity/permeability nature of the Chalk is very important with regard to pollutant transport. Barker and Foster (1981) proposed that solute movement was largely controlled by solute exchange (via molecular diffusion), between mobile fracture water, and the relatively immobile matrix component. It was suggested that the fracture water eluted solute from regions of high concentration in the matrix, transferring it to regions of lower concentration in the direction of flow. This could be of great significance when interpreting transport of pollutants through the unsaturated zone, and also in predicting the migration of contaminants in the saturated zone (Foster, 1975). The extent of this process may be limited in major fractures because of high flow velocities. Another important process is hydrodynamic dispersion, with dilution of the solute occurring as water flows through a complex system of branching fractures.

Aquifer properties data

Data on the aquifer properties of the South Downs have been collected over the past 30 to 40 years from many different projects and studies. A recent study by BGS and the Environment Agency reviewing the aquifer properties of the major aquifers in England and Wales, collected and reviewed pumping test data, including data for the Chalk of the South Downs (Allen et al., 1997).

Information on aquifer properties can also be gained from more sophisticated tests, including packer tests and geophysical logs, which can give information on the *vertical* distribution of aquifer properties. Packer tests have recently been carried out in the Chichester Block (National Rivers Authority, 1993). Geophysical logging has also been carried out, and fractures can be detected from flow logs, and an estimate given of the relative contribution of each fracture to the overall yield of the borehole. In addition, the increased power and sophistication of numerical modeling has made it possible to estimate aquifer properties *indirectly* by optimising the various inputs to the model and calibrating against water level measurements. However, the solution of numerical models is by nature non-unique, and different estimates of transmissivity can be obtained by changing inputs to the model. On a smaller scale, analysis of drill core provides information on the movement of groundwater through the matrix and micro-fractures.

Pumping test statistics

Most of the pumping test information for the area was gathered during the South Downs Groundwater Investigations of the 1970s (Sussex River Authority, 1972; 1974; Southern Water Authority, 1976; 1979; 1984). The purpose of this investigation was to estimate the overall yield of the Chalk and to identify optimum locations for boreholes to maximise yield and minimise contamination of the groundwater resources by saline intrusion (see Chapter 7). Numerous boreholes were drilled and tested during the 12 years of this investigation. Additional pumping tests have since been carried out in the South Downs for smaller investigations or licensing purposes. In total, data exist for 28 different locations, with 45 estimates of transmissivity and 22 estimates of the storage coefficient (Allen et al., 1997).

The transmissivity distribution for available pumping tests in the South Downs approximates to a log-normal distribution (Figure 27). Values range from 16 to 9500 $m^2 d^{-1}$ with a geometric mean of 500 $m^2 d^{-1}$ and median of 440 $m^2 d^{-1}$; 25 and 75 percentiles are 230 and 1600 $m^2 d^{-1}$ respectively. There is very little apparent correlation between specific capacity and transmissivity from the available data.

The storage coefficient also approximates to a log-normal distribution (Figure 28). Values range from 2×10^{-4} to 0.032 with a geometric mean and median of 0.0018 and 0.0022 respectively. The 25 percentile of the data is 6.1 H 10^{-4} and the 75 percentile is 0.0040.

The aquifer properties data from individual pumping tests cannot meaningfully be extrapolated across the whole of the aquifer. Production boreholes are usually located in areas where higher yields are anticipated, for example in valleys. If a preliminary or exploratory borehole has a low yield it is often abandoned without testing to determine the aquifer properties. Pumping test data are consequently often biased towards the higher yielding areas, and aquifer properties data from pumping tests tend to give *higher* values of transmissivity and storage coefficient than are representative of the aquifer as a whole.

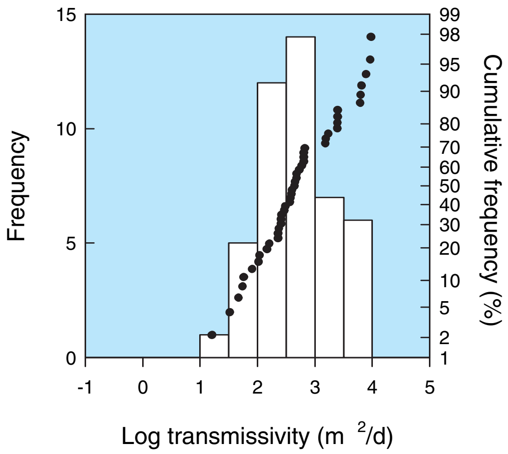


Figure 27 Transmissivity data for pumping tests undertaken in the Chalk of the South Downs; the median value is 440 $m^2 d^{-1}$ and geometric mean, 500 $m^2 d^{-1}$.

Core data

Aquifer properties of the Chalk based on laboratory analyses of borehole cores are available for a small data set of 12 samples collected at six different locations throughout the South Downs (Figure 29). Porosity ranges from 15 to 40% with an arithmetic mean of 32%. A general study of the porosity of the Upper, Middle and Lower Chalk of England, reported mean values of porosity for Southern England of 38.8%, 28.4% and 22.9% respectively (Bloomfield et al., 1995). Matrix porosity is, however, linked to the detailed lithostratigraphy and as such is variable.

Hydraulic conductivity for the South Downs was determined using a gas permeameter and then corrected to give an estimate of the liquid permeability. Values ranged from 0.0016 m d^{-1} to 0.0055 m d^{-1} with a geometric mean of 0.0025 m d^{-1}. When integrated over the thickness of the aquifer, these values represent extremely low transmissivity: for example, an aquifer 100 m thick with hydraulic conductivity of 0.0025 m d^{-1}

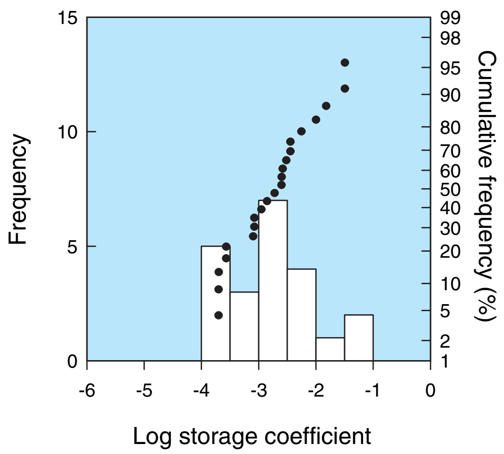


Figure 28 Storage coefficient data for pumping tests undertaken in the Chalk of the South Downs; the median value is 0.0025 and geometric mean, 0.0023.

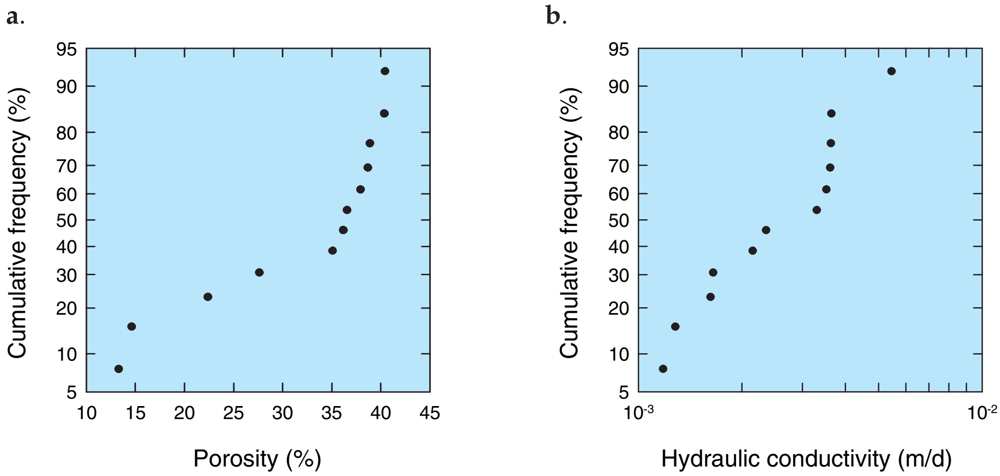


Figure 29 Core data for six different locations within the South Downs:
a. porosity
b. hydraulic conductivity. Data from the BGS core database.

would have a transmissivity value of only 0.25 m^2 d^{-1}. This is very much smaller than that demonstrated by pumping tests, where the average is approximately 500 m^2 d^{-1} and this illustrates the importance of the secondary permeability for groundwater flow in the Chalk.

Geophysical logs

Fluid electrical conductivity (EC) and fluid temperature logs help determine fluid entry points to boreholes. These measurements create a picture of groundwater movement through the rock mass when used in conjunction with stratigraphical information.

At Pyecombe [TQ 288 113] an exploratory borehole was tested at 3 l s^{-1} with a 3 m drawdown. An adjacent production hole, only 2 m away, was dry. The holes commenced in the Holywell Chalk and went through into the Zig Zag Chalk. Geophysical logging subsequently showed that seasonal decline in the water table had exposed the principal flowing horizon at the Melbourn Rock so that in fact both holes had gone dry at that time.

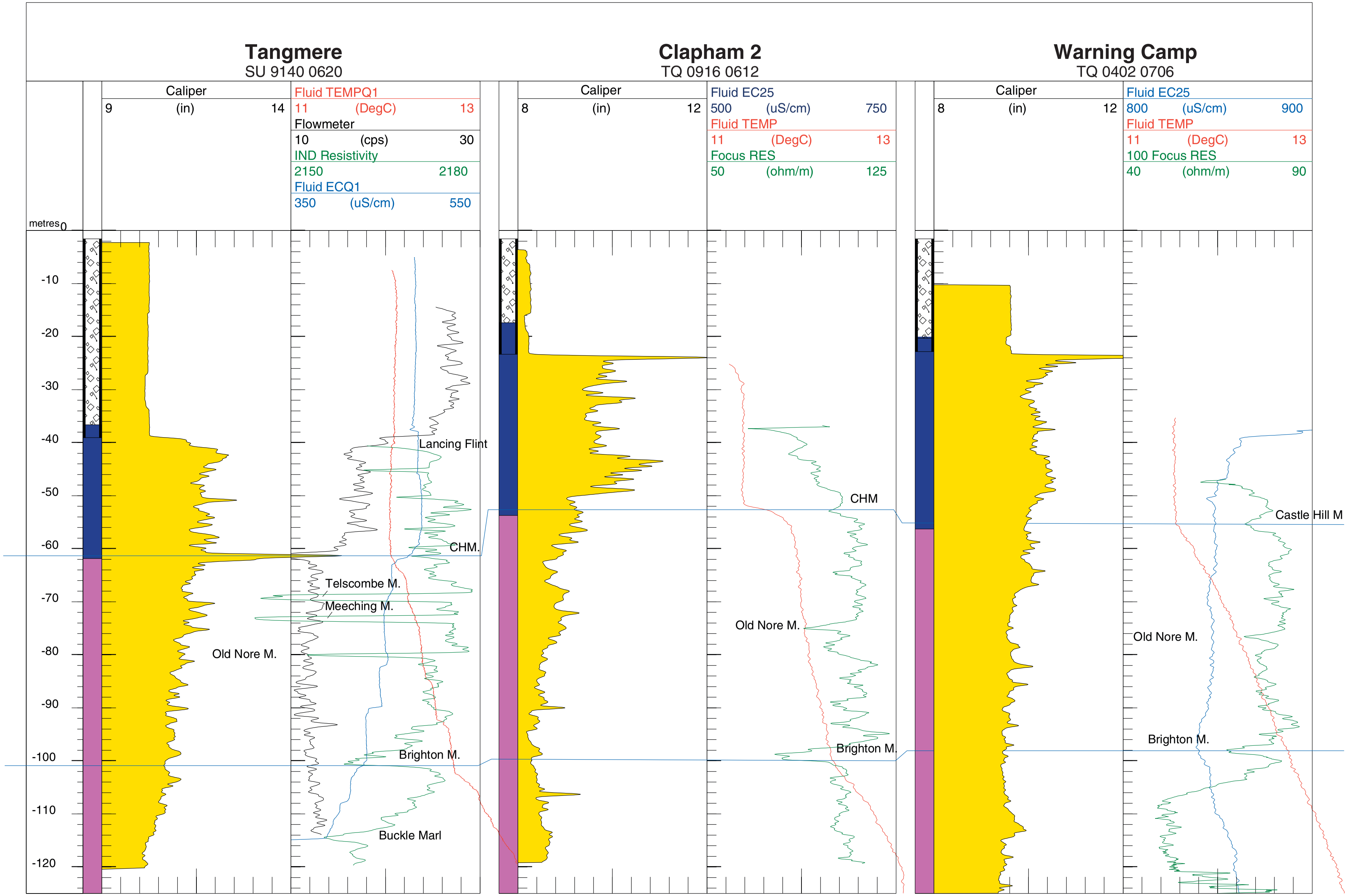
Figure 30 shows three logs in the Tarrant Chalk in the Chichester Block. Caliper, resistivity and fluid logs are compared. The fluid temperature logs show a general increase with depth below the Castle Hill marls and the Brighton Marl horizons. The cooler water above the Castle Hill marls provides evidence of a more active groundwater circulation through fissures, and a reduced circulation between the named marl horizons. Stepped changes in fluid conductivity and temperature in the Tangmere borehole (which was logged whilst pumping) reveal the individual inflow positions. It is evident there is little groundwater movement below the Brighton Marl horizon in each borehole. Flowmeter logging during pumping in the Tangmere borehole indicated around 60% of the yield was derived at shallow depth from above the Lancing Flint, and around 40% is obtained from above Castle Hill marl (in detail the water inflow is associated with flint bands close to the marl).

Hence the Castle Hill marl at the top of the Newhaven Chalk and the Lancing Flint are important water inflow horizons. The Tangmere borehole becomes artesian in winter when inland water levels increase sufficiently. Flowmeter logging has only occasionally been used in the South Downs Chalk boreholes but is clearly of importance.

Some of the information shown in Figure 30 is incorporated in a scaled north–south hydrogeological cross-section of the Chichester Block shown in Figure 31. The section has been drawn using the geophysical logging data for the boreholes shown. It illustrates the relatively steep dip of the Chalk units from the Duncton 1 borehole in the north to Shripney borehole in the south across the Chichester syncline and Littlehampton anticline. Groundwater flows from high elevation outcrop areas downdip to lower elevations and eventually discharges at the coast where saline intrusion is evident in the Shripney borehole.

It is clear from the section that the water table under the high land in this area of the Downs is not close to ground level. In fact the SWL in East Dean, Oxendown [SU 9270 1440] was 102.5 m below surface, and the cored Duncton 1 borehole was dry at 74 m, total depth and water level was estimated to be about 50 m below the Plenus Marls. Hence, although the South Downs rise to 200 m+ elevation, maximum water level is only around 100 m above OD (fluid temperature and fluid EC at these sites are both low, 9.58°C and 330 µS/cm, Oxendown). Caliper logging revealed a surprising concentration of fissure enlargements in the Oxendown and Westburton Hill boreholes well above present water level. It may be that those observed at high elevation could be related to Palaeogene times when sea level is reported to have been up to 180 m above present. Similarly, coincidence of the fissured horizons revealed by caliper logging in Halnaker borehole [SU 9180 0880] at elevations of +7, +25 and +40 m OD align strongly with the known marine erosion surfaces developed in the recent past. At the times of higher sea level the site would have been close to the shoreline. The contribution of Chalk-derived groundwater to the surface streams (rifes) on the Palaeogene in this area as indicated, clearly

Figure 30 Comparison of formation and fluid logs for selected boreholes, Chichester Chalk Block, showing important water inflow horizons. See Figure 31 for key to lithologies.



NOTE: Fluid EC/TEMP log changes show water inflow on Castle Hill Marls (CHM) and Brighton Marl, also indicate more active circulation above the Castle Hill Marl
Flowmeter logging in Tangmere borehole reveals 60% of flow above Lancing Flint and 40% above Castle Hill Marl horizons
Yellow infill is caliper log emphasis. The hole shape suggests more active dissolution above approximately 60m depth

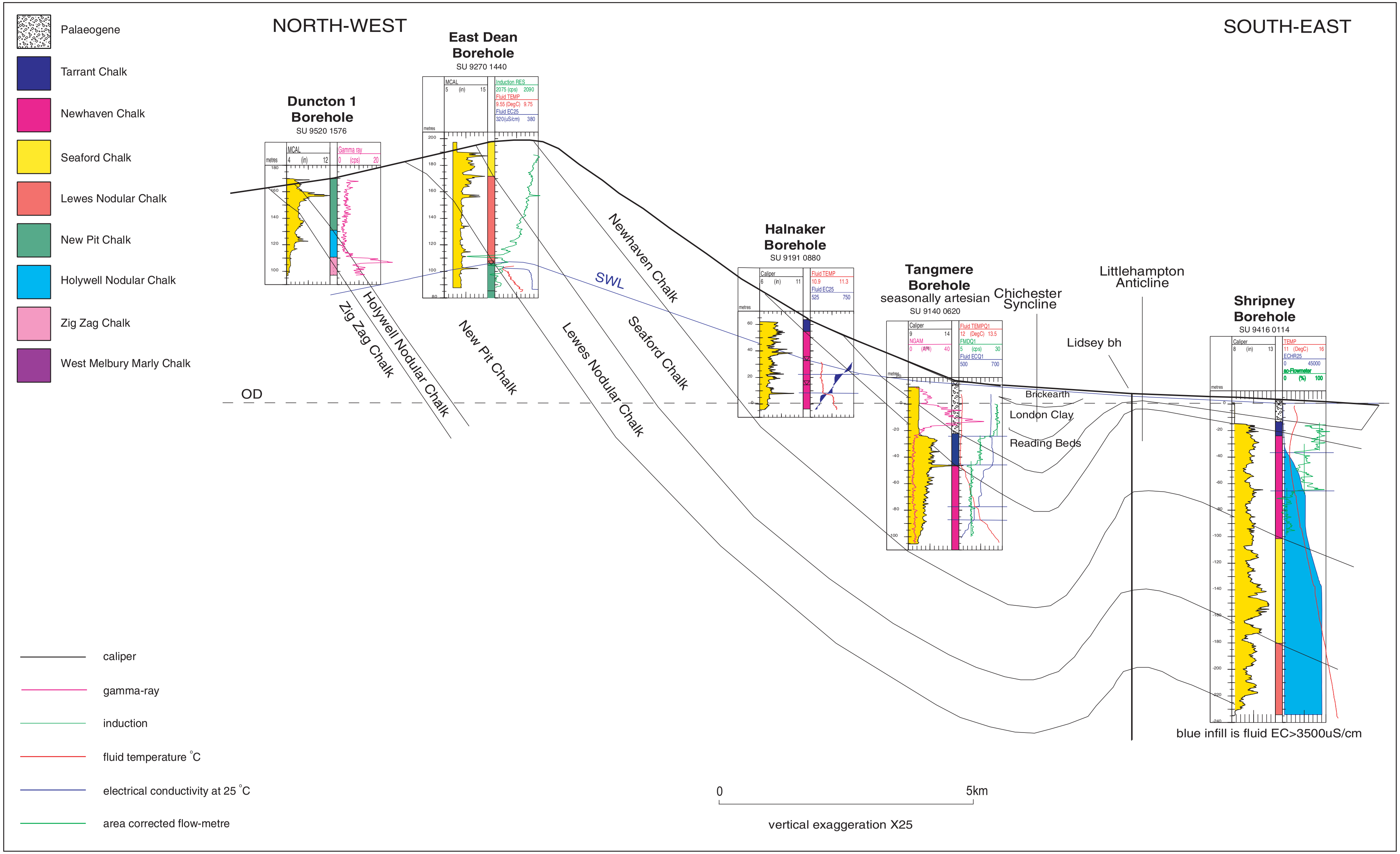


Figure 31 North–south cross-section of the Chichester Block based on geophysical logging.

depends on the water level. Measurements of water level in the Halnaker borehole in mid-March 1995 (32 m) and end-April 1997 (50 m) demonstrate a rapid change (5 m/month). The stratigraphical position of the Shripney borehole [SU 9416 0109] is known because it was cored. The fluid temperature at the water table in the borehole when logged was 12.3°C.

Figure 32 is a similar north–south cross-section drawn using geophysical log data at the seaward end of the Brighton Block. It is based on geophysical logging by BGS in the St Peters Church [TQ 3150 0490] and Victoria Gardens boreholes and existing log data of the now inaccessible East Street Car Park borehole [TQ 311 039].

The resistivity logs reveal a seaward dip of the strata of at least 10 to 12 km but increasing towards East Street. (The exact stratigraphical position of the East Street borehole is uncertain because it is impossible to correlate the resistivity log because it is influenced by saline water. It is possible a fault could be present between the East Street borehole and Victoria Gardens borehole).

However the section illustrates the change in fluid properties of the groundwater when traced towards the coastline. Fresh waters are present in the two inland boreholes to at least 220 m below OD. In the East Street borehole close to the coast groundwater is brackish (around 1500 µS/cm down to 83 m below OD) it increases to 2000 µS/cm at 105 m below which it increases sharply to 9000 µS/cm between 106 and 112 m below OD. The elevated salinity is reflected by the resistivity log which shows corresponding lower resistivity coincident with higher salinity and lower temperatures shown by the differential temperature log. These changes represent invasion of the Chalk fissures by cold saline waters. The fluid temperature logs show a progressive cooling of the aquifer water when traced towards the coast. The temperature logs show a base of active circulation at 85 to 90 m below OD and corresponding to a horizon in the Lewes Nodular Chalk below which the temperature gradient is typically greater than 2.5°C/100 m where groundwater flow is very slow. Waters sampled from this zone have been dated as probable Holocene and late Pleistocene age. Note the higher fluid EC entry on the Melbourn Rock in St Peter's Church. Similar increases up to 2000 µS/cm have been observed on occasions (unexplained) by the routine saline monitor logging in both boreholes.

Controls on aquifer properties distribution

Many factors have contributed to the development of the aquifer properties within the Chalk. Throughout southern England a general pattern of high transmissivity and storage coefficient within valleys is observed, and low transmissivity and storage on intervening interfluves. The aquifer properties thus generally reflect the topography. Superimposed upon the general topographical distribution are other effects which sometimes result in high permeability, even karstic behaviour (Figure 33). Detailed discussions of how the observed pattern of transmissivity and storage coefficient have developed are given elsewhere (e.g. Price, 1987; Downing et al., 1993; Mortimore, 1993; Price et al., 1993). A summary of the factors relevant for the South Downs is given here.

Factors contributing to the topographical pattern

Transmissivity and storage mirror the topography throughout the Chalk aquifer. Aquifer properties tend to be favourable beneath the valleys, while beneath the interfluves both transmissivity and storage are significantly reduced. This topographic pattern could have developed for a number of reasons:

- Many valleys follow lines of structural weakness, with a higher frequency of fractures. Remote sensing has shown that many of the dry valleys are linear, consistently trending in a limited number of directions, and that the frequency and regular spacing of the valleys (lineaments) indicates a relationship to fractures, possibly in the form of joints (Marsh, 1993).

- Erosion along valleys reduces effective stress which can lead to the opening of horizontal fractures (Ineson, 1962; Price, 1987; Price et al., 1993).

- The concentration of groundwater flow towards valleys as discharge areas, and mixing of groundwaters near the points of discharge which have different chemical compositions. The mixing may result in aggressive groundwaters that are undersaturated with respect to calcite. These factors combine to enhance chalk dissolution, ultimately creating larger-diameter conduits (Rhoades and Sinacori, 1941; Robinson, 1976; Connorton and Reed, 1978; Owen and Robinson, 1978; Price, 1987; Price et al., 1993). This may be a more important factor in developing permeability than the frequency of fractures. The major fractures were probably initiated during the late Pleistocene when, due to lower sea levels, hydraulic gradients, and hence rates of groundwater flux, were greater.

- Periglaciation could also have contributed towards the enhanced permeability along valleys. Repeated freezing and thawing within the active layer would have broken down the top few metres to provide a mantle of weathered chalk which could easily be eroded; within the valleys, repeated freeze–thaw may have opened up fractures to a depth of 20 to 30 m (Higgenbottom and Fookes, 1970; Williams, 1980; 1987; Gibbard, 1985). Furthermore, the flow of surface water would have kept the ground unfrozen to a greater depth within valleys during periglacial periods. The concentration of flow in the talik and the colder temperatures may have increased dissolution of the Chalk, resulting in enhanced permeability (Younger, 1989).

Rather than a single factor, it is probable that more than one of the above have combined to give the Chalk its characteristic topographical distribution

Lithological controls

Lithology has a marked effect on fracturing, and hence on aquifer properties. For example, soft Chalks tend to have less well-developed fractures, and aquifer properties are consequently poorer.

The influence of lithology on groundwater movement can be examined by geophysical logging. Geophysical logs identify the Belle Tout Marl and associated hard bands as important flow horizons in the St Peters Church borehole and in the Victoria Gardens borehole

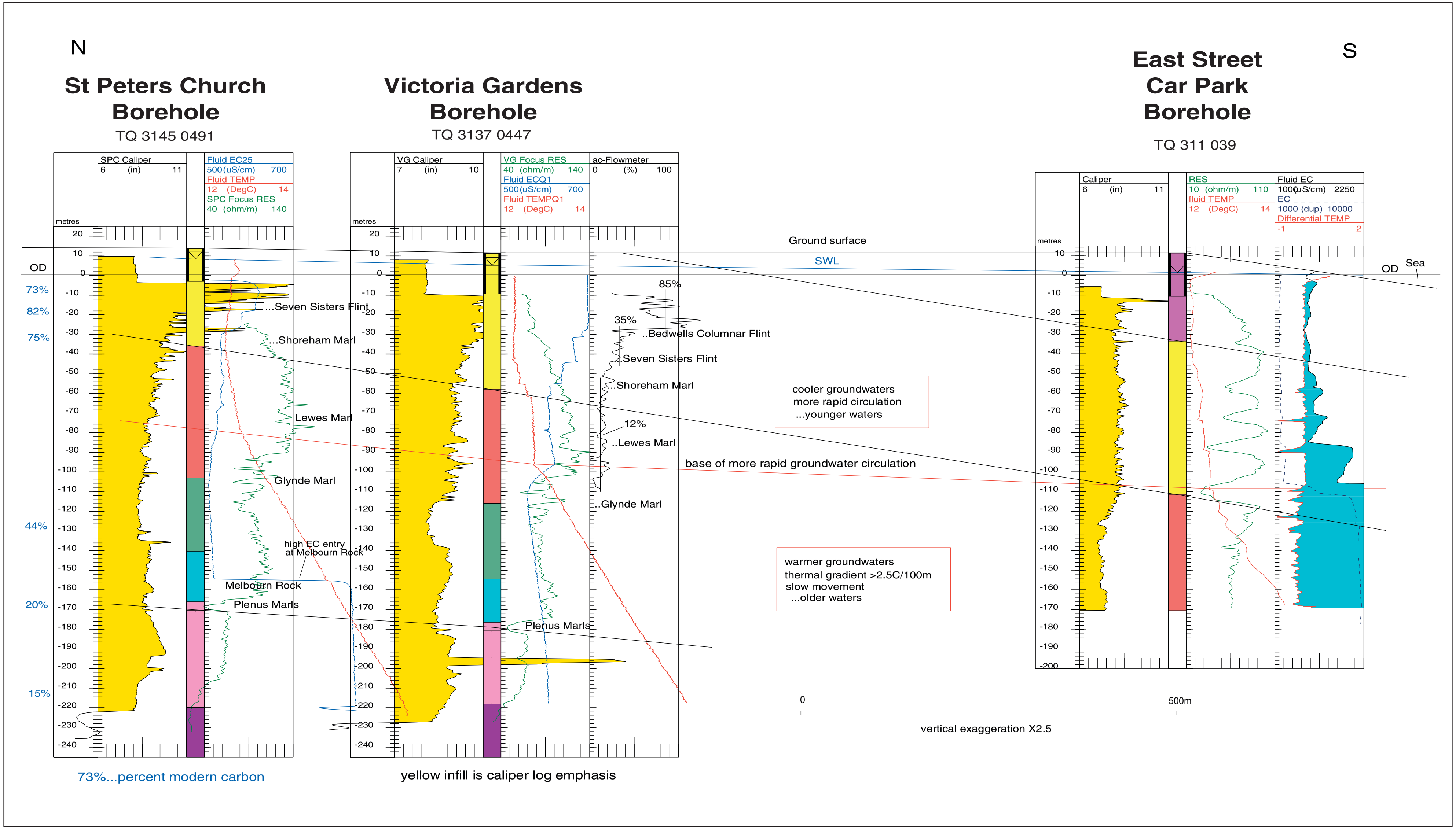
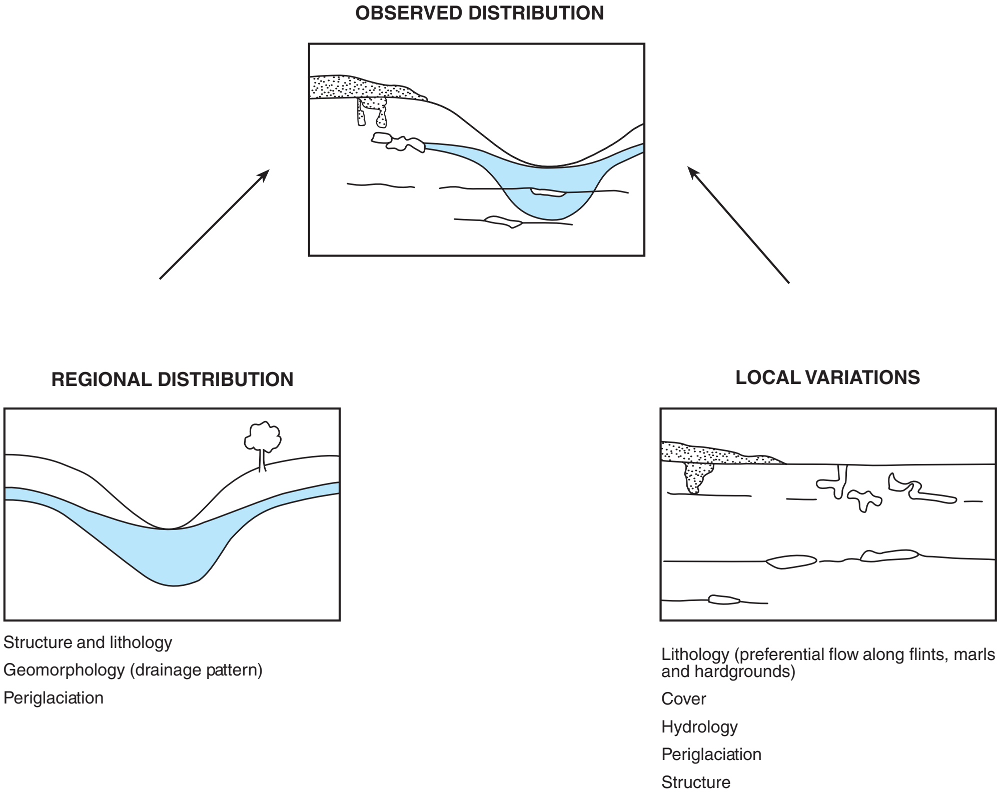


Figure 32 North–south cross-section based on geophysical log data, Brighton area coastal boreholes. See Figure 31 for key to lithologies.

Figure 33 The controls on the development of transmissivity within the Chalk.



in Brighton (see Figure 34 and Table 7). Pumped fluid and flowmeter logs in the Victoria Gardens borehole identified the largest inflows on the semitabular, Seven Sisters Flint and on the Belle Tout Marl at 39 to 43 m depth. The same horizons have also been identified in a borehole in Hampshire. The temperature logs and heat pulse flowmeter measurements (not shown), confirmed a local base of groundwater movement at 110 m on the Bridgewick Marl, and upward movement of water in the borehole.

The importance of lithostratigraphical controls on aquifer properties is also illustrated by the high-yielding Seaford Chalk, which has frequently been considered to be the major water-bearing unit of the South Downs Chalk.

Hardgrounds fracture more cleanly than softer chalks. As a result of the greater density of open fractures, the permeability of hardgrounds is commonly higher than in the surrounding rocks. In the South Downs, as in other areas, the Melbourn Rock usually exhibits higher permeabilities than surrounding chalk, especially when not deeply buried so that the joints remain open. The higher yields from this layer have been exploited by many adit systems extended from large-diameter wells. It should be noted that hardgrounds may also act as impermeable layers when not fractured, encouraging dissolution on their upper surface.

It is also apparent that marl layers within the Chalk are important for the development of permeability. The marl layers may be thin (commonly only a few millimetres), but may persist laterally for distances of over 100 km, and are relatively impermeable due to a lack of fractures. Dissolution features have been noted both along the surface of, and *beneath*, marl layers. In the case of the former, it is probable that they have developed as a result of groundwater flow being concentrated along the top of the layers, leading to dissolution.

The marls, however, may be disturbed and are faulted out in places as a result of shearing. Since they are weak and also quite extensive, regional stresses in the Chalk have often been accommodated by horizontal movement along the marl layers. Where they have been removed, groundwater exploits the fracture surface which can be important for both local and regional groundwater flow.

Flow horizons may also be developed preferentially along flint bands. Karstic features along and above sub-horizontal sheet flints provide evidence for water once having being held along and above them (Lamont-Black, 1995). The almost continuous, semitabular flints such as the Seven Sisters Flint Band and other prominent flint seams in the Seaford and Culver Chalks are typical examples. On the French coast south of Dieppe, the Seven Sisters Flint Band has a cavern system developed along its top surface. Similar cavern systems along this flint are present in the Swanscombe quarries in the North Downs. The same style of 'sheet' flow into tunnels occurs in the Sussex Downs (Figure 35). The slightly different composition of chalk associated with the flint layers, or small cavities created around the flint by differential stresses, may also be important in initiating the original fracture development.

Whatever the specific mechanisms involved, further study of the detailed lithostratigraphy of the Chalk in conjunction with geophysical logging evidence of water occurrence and movement, should aid in understanding the development of the aquifer properties of the Chalk, and their local and regional distribution.

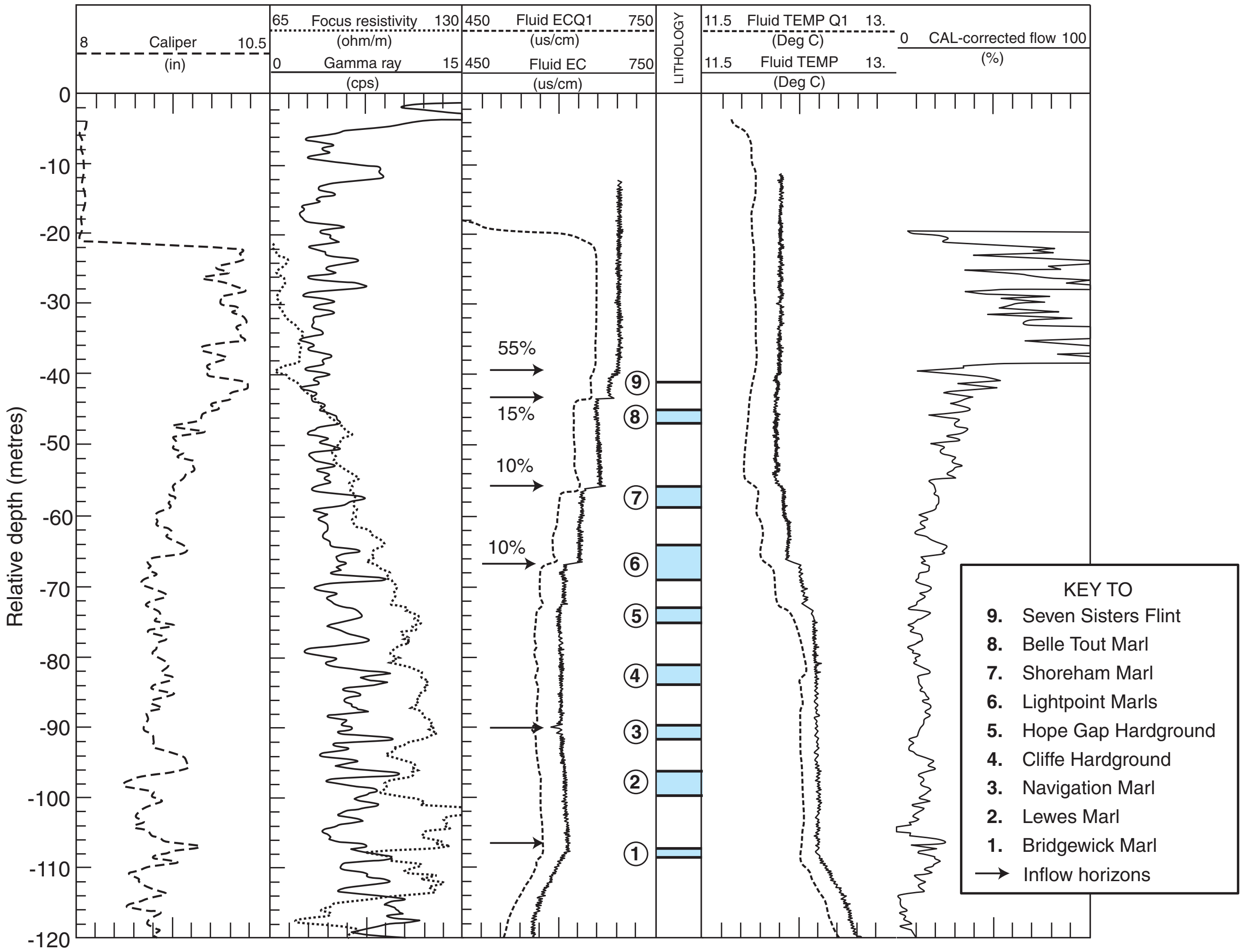


Figure 34 Geophysical logs showing water inflow horizons, Victoria Gardens Borehole, Brighton.

Structure

The role of structure in providing the general topographical control of aquifer properties has been discussed previously; structure can also have a *direct* influence. Faulting can produce zones of high transmissivity and rapid groundwater flow. Where fault gouge is present, however, the permeability can be reduced. Folding can also affect the permeability of the Chalk, both because of the associated fractures and also by raising or lowering Chalk with different lithological properties into the zone which is the effective aquifer.

In the Chichester Block, a series of flexures, striking east–west are developed — the most significant to

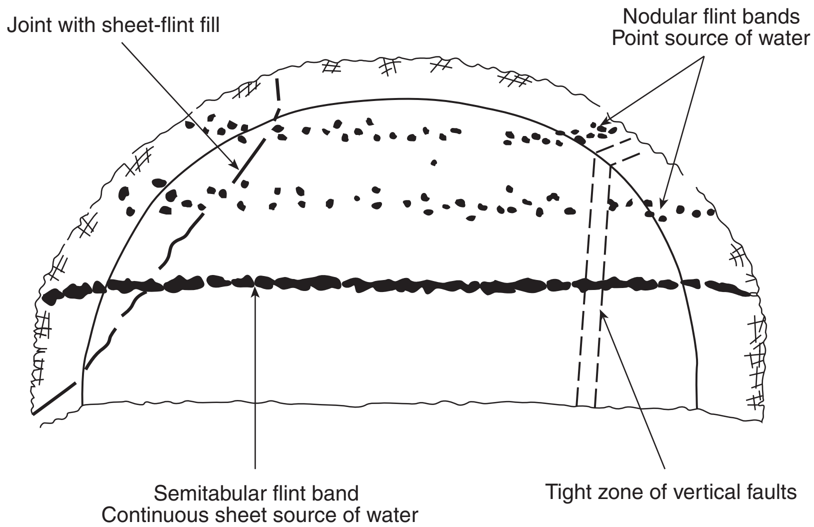


Figure 35 Semitabular flint providing a potential horizon of sheet flow in a tunnel.

Table 7 Water inflow horizons in South Downs boreholes.

Chalk Member	Victoria Park (TQ 1419 0290)	Victoria Gardens (TQ 3137 0447)	St Peters Church (TQ 3145 0491)	East Preston (TQ 0707 0273)
Portsdown/ Spetisbury Chalk				
Tarrant Chalk				
Newhaven Chalk				
Seaford Chalk		39 — above Seven Sisters Flint 43 — above Belle Tout Marl	42 — on Belle Tout Marl	
Lewes Chalk	77 — at Lightpoint Marl 96 — on Navigation Marl 150 — on Shoreham Marl 112 — on Bridgewick Marl	55 — on Shoreham Marl (20%) 66 — in Lightpoint Marls 72 — on Hope Gap HG 90 — on Navigation Marl 107 — on Bridgewick Marl	50 — on Shoreham Marl 80 — in *Culfail zoophycos* soft Chalk under Navigation Marl 114† — at Southerham Marl	
Holywell/Newpit Chalk	143* — on New Pit Marl 3 145* — on New Pit Marl 2 166* — on Malling Street 181* — below Gun Gardens		123† — at New Pit Marl 168† — at Holywell Marl	29 — on New Pit Marl 38 — on Ilford Marl 44 — on Malling Street Marl 56 — on Gun Gardens Marl
Lower Chalk			187† — below Plenus Marl	79 — at Plenus Marl 93 100 — in Grey Chalk 114 — in Chalk Marl

Chalk Member	Park Bottom Arundel (TQ 005 076)	Warning Camp WP100 (TQ 0402 0706)	Clapham obs well 2 (TQ 0916 0612)	Middle Road Kingston (TQ 2340 0540)
Portsdown/Spetisbury Chalk		29 —	28 —	
Tarrant Chalk	16 — on Castle Hill Marl	31 — 33, 37 — 40 — ? On Castle Hill Flint 48 — above Castle Hill Marl	32 — 42 — ? On Castle Hill Flint 51 — above Castle Hill Marl	
Newhaven Chalk	36 — at Peacehaven Marl 43 — on Old Nore Marl 50 — on Roedean Triple Marl 52 — on Rottingdean pair 80 — on Buckle Marl	88 — on Old Nore Marl 99 — on Roedean Triple Marl		56 — on Roedean Triple Marl 79 — under Brighton Marl
Seaford Chalk				120 — at Flat Hill Flint
Lewes Chalk				
Holywell/Newpit Chalk				
Lower Chalk				

* brackish water
† evidence of water movement from saline intrusion monitoring (Southern Science, 1992).
All depths (metres) below surface.

Plate 12 Dissolution cavities along a marl seam in the Newhaven Chalk (GS 635).

groundwater movement are the Singleton Anticline and the Chichester Syncline. The low permeability Lower Chalk is near to the surface in the core of the Singleton Anticline. This has the effect of impeding groundwater flow to the south, across the axis of the anticline (Southern Water Authority, 1984).

The Chichester Syncline is infilled with over 100 m of Palaeogene deposits and also acts as a barrier to groundwater flowing south to the sea (Figure 36). Groundwater flow is focused on several discrete discharge points along the structure, including those at Arundel, Fishbourne Springs, and Bedhampton Springs (to the west of the area). The increased groundwater flux to these discharge points has, in turn, led to enhanced dissolution, and helped to create narrow zones of high transmissivity. One such point is Arundel on the River Arun, where groundwater flow that has been diverted by the syncline, is discharged. Seismic surveys of the area have indicated a large fault striking north-west running through Arundel (D Aldiss, personal communication) and this might explain the concentration of groundwater flow towards this outlet. The other main discharge points are at Fishbourne and, just to the west of the region, at Bedhampton. The detailed form of the groundwater levels in the Chalk north of Bedhampton, between Hambledon and Finchdean, indicate that flow is focused on the Bedhampton–Havant area where the springs issue at a culmination in the Chichester Syncline. The Chalk is probably fractured at this point, allowing the water to cross the synclinal axis and issue on the south side (Day, 1964). At Fishbourne groundwater is focused under an arch in the syncline and discharges through a series of springs.

Pleistocene history

Alternating glacial and interglacial periods, and the consequent changing sea levels during the Pleistocene, have affected both surface drainage and groundwater flow in the South Downs. Present day dry valleys are possibly remnants of active stream valleys, formed at time of higher sea levels (see Chapter 2). The variations in sea level also resulted in the maintenance of the water table at various levels, and hence allowed the development of numerous horizons of enhanced permeability through the vertical sequence. During glacial periods, circulation of groundwater took place at much greater depth than occurs today; this accounts for water movement identified by borehole fluid logging at depths of greater than 100 m.

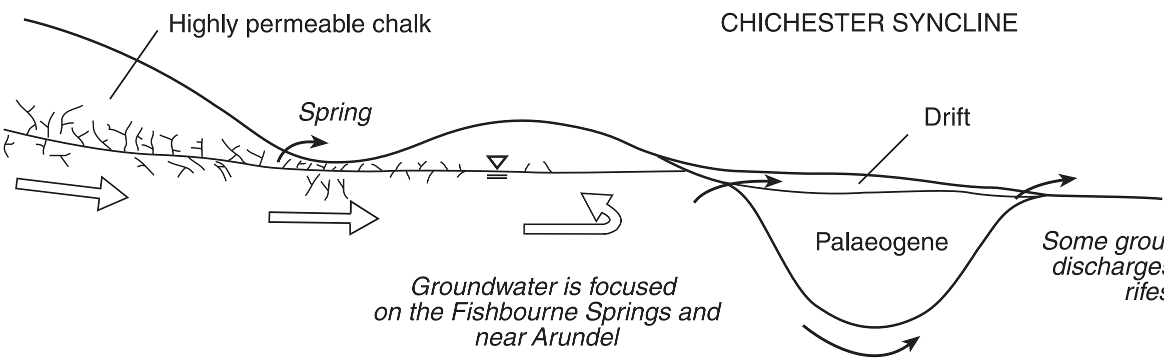


Figure 36 The role of the Chichester Syncline in controlling groundwater flow in the South Downs (adapted from Harries, 1979).

The effect of Palaeogene cover

Rapid groundwater flow and high transmissivity may be associated with Palaeogene cover. Several factors contribute to the increase of dissolution close to cover (Allen et al., 1997). Soil water associated with Palaeogene deposits and clay-with-flints tends to be acidic, and recharging water draining from these deposits is geochemically aggressive. Soils associated with cover can also be clayey and therefore concentrate runoff onto the Chalk aquifer at specific points.

Solution pipes and swallow holes can allow acidic recharge to penetrate deep into the unsaturated zone, and in mature areas even below the water table. The acidic recharge can then access fracture systems within the aquifer and allow enlargement of fractures into conduits. Once the cover and other geomorphological features have been removed by erosion, the deeper hydrogeological features remain, allowing rapid groundwater flow along preferred flow paths.

Sands and gravels from the overlying Palaeogene deposits may be washed down through solution features to clog the fracture network. Problems caused by running sand in chalk fractures were experienced during groundwater abstraction from the Warningcamp borehole [TQ 058 067] (Southern Science, 1992a). Pumping tests combined with geophysical logging have demonstrated that sand entered the borehole from fractures as deep as 70 m. Rapid groundwater flow caused by pumping disturbed the sands within the fractures and transported them to the borehole.

Variation in aquifer properties

The various controls described above conspire to produce the distribution of aquifer properties seen today in the South Downs, but insufficient data exist to describe the detailed areal or vertical distribution.

Vertical distribution

As with most Chalk aquifers the zone of water-table fluctuation is believed to be important for the development of a solution-enhanced fracture system, and hence for groundwater flow. For example, Headworth et al. (1982) illustrated that the bulk of the yield in boreholes in the Chalk of Hampshire was obtained from the top 20 to 50 m below the water table. However, the situation is further complicated in the South Downs by the fluctuations in sea level that occurred during the Pleistocene. This resulted in changing base levels, and allowed the dissolution of fractures at several different horizons. Such horizons of enhanced permeability exist through a great thickness of the Chalk, and have been identified from 140 m depth to above the present water table (Southern Water Authority, 1979).

Much information has been collected about the vertical profile of permeability from flow logs and packer tests throughout England (Tate et al., 1970; Headworth, 1972; Foster and Milton, 1974; Foster and Robertson, 1977; Price et al., 1977; Owen and Robinson, 1978; Connorton and Reed, 1978; Southern Water Authority, 1979; Price et al., 1982). Several general observations can be inferred:

- permeability measured throughout a sequence in a borehole is about an order of magnitude greater than the matrix permeability;
- only a few large fractures are necessary to give the high transmissivity indicated by pumping tests;
- zones that have very high permeabilities correspond to fracture horizons;
- the most important flow horizons are almost invariably concentrated near the top of the Chalk, with less flow from depths greater than 50 m below the surface of the Chalk (see Figure 37);
- the presence of hardgrounds, flints and marls can significantly increase dissolution of the Chalk adjacent to these features.

Packer testing of the unconfined Chalk of the Chichester Block at three inland locations showed that aquifer properties were best developed within the 40 m below the present water table (NRA, 1993). High permeabilities were also measured above the present water table, especially on an interfluve site. This suggests a potential for high transmissivity at high water levels, even over the interfluves, and partly explains the severe flooding experienced in Chichester in 1993 (Posford Duvivier, 1994; Taylor, 1995).

The Victoria Gardens borehole in central Brighton was specifically logged to examine fluid inflow. The pumped fluid conductivity and temperature logs (ECQ1/TMPQ, Figure 31) were virtually identical to the unpumped fluid logs (EC25,TEMP) indicating that a natural upward movement was present at the site. When pumped, water movement was identified by the ECQ1/TMPQ logs at the Seven Sister Flint, from the Belle Tout Beds, on the Shoreham Marl, within the Lightpoint Marls and on the Hope Gap Hardground (see Figure 34).

For the flowmeter logging the borehole was pumped at 15.9 $m^3 h^{-1}$, the maximum of the pump and, to increase the flowmeter response, a centraliser guide and basket was fitted to the flowmeter. The flowmeter identified major inflows at 38 m depth at the Seven Sisters Flint (approximately 55% of the total discharge), from

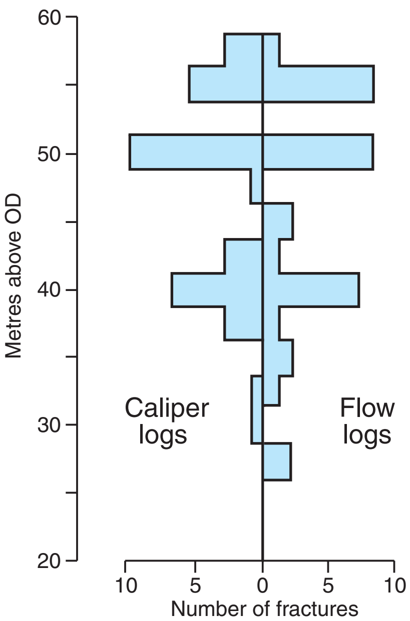


Figure 37 Histograms of fractures and water inflows in the Chalk aquifer determined by geophysical logging in Hampshire (from Headworth, 1978).

the Belle Tout Beds (approximately 20%), and at 55 m on the Shoreham Marl (approximately 20%). Below this depth the vertical velocity was too low to be resolved. However, the pumped ECQ1 and TMPQ logs suggested the remainder (approximately 5%) is obtained from above the Lightpoint Marl, and above the Hope Gap Hardground. Heat pulse flowmeter measurements confirmed upward water movement down to the Bridgewick Marl (108 m), which temperature logging suggests is the local base of groundwater movement.

Areal distribution of aquifer properties

The distribution of the transmissivity data that are available is plotted in Figure 38. The most characteristic feature of the saturated zone of the Chalk is the close association of high permeability with valleys. Aquifer properties data in the South Downs are biased towards higher transmissivity sites, it is only possible to infer an approximate relationship between transmissivity and depth to water levels (Figure 39). Where water levels are shallow (for example in discharge areas and valleys) transmissivity tends to be high; in areas with greater depth to the water table (such as beneath interfluves) transmissivity values are generally low. For example, a borehole on an interfluve in the Chichester Block gave a transmissivity value of only 1 $m^2 d^{-1}$ while pumping tests in the Winterbourne Valley at Housedean Farm [TQ 363 092] indicated values of greater than 1000 $m^2 d^{-1}$ (Sussex River Authority, 1974).

The size of the valley is also important in the development of an active fracture network. Aquifer properties are best developed in main valleys where groundwater flow is concentrated, for example along the River Adur, River Lavant and the Winterbourne Valley. Borehole tested in dry valleys high up on the interfluves, for example Balmer Down on the Brighton Block [TQ 369 103], Lychpole [TQ 155 083] and Annington [TQ 179

Vertical variation in aquifer properties: a case study

Headworth (1978) described artesian flows from more than 50 observation boreholes on 12 watercress farms in the Micheldever–Alresford area of Hampshire. The copious artesian flows were driven by a shallow and fairly uniform head. These heads are likely to be due to the boreholes tapping curvilinear equipotentials at shallow depth, representing greater heads higher up on the Downs. Caliper and flowmeter logging showed that water inflows were from shallow depths and increased stepwise at certain horizons. The caliper logs showed openings up to 300 to 360 mm diameter, i.e. twice the drilled diameter and flow logging demonstrated that the stepwise increases in discharge coincided with the caliper enlargements. Approximately 90% of the natural flow was found to be obtained above 27 m depth and in 50% of the boreholes the lowest major flow was between 9 and 16 m depth. Plots of inflow positions relative to OD revealed a clustering of positions at preferred horizons, notably 40, 50 and 55 m above OD (Figure 37). The lowest inflow (+40 m concided with the floor of the main valley of the River Itchen which drains the catchment. This gives a clue to processes involved in the development of the water-bearing horizons. Monitoring the flow of the boreholes over the period 1972–75 indicated a seasonal relationship of discharge to water level, discharge being highest in January and lowest in November. More consistent ranges of flow discharges were observed for boreholes in valley bottom sites compared to the discharge from boreholes on the valley sides.

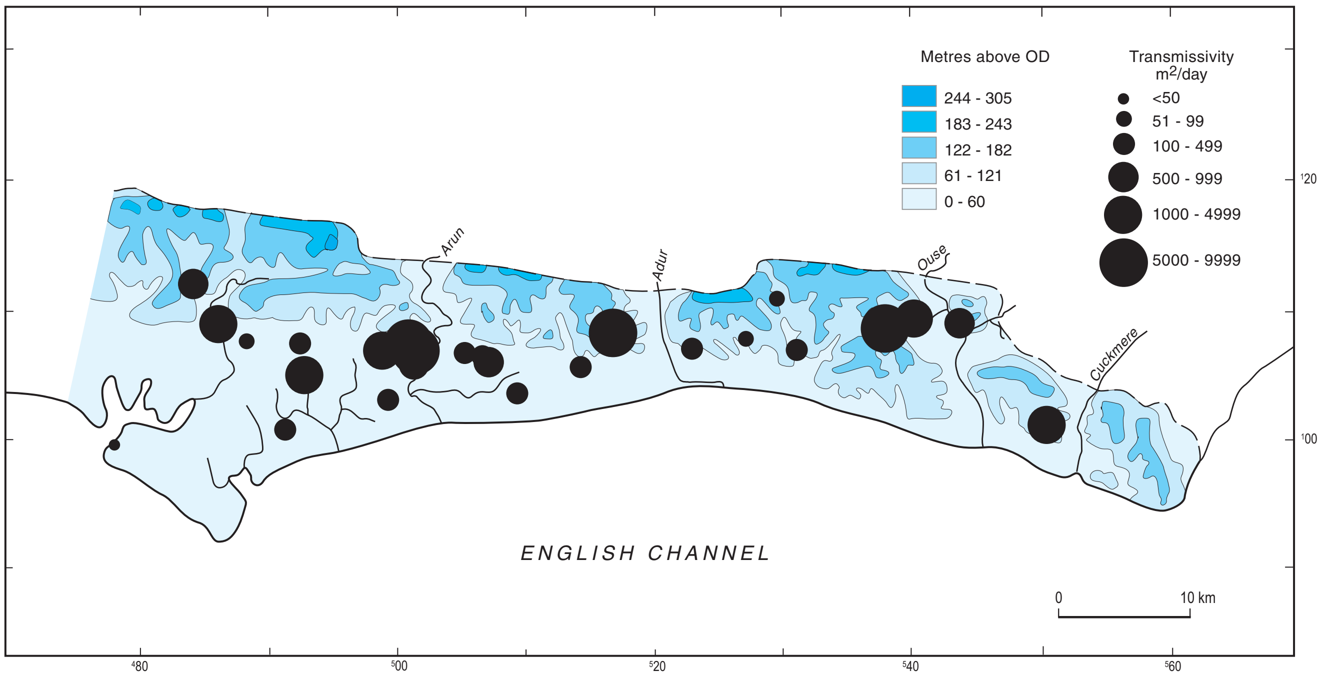


Figure 38 Transmissivity distribution across the South Downs.

085] on the Worthing Block, indicated very poor yields (Headworth, 1994). Groundwater flow through these small valleys is generally quite limited, therefore solution enhancement of the fracture system has taken place to a lesser extent.

The relationship between aquifer properties and topography is not perfect. Between neighbouring valleys, properties can sometimes be very different; good yields may be recorded below interfluves whilst boreholes drilled in valleys are dry. Such data emphasise the fact that other controls also operate. For example, boreholes drilled in the Benfield Valley [TQ 262 083] have low yields; this has been attributed to the fact that, the White Chalk is compact, soft and marly with little fracture development throughout the valley (Sussex River Authority, 1974).

The Chalk of the South Downs shows evidence of karstic development, with collapse features such as swallow holes and dolines, as well as deeper features, in the form of solution enlarged fractures and cave systems. Surface karstic features can be an important indicator of enhanced aquifer properties (e.g. Mortimore, 1990; Edmonds, 1983; Banks et al., 1995). These karstic features are typically located close to the boundary of the Upper Chalk with overlying Palaeogene sediments.

At the feather edge of the Palaeogene deposits on the Chichester Block, there are several examples of rapid groundwater flow. Pumping tests at a source in Madehurst had a rapid effect on outflows 4 km away around Arundel and Swanbourne lake. Within eight hours of the start of the pumping test the spring outflow was reduced, implying the presence of a well-connected network of fractures. The hydrogeology of this area is extremely complex and is currently under review by the Environment Agency and Southern Water. However, it does appear that, structure and acidic recharge have combined to produce a large and highly connected fracture network. Springs at Fishbourne also appear to be fed by a network of large fractures, with groundwater flow concentrated towards the springs under an arch in the Chichester syncline. A similar scenario is observed at the Havant and Bedhampton springs in Hampshire where tracer tests have indicated flow velocities of 2 km d^{-1} (Atkinson and Smith, 1974).

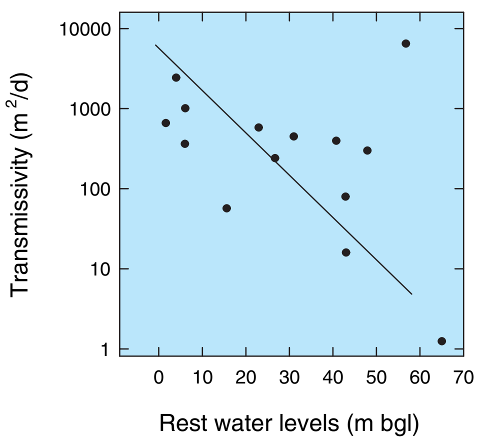


Figure 39 Lack of relation between groundwater level and transmissivity data in the South Downs.

True karstic cave systems have been recorded in the Chalk, from well drilling, tunnel construction, and direct cliff exposure (Banks et al., 1995). The most extensive recorded system in the South Downs is at Beachy Head near Eastbourne, and includes 354 m of explored passages (Reeve, 1981). This is developed along a series of faults and joints and although generally subhorizontal., has occasional vertical steps. The retreat of the cliff line at Beachy Head intersected and exposed the system allowing speleologists the opportunity to examine it. A tabular flint layer appears to be associated with the cave development and was observed to follow the caves even through vertical displacements. It is possible that the perturbation in groundwater flow caused by the presence of the flint layer initiated the dissolution and enlargement of the fractures which were then further enlarged by the concentration of flow through the fractures. As the caves are now mainly above the water table they must have developed when water levels were higher, possibly during the interglacial periods of the Quaternary, or as a result of Palaeogene sea level fluctuations.

DISCUSSION

The various zones of weakness and incipient weakness in the Chalk have developed as a result of stresses initiated as the Chalk was deposited, and modified by diagenesis during its subsequent uplift, as well as a result of the Cretaceous–Palaeogene movements. Fractures of tectonic origin can extend through much

Areal distribution of transmissivity

Transmissivity is related to:
Topography: it is highest in the main valleys, sometimes in excess of 1000 m^2d^{-1}: below the interfluves it may reduce to less than 20 m^2d^{-1}. Smaller dry valleys, tend to exhibit intermediate values, and the yields are poor.

Lithology: Chalk lithology affects the frequency and openness of fractures, which consequently influence transmissivity. For example marly Chalk, such as that in the core of the Singleton Anticline and in the Benfield Valley, has low transmissivity. Marl and flint layers, as well as hardgrounds may focus groundwater flow and encourage dissolution, hence increasing the transmissivity of the Chalk near these horizons.

Major structural features: the Chichester Syncline has affected transmissivity by focusing groundwater in three discharge areas, the Fishbourne springs, Bedhampton springs, and at Arundel, producing zones of high transmissivity.

Proximity to Palaeogene cover: adjacent to the Palaeogene deposits, high transmissivity can be developed due to concentration of chemically aggressive runoff.

of the Chalk sequence, acting as potential preferred flow routes. All these lines of weakness have been selectively developed and enlarged by weathering processes including solution, contraction and expansion through freeze–thaw cycles, and the relaxation of stress in the rock as erosion proceeded and the post-Palaeogene landscape was created. The fractures have been further modified by groundwater flow and dissolution.

The factors that influence the hydrogeology of the Chalk are not always complimentary; for example, structural features do not always coincide with topography, hence the effects of lithology and topographical position may cancel each other out. Lithology, or more precisely lithologicalal contacts, are the most significant factor according to borehole logging investigations. However, there is also some alignment of water inflows according to elevation (Headworth, 1978), reflecting the influence of groundwater circulation on the development of dissolution-enhanced fractures. Flint bands appear to be the single most important lithological horizon with respect to groundwater flow.

Fluid logging is an essential tool for identifying horizons of water movement, and for monitoring temporal changes. Temperature logs indicate that present-day groundwater movement is generally in the top 100 m of the aquifer. At the coast, there may be conductivity variations at greater depth, possibly indicative of water movement relating to previous low base levels during the Pleistocene.

Aquifer properties vary greatly across the South Downs due to the number of independent factors affecting the development of the Chalk. For example, the Seaford Block is notable for very high transmissivities, and very flat hydraulic gradients. An attempt to model transmissivity variations in the South Downs, combining various parameters into a GIS to produce transmissivity maps, was abandoned because insufficient data were available to calibrate the models. A more representative data set would be required, with more detailed aquifer properties data from interfluve and low-value sites, to develop an appropriate model. In the absence of a more sophisticated data set, the topography of the South Downs remains the best regional indicator of transmissivity variations; on a local scale, transmissivity is enhanced close to Palaeogene deposits, and also above flint and marl bands, and in hardgrounds.

4 Hydrogeochemistry

INTRODUCTION

The baseline geochemical conditions and geochemical processes operating in the South Downs aquifer can be described from three lines of investigation:

- sampling of representative public supply sites across the region,
- use of previously unpublished BGS data on pore waters from the Sompting borehole (Young and Monkhouse, 1980) to investigate quality changes through the complete Chalk profile,
- looking at the origins and geochemical characteristics of salinity occurring in the South Downs area using analogies from other studies on the Chalk in other regions.

The groundwater is generally of good quality apart from the local effects of coastal saline intrusion and the threat of pollution, largely from agrochemicals (see Chapters 5 and 6). Intrusion of saline water is mainly a near-surface problem since water of good quality is found below the intruding saline water which tends to move along discrete horizons.

The geological structure of the South Downs has a marked impact on the hydrogeology, and hence the hydrogeochemistry, of the area. A number of east– west folds cross the area (Chapter 3). The most important are the Chichester syncline and the Portsdown anticline which becomes the Littlehampton anticline in the east. Up to 160 m of Palaeogene sediments and drift cover the Chalk near the syncline axis.

Little has been published on the water quality across the South Downs area. During 1994 and 1995 some 31 spring and borehole samples were collected from sites representative of the aquifer in the Chichester, Worthing and Brighton blocks (Figure 40). All waters were sampled from pumped sources, either private or public supply. Measurements of pH, temperature, alkalinity and dissolved oxygen were made in the field and samples (filtered through 0.45 μm) taken for analysis; samples for trace element and cation analysis were acidified to less than pH 1.5 with 1% HNO_3. Analysis for anions was carried out by automated colorimetry and for cations and trace elements by ICP-AES and/or ICP-MS. The analysis of stable isotopes ($\delta^{18}O$, δ^2H) was carried out by mass spectrometry and the results are reported relative to standard mean ocean water (SMOW). This is the most comprehensive suite of low-level trace element data for the Chalk and comparisons with other areas cannot be made.

Results are also presented for interstitial waters from core material from a borehole at Sompting [TQ 1661 0636] obtained to a depth of 250 m above OD in the Chalk. These samples were collected during exploratory drilling into the underlying Lower Greensand (Young and Monkhouse, 1980, figs. 1 and 2) and illustrate the quality of water within the relatively immobile water of the Chalk matrix. Samples were extracted by centrifuge

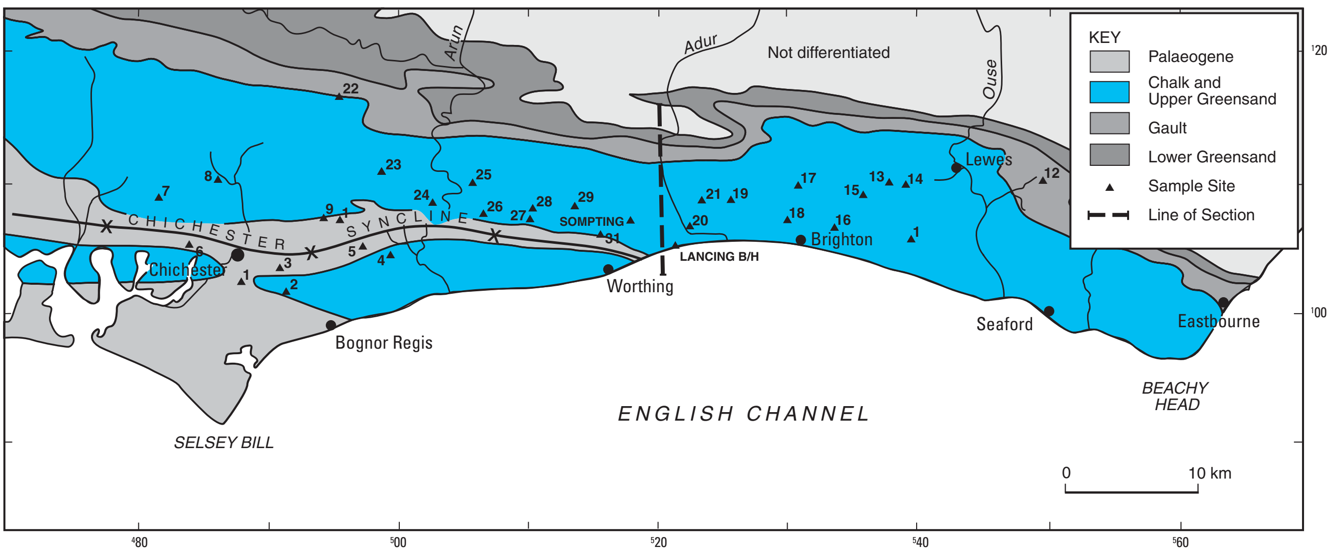


Figure 40 Area of the South Downs showing locations of samples discussed in the present study.

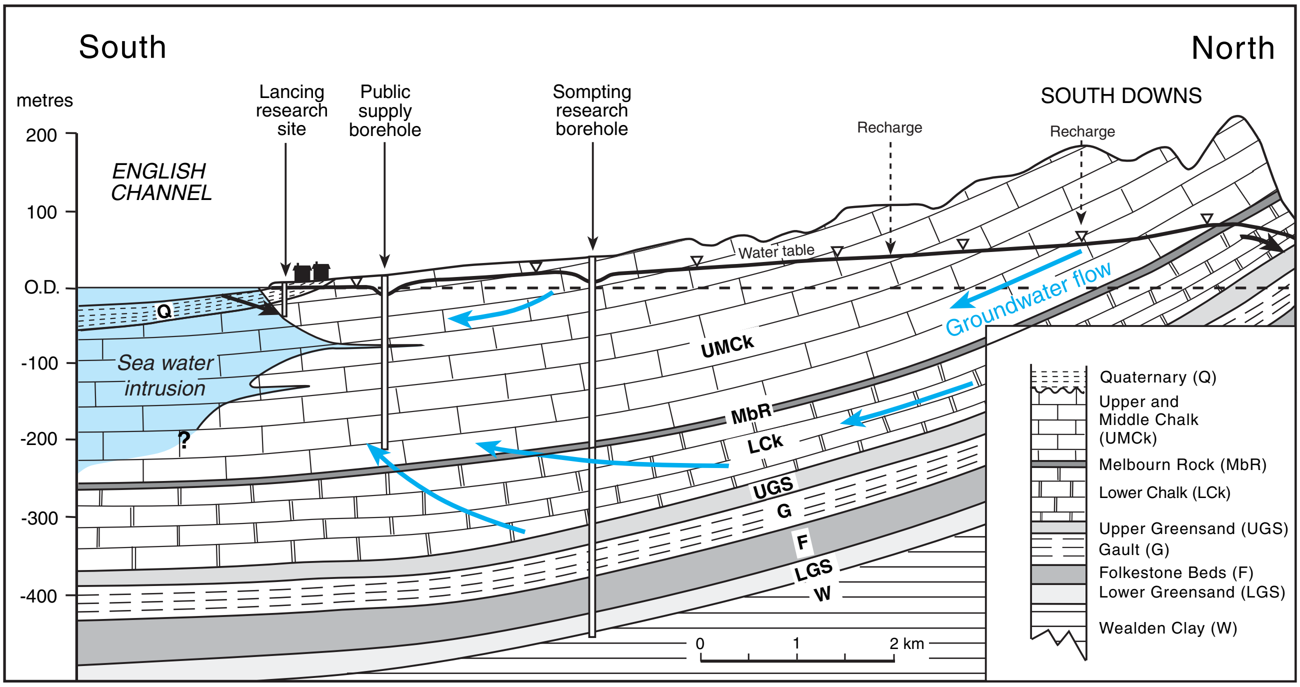


Figure 41 Cross-section through the coastline near Lancing showing the Sompting and Lancing boreholes in relation to the probable (schematic) extent of modern sea water advance.

drainage (Edmunds and Bath, 1976) and analysed for major ions and some minor elements as described below.

Data are also available from a borehole drilled at Widewater lagoon near Lancing (Figures 40 and 41). The borehole was drilled to intercept the saline–fresh water interface at a location where this was considered possible at shallow depths. The Chalk was reached at a depth of 22 m beneath Quaternary sediments, and a gradient between freshwater and sea water found within the cored interval from 22 to 39 m.

MAJOR HYDROCHEMICAL CHARACTERISTICS

The mineral composition of Chalk groundwater is established rapidly as it is controlled largely by reactions involving CO_2. Carbonic acid (HCO_3) is produced in the soil zone by solution of CO_2. Thus HCO_3 concentrations in groundwaters under conditions of equilibrium reflect the partial pressure of CO_2 (pCO_2) of the open system conditions established in the soil or the unsaturated zone. However, the reactivity of the soil water is greatly enhanced by the solution of CO_2 produced biogenically in the soil zone. Therefore the pCO_2 will be greater than atmospheric, and will vary depending on the soil type and depth. The pCO_2 values in the South Downs waters range from 16 to 80 times atmospheric values (Table 8), although many groundwaters lie close to the mean value of 30.6 times atmospheric.

Saturation with calcite is typically attained within a few metres of the ground surface (Edmunds et al., 1992); the saturation of the Chalk groundwaters of the South Downs is illustrated in Table 8. During infiltration, the groundwater acquires a calcium-rich composition with Mg/Ca ratio close to that of the Chalk (Figure 42). Chalk dissolution is greatly reduced below the first few metres of the unsaturated zone, although a small percentage of by-pass flow through open fractures may result in calcite-undersaturated water being transported to deeper levels. This potentially aggressive water has the capacity for fracture enlargement.

The chemical analyses of groundwaters from the South Downs aquifer are given in Table 8. All the sites are sufficiently remote from the coastline to be considered free from the influence of modern saline intrusion, with the possible exception of Shoreham which has a Cl concentration of 52 mg l^{-1}. The elevated chloride concentrations in a few of the other groundwaters (samples 1 to 5 with a maximum 202 mg l^{-1} at Northmundham) probably represent residual salinity from former, possibly connate marine water from the geological past (Bath and Edmunds, 1981). The human inputs of Cl in this area are small.

Cl is a conservative ion (not added or removed by water–rock interaction), and can be used in a mass balance equation to estimate recharge. If it assumed that the average Cl (29.0 mg l^{-1}) in sources (excepting those with elevated levels of Cl) must be principally derived from rainfall, it is possible to provide a minimum estimate of the areal recharge using the formula:

$$R = P.Cp/Cg,$$

where P is the mean annual precipitation, Cp is the spatially averaged mean concentration of Cl in rain and Cg the spatially averaged concentration in groundwater. Using a value for P of 844 mm yr^{-1} and a mean chloride in rainfall of 7 mg l^{-1} a recharge value of 204 mm yr^{-1} is calculated which compares with that calculated from physical measurements of 337 mm yr^{-1} (Monkhouse et al., 1982). The lower chemically derived value for recharge suggests that the Cl concentration in groundwater may include a contribution from dry deposition or agricultural sources.

Table 8 Chemical analyses of groundwater from the South Downs (mg l^{-1}).

No.	Locality	Temp.	Ph_field	O_2	SEC*	Na	K	Ca	Mg	HCO_3-fld	SO_4	Cl	NO_3-N	Si	Sr	Ba	Li	Rb	B
1	Northmundham	11.20	7.11	0.90	1281.00	153.1	9.13	30.50	30.51	276.00	38.1	202.00	-0.3	6.89	6.357	87.9	17.19	2.91	250.40
2	Park Farm	12.00	6.56	1.90	949.00	38.9	1.85	121.57	11.68	370.00	27.5	68.1	-0.3	4.81	0.855	104.1	3.63	1.22	36.70
3	Groves Farm	13.00	7.52	4.10	970.00	33.8	4.34	153.32	6.48	398.00	65.8	58.5	-0.3	3.56	0.341	56.2	2.00	1.15	41.30
4	Wicks Farm	12.90	6.69	5.80	1003.00	35.1	1.95	146.82	10.56	345.00	57.8	67.5	10.5	3.69	0.262	25.3	1.31	0.45	37.10
5	Hollards Farm	14.40	6.82	9.90	814.00	41.7	3.92	83.32	12.39	273.00	21.6	75.3	1.6	4.06	2.257	98.0	4.48	1.13	52.60
6	Fishbourne	10.90	6.11	8.30	633.00	13.0	1.93	109.42	3.47	293.00	18.1	25.1	7.7	4.08	0.280	17.7	0.76	0.76	26.00
7	Funtington	13.00	6.74	9.50	640.00	10.0	0.97	94.06	1.71	272.00	10.8	20.3	5.4	3.18	0.234	16.5	1.01	0.73	12.90
8	Lavant	12.30	7.29	8.70	576.00	12.1	1.51	103.58	1.98	244.00	11.0	24.7	6.8	4.43	0.232	24.1	0.48	0.40	12.70
9	Westergate	11.60	6.57	8.90	757.00	18.3	1.60	118.46	4.07	314.00	17.6	35.9	10.0	3.88	0.334	23.6	0.99	0.73	27.30
10	Eastergate	10.90	6.67	7.80	687.00	16.9	1.55	115.60	3.80	294.00	15.9	32.4	8.5	3.96	0.341	21.9	1.03	0.66	31.70
11	Balsdean	11.10	6.89	9.30	602.00	22.6	0.93	87.00	2.98	218.00	10.7	40.4	6.3	3.06	0.185	10.3	1.05	0.59	23.60
12	Southover	12.20	6.96	9.30	594.00	13.8	1.04	92.86	2.15	241.00	13.7	27.3	5.5	3.20	0.184	10.2	0.68	0.55	14.50
13	Housedean	10.80	6.90	10.40	579.00	14.1	1.93	90.61	2.41	248.00	9.5	27.6	6.5	3.01	0.194	11.3	0.58	0.85	16.30
14	Newmarket	11.30	6.87	9.20	560.00	13.6	0.89	89.78	2.14	247.00	10.9	25.9	5.6	3.02	0.191	11.4	0.64	0.71	15.50
15	Falmer	11.10	6.99	7.10	684.00	17.7	0.86	101.34	2.57	269.00	16.4	32.3	6.5	3.10	0.230	15.9	0.71	0.64	26.50
16	Lewes Road	11.70	6.90	9.50	622.00	22.1	1.85	98.81	2.98	213.00	30.8	38.6	7.8	3.06	0.208	15.9	1.63	0.94	46.00
17	Patcham	11.50	6.86	9.40	580.00	12.5	0.92	84.34	2.07	215.00	11.8	24.3	4.5	3.23	0.212	17.7	1.17	0.86	13.80
18	Goldstone	11.70	6.99	8.70	696.00	18.4	1.63	101.92	2.81	252.00	17.2	33.1	8.4	4.19	0.234	15.0	0.93	0.90	23.10
19	Mile Oak	11.40	6.94	9.20	585.00	14.4	0.51	80.97	2.06	221.00	10.3	25.6	5.4	3.54	0.182	7.6	2.15		23.70
20	Shoreham	11.90	6.95	8.50	671.00	29.4	1.32	98.83	4.34	238.00	24.9	52.0	7.3	4.52	0.218	10.8	0.88	0.75	28.60
21	Mossy Bottan	11.70	7.01	8.90	544.00	15.5	0.70	89.89	2.21	239.00	14.7	28.3	6.0	4.10	0.182	8.7	0.53	0.47	18.60
22	Dunctan Mill	9.80	7.02	6.90	603.00	8.0	3.12	109.31	3.79	298.00	30.2	17.9	3.2	8.30	1.773	12.4	5.33	1.75	23.70
23	Madehurst	13.20	6.85	9.30	396.00	11.0	1.13	88.52	1.65	250.00	5.0	20.3	3.1	3.12	0.210	15.0	0.53	0.49	15.10
24	Arundel	13.20	6.77	8.60	512.00	11.6	0.70	89.56	1.81	249.00	6.1	22.1	3.0	3.51	0.203	12.7	0.53	0.46	9.60
25	Burpham	10.50	6.97	7.20	636.00	12.3	1.07	89.03	2.01	241.00	8.0	22.9	4.8	4.26	0.204	11.5	0.67	0.55	13.4
26	Angmering	11.40	6.90	5.10	755.00	19.4	1.62	83.90	3.56	328.00	11.2	34.0	4.9	4.33	0.263	16.0	1.40		
27	Clapham	11.50	6.89	8.80	698.00	18.9	1.54	105.33	2.62	265.00	11.3	33.7	5.1	5.12	0.284	15.7	5.46	0.92	21.60
28	Patching	11.90	6.83	9.50	705.00	12.7	1.27	70.16	2.37	257.00	7.4	23.4	6.0	5.71	0.241	58.1	1.88		42.40
29	Findan	12.80	7.00	6.00	695.00	13.9	1.72	99.49	2.56	250.00	9.6	26.1	5.9	3.19	0.311	21.8	1.27	1.27	21.80
30	Sompting	11.10	6.92	7.30	639.00	18.5	1.34	99.81	2.80	233.00	18.2	32.9	6.6	4.63	0.222	20.9	0.75	0.64	25.80
31	Broadwater	11.10	7.04	0	775.00	14.4	1.76	100.87	2.50	244.00	17.0	27.0	40.9	3.82	0.243	1746.1	0.99	1.14	28.60

SEC* Specific electrical conductance (µS cm^{-1})

Table 8 *(continued)*

No.	Locality	Fe (tot)	Mn	Cu	Ni	Zn	Pb	F	Br	I	pCO_2 × atmos	SI (calcite)
1	Northundham	10.6	1.6	1.60	1.50	1.08	0.38	5.90	630.00	45.0	16.4	-0.27
2	Park Farm	373.8	6.7	0.31	3.47	10.90	0.25	0.67	250.00	6.3	79.7	-0.06
3	Groves Farm	4369.6	111.0	1.59	4.28	52.21	0.25	0.26	190.00	19.3	29.8	0.52
4	Wicks Farm	40.0	5.0	0.64	4.75	172.19	0.40	0.09	230.00	3.0	55.3	0.11
5	Hollards Farm	4.6	1.0	0.49	8.87	15.29	0.32	0.47	230.00	4.3	33.5	-0.04
6	Fishbourne	9.4	1.0	21.88	10.17	44.65	1.68	0.09	83.00	5.1	56.1	-0.14
7	Funtington	0.1	-0.1	10.07	5.51	7.83	0.73	0.07	68.00	3.7	39.8	-0.06
8	Lavant	1.9	0.4	10.75	47.67	19.65	2.07	0.07	68.00	11.3	31.5	-0.04
9	Westergate	-0.1	-0.5	4.84	5.95	28.86	0.91	0.10	110.00	7.7	66.3	-0.12
10	Eastergate	1.6	0.1	16.21	5.71	14.88	1.06	0.10	110.00	7.1	48.9	-0.06
11	Balsdean	0.2	-0.1	7.26	4.00	3.16	0.97	0.10	150.00	6.0	22.0	-0.07
12	Southover	6.4	0.0	1.13	3.32	3.95	0.27	0.07	98.00	4.6	21.0	0.09
13	Housedean	-0.1	-1.0	1.65	3.70	5.31	0.40	0.08	96.00	4.2	24.4	0.01
14	Newmarket	-0.1	0.1	1.55	3.26	4.39	0.20	0.08	92.00	4.5	26.2	-0.02
15	Falmer	3.5	0.2	1.23	3.89	5.52	0.48	0.08	92.00	4.5	21.5	0.17
16	Lewes Road	4.3	0.6	1.63	4.39	4.77	0.40	0.08	130.00	5.7	21.1	0.02
17	Patcham	2.3	0.1	1.19	3.84	3.98	0.33	0.09	82.00	3.9	23.5	-0.11
18	Goldstone	1.6	0.0	11.65	6.84	14.31	1.39	0.09	120.00	5.0	20.3	0.16
19	Mile Oak	-0.1	-0.2	0.92	6.94	2.11		0.09	96.00	4.3	20.0	-0.03
20	Shoreham	2.6	0.1	3.19	5.78	16.21	0.53	0.09	190.00	5.2	21.0	0.07
21	Mossy Bottan	2.2	0.0	1.69	5.44	3.77	0.47	0.09	110.00	4.6	18.4	0.11
22	Dunctan Mill	2.5	0.2	2.58	6.01	3.36	0.49	0.01	57.00	5.8	21.8	0.26
23	Madehurst	3.4	0.0	3.03	5.51	5.98	0.57	0.10	66.00	4.1	28.6	-0.01
24	Arundel	2.6	-0.2	3.83	5.16	4.97	1.10	0.09	71.00	3.9	34.2	-0.08
25	Burpham	4.6	-0.3	4.33	4.81	17.32	0.66	0.09	81.00	4.0	20.1	0.06
26	Angmering	-0.1	-0.1	1.32		3.97		0.09	120.00	6.4	32.5	0.10
27	Clapham	54.6	0.4	4.49	5.68	15.60	0.70	0.10	110.00	4.8	26.8	0.09
28	Patching	3.8	0.6	0.60	4.46	1.81		0.08	78.00	4.6	30.3	-0.13
29	Findan	2.3	-0.1	1.60	5.51	3.81	0.50	0.10	100.00	4.4	20.0	0.18
30	Sompting	4.7	0.4	5.30	6.98	3.84	1.06	0.09	140.00	5.1	21.9	0.04
31	Broadwater	4.2	0.2	2.57	7.68	18.79	2.06	0.09	110.00	5.5	17.3	0.17

All concentration in mg l^{-1}

The Mg/Ca ratio of groundwater provides an indication of its residence time; the closer the ratio is to that of the chalk itself, the shorter is the residence time. Groundwaters in the saturated zone beneath the South Downs have Mg/Ca ratios only slightly above those of the chalk implying that their composition has evolved very little since infiltration, and providing indirect evidence of a short groundwater residence time. Within the Chichester Syncline some groundwaters have a higher Mg/Ca ratio, indicating a degree of water–rock interaction, and preferential release of Mg from the Chalk. Although the direction of hydrochemical evolution differs from that of the Berkshire Chalk (due mainly to the higher Na concentrations in the rainfall in the coastal area), the same trend of increasing Mg/Ca is indicated in both areas.

Dissolved oxygen concentrations average 8.5 mg l^{-1} and confirm that, as recorded elsewhere in the Chalk, aerobic conditions are widespread in the saturated zone (Edmunds et al., 1987; 1992). The concentrations of dissolved oxygen in groundwater are only slightly below atmospheric values and indicate that very little reaction of oxygen has taken place during infiltration through the soil. It is, however, likely that inorganic reactions are important in the gradual reaction and removal of oxygen in some parts of the aquifer.

The aerobic conditions help to maintain very low concentrations of dissolved iron (typically less than 5 µg l^{-1}) and also favour the persistence of nitrate and some other degradable pollutants in the groundwater. Iron (Fe^{2+}), as well as Mn^{2+} and other trace elements are released stoichiometrically from the impure chalk sediment during the initial reactions and are subsequently added at a much slower rate due to incongruent reactions. However, under the prevailing neutral pH and aerobic conditions in the unsaturated zone, the iron is oxidised and precipitates as oxides on the fracture surfaces.

Within the confined Chalk aquifer of the Chichester syncline there is a region of reducing groundwaters. Here groundwaters have zero nitrate (due to denitrification) and elevated concentrations of total dissolved iron (maximum 4.4 mgl^{-1}).

Elsewhere nitrate levels are generally higher than the expected baseline of <2 mg l^{-1} NO_3-N; the mean concentration of nitrate (5.9 mg l^{-1} NO_3-N) must reflect the extent of leaching from improved grassland or arable areas. Leaching of nitrate from agricultural land is covered in Chapter 6.

Saline intrusion of the aquifer a problem in the shallow aquifer near the coast. The interstitial waters at Sompting show low salinity water throughout the saturated thickness of the Chalk (maximum 51 mg l^{-1} Cl)

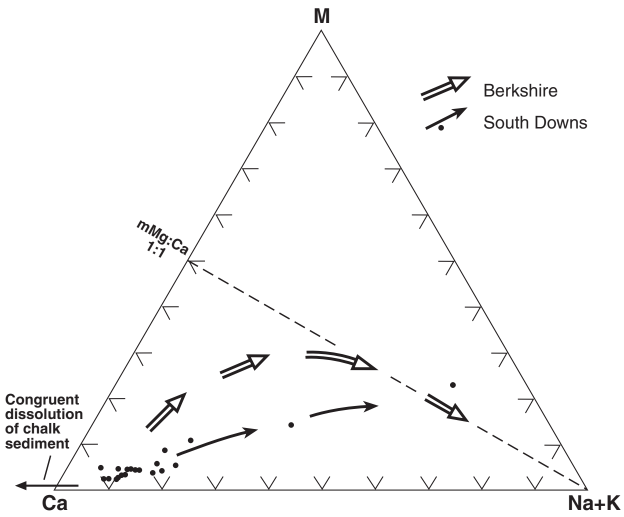


Figure 42 Trilinear diagram showing the evolution of cation composition in groundwaters from the South Downs in relation to the Berkshire area.

to a depth of at least 250 m. Groundwater with low salinity (9 mg l^{-1} Cl) is also found beneath the Chalk at depths in excess of 400m in the Lower Greensand (Young and Monkhouse, 1980). Closer to the coast, interstitial waters from the saline-freshwater interface at Lancing (Table 10) show increasing salinity to almost sea water values at around 37 m. The origin of salinity in the Chalk groundwater is discussed in further details in following sections.

EVOLUTION OF THE CHALK GROUNDWATER OF THE SOUTH DOWNS AQUIFER

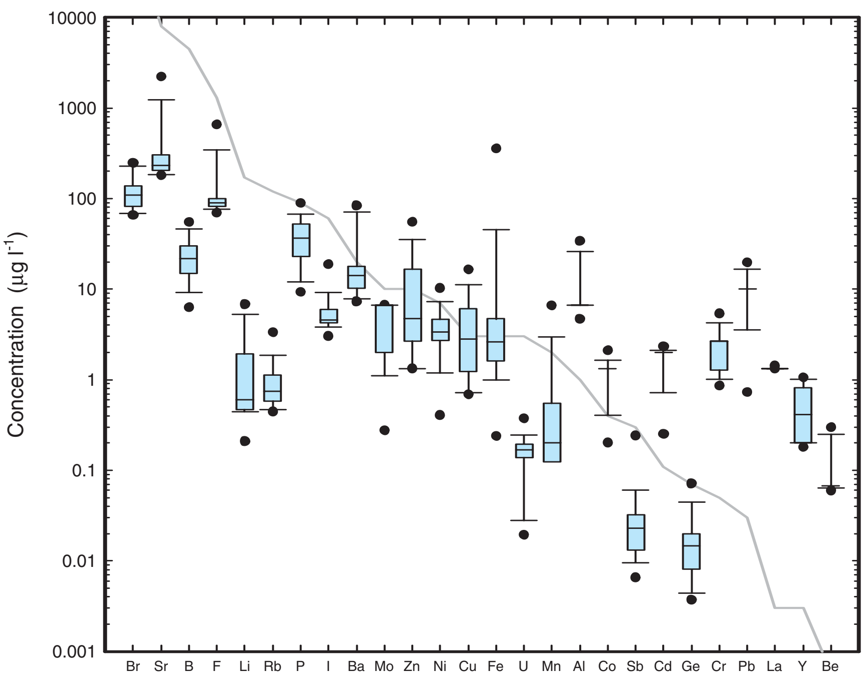
The evolution of the hydrogeochemistry in the South Downs is best described in the context of other areas of the Chalk in southern England (Edmunds et al., 1987). In Figure 42 the cation data for both regions are plotted on a trilinear diagram and in Figures 43 to 46 analyses of interstitial waters and groundwaters are plotted for Na, K, Mg and Sr versus Cl to follow the cation evolution from rainfall inputs and to determine the origins of salinity.

Minor and trace elements in the Chalk groundwater

The concentrations of trace elements and their relationships to major elements, especially chloride, can be used to assist in the interpretation of Chalk groundwater evolution and provide information on baseline characteristics and potability. The concentrations of a number of key minor and trace elements are given in Table 8. In Figure 43, the overall ranges in concentration of a wider spectrum of trace elements is given in order of their abundance in sea water. The data are summarised in terms of their median concentrations as well as the 25th and 75th percentile values. Also shown are the maxima and minima and the 5th and 95th percentile values. Not all the individual elements are described in detail here but a summary of the controls on several elements is given in Edmunds et al. (1989). Since the broad-scale lithology of the aquifer is essentially uniform, the concentrations of trace elements depends firstly on water–rock interaction (dependent on residence-time) and secondly on redox conditions.

In the same way that Mg increases in the groundwater as a result of incongruent solution, so too is a relatively high strontium concentration generally an indicator of evolved groundwater. The rather low and uniform Sr concentrations in the South Downs groundwater therefore indicate short residence times. The three waters from the confined aquifer of the Chichester Block with relatively high Sr relative to Cl (see Figure 48) are likely to be the only ones having long residence times (e.g. > 10^3 yr) in contrast to most groundwaters which

Figure 43 Element ranges and concentrations in water from the South Downs. For each element the data within the 25 and 75 percentile range are highlighted with the median concentration. The outer bars show, respectively, the 5 and 95 percentile data limits. Maxima and minima are given as solid symbols.



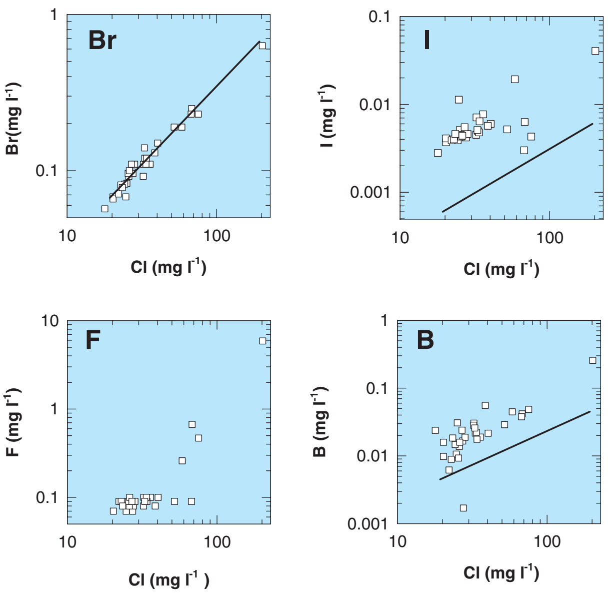


Figure 44 Halogen elements and B plotted relative to chloride. The behaviour of Br is conservative in relation to the other three elements.

probably have a residence time measured in decades at the most.

Under oxidising conditions Mn together with Fe remains at low concentrations, but the concentrations of both elements increase in the reducing environment. The concentrations of other metals (Cu, Ni, Zn, Pb and others — shown in Table 8 and Figure 43) are generally low. Several trace metals are found in chalk and are released during the reactions described above. It is considered more likely therefore that the concentrations represent natural conditions rather than any anthropogenic pollution. The concentration range for most groundwaters is rather small but with some notable departures from the median values. For example in the case of Cu the average 'baseline' concentration in the aerobic groundwaters is between 1 and 5 µg l^{-1} but several waters have values above 10 µg l^{-1}. In the reducing environment the Cu concentrations are significantly lower.

The concentration of the halogen elements (and B) relative to chloride are shown in Figure 44. Bromide is closely correlated with chloride suggesting that it behaves conservatively and the Br/Cl ratio is close to that of sea water (or marine aerosols). Fluoride concentrations, like Sr, are directly related to water–rock interaction, probably released from phosphatic minerals such as fluorapatite in the chalk. Groundwaters with high fluoride (above 0.25 mg l^{-1}) only occur in the Chichester Syncline, and they indicate a longer residence time than other waters in the South Downs area where the fluoride is typically below 0.1 mg l^{-1}. Iodine is also above the sea water line; this conforms with observations of fractionation and enrichment in marine aerosols (Duce and Hoffman, 1976).

Stable isotope composition

The range of stable isotope compositions is relatively narrow and the mean values of $\delta^{18}O$ = -6.45 and $\delta^{2}H$ = -38.6‰ are typical of those for recent meteoric waters for the southern UK (Darling et al., 1996). One sample only, from Northmundham in the Chichester syncline area has a lighter isotopic composition (-7.7‰ $\delta^{18}O$) which

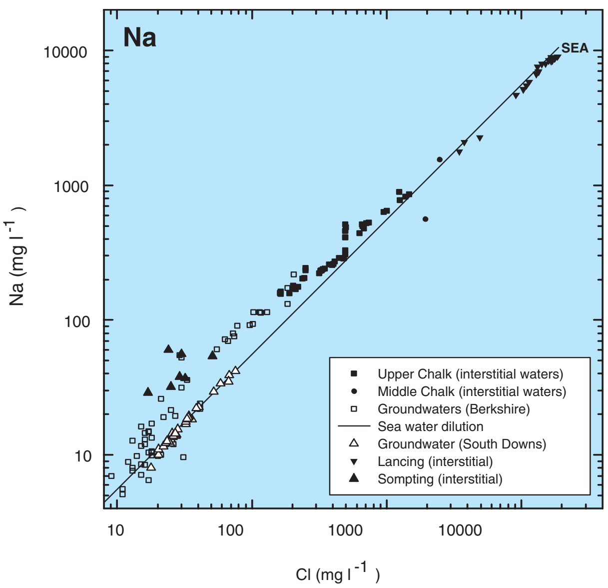


Figure 45 Hydrogeochemistry of Na in groundwaters from the South Downs area in relation to those from Berkshire (interstitial waters from the Upper and Middle Chalk as well as pumped groundwaters).

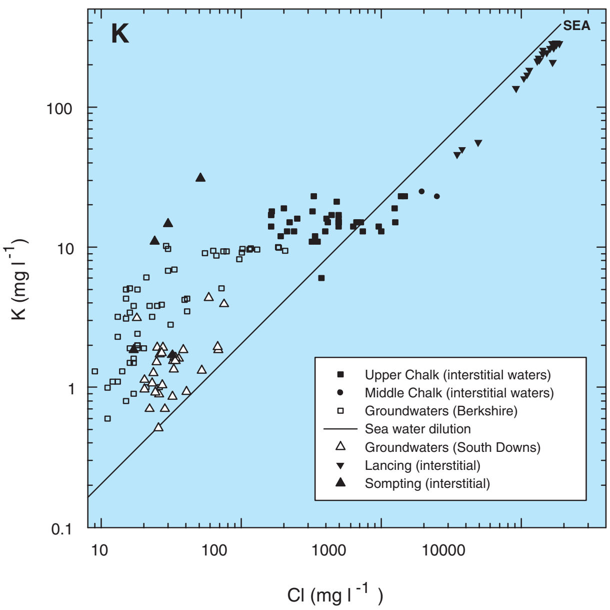


Figure 46 Hydrogeochemistry of K in groundwaters from the South Downs area in relation to those from Berkshire (interstitial waters from the Upper and Middle Chalk as well as pumped groundwaters).

indicates a probable palaeowater signature. Therefore, most of the groundwater currently is modern.

The carbon stable isotope values (Table 8) lie in the range -12.1 to -17.3‰ which is well within the range of values indicating congruent reaction between infiltrating groundwater and chalk. The overall range of values confirms the recent infiltration of the groundwaters since more positive values are characteristic of palaeowaters. However, the value for Northmundham (-12.1‰) is rather negative when compared with the oxygen isotope ratio which indicates palaeowater, since enrichment in the heavy carbon isotope in palaeowaters is normally observed elsewhere in the Chalk.

Saline water in the Chalk

In addition to modern sea water, which is clearly recognisable by its high Mg/Ca ratio (as well as elsewhere by stable isotopic composition), there is the possibility that salinity found in the Chalk of southern England could have derived from ancient sea water or from formation waters trapped from a former geological era. It is probable that ancient sea water (as well as recent sea water) would have progressively lost Mg since the high Mg/Ca ratio is metastable in the presence of calcite with a tendency to precipitate dolomite towards a composition where Mg/Ca tend to 1. Thus, recent saline waters would be expected to have an Mg/Ca ratio close to that of sea water, the ratio decreasing with the age of the interstitial water.

It has previously been proposed by comparing interstitial water profiles from cored boreholes in East Anglia and Berkshire (Bath and Edmunds., 1981, Edmunds et al., 1987; 1992) that residual salinity in Chalk profiles is derived from original Cretaceous sea water and is thus *sensu stricto* connate water. In areas such as the North Sea coast where subsidence has taken place within the context of the evolution of the North Sea Basin, it is quite feasible that something close to the original marine chemistry (allowing for diagenetic modifications) has been preserved. In other areas of Britain, including inland areas, the original connate water has been removed to a greater or lesser extent by groundwater circulation, depending on antecedent hydraulic gradients. According to this model, the chalk of the south coast of England, where around 1% maximum of the original sea water remains, has clearly undergone considerable flushing in contrast to, for example, the coastal area of East Anglia.

The chemistry of modern saline water in the Chalk of the South Downs is illustrated in the cored borehole at Lancing. The overall salinity gradient is summarised in Table 10 and also shown on Figures 45 to 48. From the element ratios of the more saline samples compared with sea water it can be seen that Na and Ca concentrations remain close to or a little below sea water. The elements K, Mg and also Sr are all relatively depleted with respect to sea water implying that there has been some exchange with the solid phase.

Hydrogeochemical evolution

Salinity ranges from fresh to about one third sea water (excepting the areas such as the Lancing borehole where modern invasion has clearly occurred).

Sodium is enriched to a limited extent in the fresh groundwaters probably by exchange reactions with

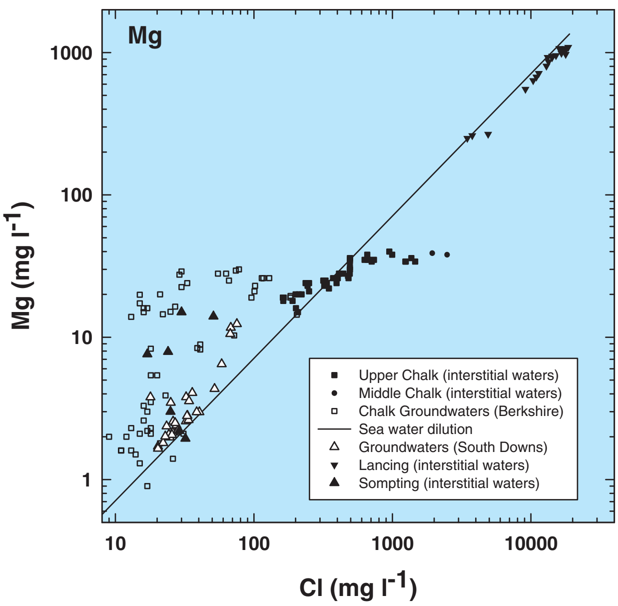


Figure 47 Hydrogeochemistry of Mg in groundwaters from the South Downs area in relation to those from Berkshire (interstitial waters from the Upper and Middle Chalk as well as pumped groundwaters).

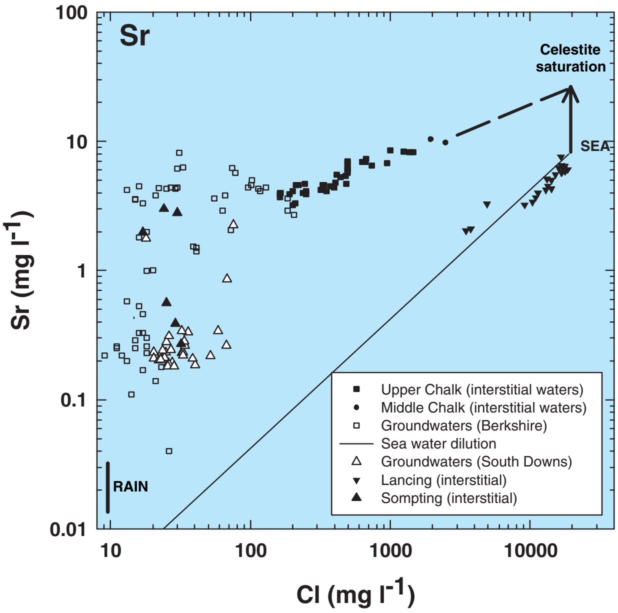


Figure 48 Hydrogeochemistry of Sr in groundwaters from the South Downs area in relation to those from Berkshire (interstitial waters from the Upper and Middle Chalk as well as pumped groundwaters).

Table 9 Partial analyses of interstitial water from the Upper, Middle and Lower Chalk at Sompting.

	Depth	Ca	Mg	Na	K	SO_4	Cl	Sr	Li	B	Ba	F
Upper Chalk	50	49	1.94	37	1.7	9.3	32	0.27	< 0.01	0.048	0.79	nd
Middle Chalk	75	58	2.2	38	11.5	13	29	0.39	< 0.008	0.051	0.35	nd
	100	69	3.0	32	16.5	23	25	0.56	0.010	0.049	0.37	0.085
	125	57	7.6	29	1.85	37	17	1.98	0.010	nd	nd	3.3
	150	56	7.9	60	11	nd	24	3.0	nd	nd	nd	4.0
	200	33	15.0	56	14.7	81	30	2.8	0.041	0.688	0.39	5.0
Lower Chalk	250	70	14.0	54	31	nd	51	nd	0.100	nd	nd	nd

Depth in metres and concentrations in mg l^{-1}

clays formed during early diagenesis. This process is residence-time dependent and the lack of enrichment in Na relative to Cl (Figure 45) implies that the residence time of groundwaters in the South Downs is relatively short. Magnesium (Figure 47) also shows a distinct enrichment in the freshwaters without any Cl increase. This is explained by incongruent reactions with the biogenic marine calcite which on freshwater reaction is stabilised by release of Mg impurities. This effect is even more clearly shown by strontium (Figure 48). Whereas the upper limit to Mg solubility is limited by the solubility of dolomite, strontium solubility is only limited by the availability of the mineral celestite (strontium sulphate). The control by celestite is seen in the most saline waters. If the strontium in the interstitial waters is extrapolated to sea water composition then this represents an enriched Sr concentration of an early pore water with Sr derived during early diagenesis from aragonitic tests and high-Mg calcite. Celestite has also been found as a fracture fill in the Chalk in East Anglia (Bath and Edmunds, 1981). In contrast to Sr the Mg does not increase with salinity since dolomite solubility would be exceeded and the Mg is removed probably onto clays. The same is true for potassium (Figure 46) and there is evidence that K is removed also at the present day during saline intrusion (see Table 9).

Some enrichment in Mg, Sr and K takes place in the fresh waters although Na enrichment is not observed. The interstitial waters from Sompting show strong enrichment in several key elements such as Sr and also F even though Cl concentrations in this borehole do not exceed 51 mg l^{-1}. This low salinity, Mg and Sr enriched composition is identical with some of the evolved groundwaters found in the Berkshire basin and also compares closely with the deepest waters found in the Chichester syncline where the Cl maximum is 202 mg l^{-1}. In the latter area the groundwaters also have compositions high in some trace elements which are distinctive of a considerable residence time.

The South Downs coastal area contrasts strongly with East Anglia where the column of original sea water, only slightly modified, is preserved. Any residual formation water at depth, represented by Cl, has been almost completely flushed out (Sompting) but some

Table 10 Representative data (mg l^{-1}) and ionic ratios for the Lancing borehole.

Depth (m)	Cl	Na	K	Ca	Mg	Sr	mNa/Cl	mK/Cl	mCa/Cl	mMg/Cl ($\times10^{-3}$)	mSR/Cl	mMg/Ca
25.7	97.9	77.4	1.18	12.7	20.6	0.046	0.79	0.012	0.13	0.21	0.47	1.62
25.9	106.3	90.9	1.28	13.3	21.5	0.048	0.86	0.012	0.125	0.2	0.45	1.62
26.2	138.4	98.3	1.43	14.1	22	0.074	0.71	0.01	0.102	0.16	0.54	1.56
27.0	257.2	203.1	3.48	16.3	45.5	0.074	0.79	0.014	0.063	0.18	0.29	2.79
28.1	292.6	223.6	4.09	15.9	52.3	0.077	0.76	0.014	0.054	0.18	0.26	3.29
28.3	308.5	108.3	4.35	16	55.5	0.084	0.35	0.014	0.052	0.18	0.27	3.46
28.4	321.4	254	4.71	15.9	58.8	0.091	0.79	0.015	0.05	0.18	0.28	3.7
29.5	364.9	290.6	5.42	16.7	66.2	0.096	0.8	0.015	0.046	0.18	0.26	3.96
29.7	377.9	303.2	5.53	17.4	71	0.103	0.8	0.015	0.046	0.19	0.27	4.08
30.5	400.8	313.6	6.55	17.3	75.9	0.098	0.78	0.016	0.043	0.19	0.24	4.38
30.7	372.6	327.6	5.73	18.6	78.4	0.117	0.88	0.015	0.05	0.21	0.31	4.22
31.3	400.2	344.5	6.14	18.6	77.7	0.114	0.86	0.015	0.046	0.19	0.28	4.18
31.4	427.6	346.7	6.24	18.6	78.4	0.125	0.81	0.015	0.044	0.18	0.29	4.21
32.5	470.0	362.4	5.32	18.8	86.4	0.131	0.77	0.011	0.04	0.18	0.28	4.61
33.1	477.5	367.1	6.75	19.4	84.8	0.131	0.77	0.014	0.041	0.18	0.27	4.38
33.2	451.4	366.7	6.7	19	88.1	0.142	0.81	0.015	0.042	0.2	0.31	4.64
33.9	502.3	382.8	7.34	18.7	80	0.134	0.76	0.015	0.037	0.16	0.27	4.29
34.0	472.2	382.8	7.29	18.9	83.9	0.149	0.81	0.015	0.04	0.18	0.31	4.45
34.1	494.0	379.3	7.32	19.7	83.1	0.139	0.77	0.015	0.04	0.17	0.28	4.22
35.9	500.5	383.7	7.11	19.1	88.1	0.146	0.77	0.014	0.038	0.18	0.29	4.62
37.5	468.5	385.8	7.26	19.7	81.5	173	0.82	0.016	0.042	0.17	0.37	4.13
37.7	523.8	391.1	7.26	19.6	89.7	0.138	0.75	0.014	0.037	0.17	0.26	4.57
sea water	535.8	456.8	9.98	20.5	111.1	0.183	0.85	0.019	0.038	0.21	0.00034	5.4299575

enrichment of other ions such as F, Sr, and Li in the fresh water indicates considerable water–rock interaction chemistry in the Chichester Syncline and in the Sompting pore waters. In the Chichester syncline some of the original salinity is preserved. It is possible that the extent of flushing could have been accelerated during the events associated with the Alpine orogeny, but also that freshwater flux could have been significant during the late Pleistocene when sea level was over 100 m lower than at present.

SUMMARY

The chemistry of groundwaters in the South Downs is controlled by:

- rainfall inputs,
- initial rapid water–rock interaction,
- modification of the chemical composition by incongruent reaction with increasing residence time,
- mixing with small amounts of saline and chemically evolved water from the matrix storage,
- mixing with sea water in localised instances near the coast.

Chalk groundwater in the South Downs is generally of good quality, although with salinity problems in certain areas. Nitrate concentrations are above the expected baseline, and indicate some leaching from agricultural land.

Generally the groundwaters are aerobic; dissolved oxygen concentrations are high, there is little degradation of nitrate, and Fe and Mn are low. The Mg/Ca ratio is close to that of the Chalk sediment, implying relatively short residence times, as do the low concentrations of ions such as F, Sr and Li. Beneath the Chichester Syncline, waters tend to be anaerobic, with loss of nitrate, and increasing concentration of metals. The Sr/Cl ratio for most of the waters indicates residence times in the order of decades, the exception again being beneath the Chichester Syncline. This is backed up by isotopic evidence, which suggests that most of the exploited groundwater in the area is modern, although one sample from the confined chalk beneath the Chichester Syncline had a lighter isotopic composition, indicating a probable palaeowater signature.

5 Saline intrusion

INTRODUCTION

The Chalk of the South Downs is susceptible to saline intrusion due to its location and to the intensive use of the aquifer. Saline intrusion along the coast and estuaries is influenced by three factors: tidal effects, natural groundwater head, and groundwater abstraction. The southward dipping Chalk of South Downs is in contact with the sea in many places, and saline water may enter the aquifer to create a wedge of relatively dense saline water beneath fresh groundwater. In the case of non-fractured aquifers, the depth to the saline interface is determined by the density difference between fresh water and sea water: the Ghyben-Herzberg relationship suggests that the depth to the interface is approximately 40 times the groundwater head above sea level.

The Chalk is extensively fractured with dual porosity and permeability characteristics, and although the overall influx of saline water depends on groundwater head, the detailed situation is complex. Borehole logging indicates that saline intrusion occurs predominantly through horizontally orientated fractures, and saline water can penetrate a considerable distance inland even when there is a net seaward flow of fresh water. Penetration depends on the size and characteristics of the fracture system, and the relationship between inland groundwater heads and tidal levels, and in some areas by abstraction for public or private water supply.

When tidal conditions change or the freshwater head increases, the saline water is flushed out of the fracture system by fresh water. When saline conditions persist, however, there is a gradual diffusion of sea water from the fractures into the pores of the Chalk. In zones of the Chalk that are not fractured, the pore water remains relatively fresh. Since the water-bearing fractures are generally found in the upper part of the aquifer, there is no mechanism for saline water to diffuse into the pores at depth and this water remains fresh. In the Brighton and eastern part of the Worthing Chalk blocks, resistivity logging showed that below about 130 m depth, the pores of the Chalk contained relatively fresh water.

Historically, the problem of saline intrusion has been most severe in the Brighton Chalk Block. Because of this, an abstraction policy was introduced in 1957 whereby coastal boreholes (leakage stations) are preferentially pumped during the winter months, intercepting freshwater outflows but allowing the water levels in the inland boreholes (storage stations) to recover. During the summer the situation is reversed, with inland boreholes preferentially pumped, utilising the storage which builds up over the winter months (see Chapter 7).

The Chichester and Worthing Chalk blocks are afforded some protection from saline intrusion by the Chichester syncline, which forms a low permeability 'barrier' to groundwater flow, extending from Chichester in the west to Lancing in the east (see Figure 4). Saline intrusion can still occur along the coast to the south of this barrier, and also in the east of the Worthing Block where the syncline runs out to sea. A second geological barrier exists at the east of the Eastbourne Block between Beachy Head and Eastbourne, where the basal (lower permeability) beds of the Lower Chalk are exposed in the cliffs, preventing any direct intrusion from the sea. However the remainder of the Eastbourne Block and the Seaford Block, like the Brighton Block, have no geological protection from the sea and saline intrusion poses a major problem for groundwater management.

There is additional potential for saline intrusion along the flanks of each of the Chalk blocks where the Chalk is in contact with tidal rivers. For example, the Chichester Chalk Block is at risk from the Arun on its eastern flank; the Worthing Block is at risk from the both the Arun to the west and the Adur to the east; the Brighton Block suffers from salinity in the Adur on its western flank and the Ouse on its eastern flank; the Seaford Block is at risk from the Ouse and Cuckmere to the west and east respectively; and the Eastbourne Block in flanked by the Cuckmere to the west.

GEOPHYSICAL LOGGING OF BOREHOLES TO INVESTIGATE AND MONITOR SALINE INTRUSION

Historical background

Borehole logging has been used in the South Downs to investigate and monitor saline intrusion, with most effort concentrated on fluid temperature and conductivity techniques in non-pumped boreholes. Much of the work was carried out within the South Downs Investigation (Chapter 7), which investigated the extent of saline intrusion along the Sussex Coast. The programme of logging was initiated in 1972 by the Water Resources Board and the Southern Water Authority and its predecessors, and was continued by the Water Research Centre after 1974.

Five new boreholes were drilled to depths of about 200 m only 100 m from the shoreline in the Brighton Chalk Block between Shoreham Harbour and Brighton, and a sixth borehole 250 m deep, about 500 m from the shoreline at Hove. Extensive geophysical logging was carried out in these boreholes during 1972 and 1973.

Fluid conductivity logging identified increased conductivity (usually warmer) water at specific horizons which coincided with resistivity lows. This was recognised as saline intrusion within fractures. The initial findings were reported in the Second Progress Report of the South Downs Groundwater Project for the period to March 1974, and by Monkhouse and Fleet (1975).

In 1975/76, ten additional saline monitoring boreholes were drilled in the Brighton Block and three were drilled in the eastern part of the Worthing Block at distances of up to 3 km from the coast. Two existing boreholes (at Sompting and Saltdean) were also incorporated into the saline monitoring network.

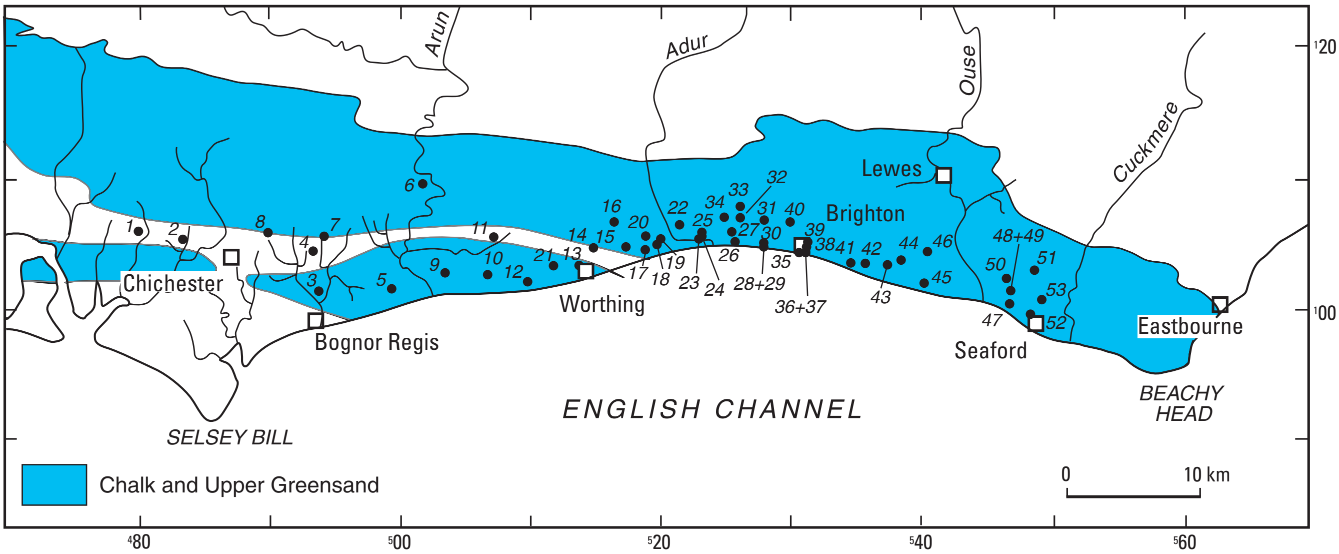
The recommendations of the 1977 report were that regular monthly monitoring should be continued at only two of the above boreholes, with annual logging in the remainder to be carried out at the time when groundwater levels were at their lowest. The monthly logging programme could be reinstated following a winter of poor recharge to track salinity changes during the following summer. Additional saline monitoring boreholes were recommended in the Chichester, Worthing, Brighton and Seaford blocks and it was recommended that these should be logged on a three-monthly interval at least for the first year.

Between 1977 and 1985, geophysical logging of the boreholes was continued by the Southern Water Authority; but none of the data collected during this period has been analysed or reported. In 1985, the saline monitoring network was expanded to include new boreholes drilled in the Chichester and Seaford blocks, together with additional boreholes in the Worthing and Brighton blocks (see Figure 49). Three cored boreholes (indicated by the initial CBH in Figure 49) were drilled at New Salts Farm, Old Steine, and Western Lawns, adjacent to the existing boreholes, in order to investigate pore water chemistry. No saline monitoring has been carried out in the Eastbourne Chalk Block.

On the reorganisation of the Water Industry in 1989, Southern Science continued the logging programme on behalf of the recently created National Rivers Authority. The results of the logging between 1985 and 1991 were summarised in reports by Southern Science for the National Rivers Authority in 1992 (1992b), and recommendations were made for future monitoring. However no logging has been carried out since this time.

Geophysical logging techniques

Geophysical logging techniques used throughout the investigations were principally static fluid conductivity and temperature, together with formation resistivity logging in some holes. The resistivity of a formation is a function of its porosity and the resistivity of the pore



1	Newells Lane	16	Sompting OB	31	Goldstone OB	46	Telscombe
2	Deeside Ave.	17	Old Salts Farm	32	Greenleas	47	Mercury Motel
3	Shrimpney	18	New Salts Farm	33	Mile Oak North	48	Bishopstone
4	Woodgate	19	New Salts CBH	34	Mile Oak South	49	Bishopstone Deep
5	Climping	20	Daniel's Farm	35	East St. Car Park	50	Poverty Bottom
6	South Stoke	21	Shaftsbury Ave.	36	Old Steine	51	Norton Top
7	Church Lane	22	Shoreham Wimpey	37	Old Steine CBH	52	Sutton Drove
8	Tangmere Road	23	BBC Transmitter	38	Victoria Gardens	53	Cradle Hill
9	Southfield	24	Kingston Middle Rd.	39	St Peter's Church		
10	East Preston	25	Kingston Stoney Lane	40	Preston Park		
11	Hammerpot	26	Travis & Arnold	41	Roedean		
12	Glynde Ave.	27	Trafalgar Road	42	Ovingdean		
13	Victoria Park	28	Western Lawns	43	Rottingdean		
14	Broadwater Elms	29	Western Lawns CBH	44	Saltdean		
15	Lancing	30	Pembroke Gardens	45	Peacehaven		

Figure 49 Location of saline monitoring boreholes.

Table 11 Saline monitoring boreholes.

Block	Borehole	Distance from coast (km)	SEC (max) (µS cm^{-1})	Comments
WORTHING	Old Salts Fm	0.5	Generally up to 20 000 in lower section of borehole 40 000 (prior to 1977)	SEC affected by private water abstraction. No seasonal change or long-term trends observed Tidal efficiency 14, delay 1 hour
	New Salts Fm	1 0.5 from R Adur	40 000	Increases from 4000 to 30 000 µcm^{-1} between 60 and 92 m depth No change in SEC over tidal cycle Tidal efficiency 6, delay 2 hours
	Daniels Barn	2 1 km from R Arun	2500	4 daily peaks Increase in SEC at 40–45 m Tidal efficiency 1.5
	Sompting OB	3 3.5 km from R. Adur	400	SEC up to 2000 µS cm^{-1} at low groundwater levels; peaks at 72 and 100 m depth
	South fields	1 1.3 km from R Arun	>10 000 below 105 m	
	East Preston	1.2	>10 000	Fracturing between 98 and 115 m. Probable increasing pore water salinity at depth
	Glynde Ave	0.4	4000	Fresh to brackish at 60 m. Low SEC for borehole in close proximity to sea
	Victoria Park	0.6	4650	Possible brackish pore water between 58 and 85 m Progressively saline below 115 m. Increase in SEC between 120 and 150 m
	Hammerpot	3.7	350–400	On Chichester syncline. Occasional influxes of a fluid with unusual chemistry and SEC ~2000 µS cm^{-1}
	Broadwater Elms	1.75	<600	Maximum SEC of 1200 µS^{-1} cm recorded in October 1986
	Lancing, Crowshaw	1.25	General increase from ~600 (1983) to 650–700 (recent)	Occasional peak to ~900 µS cm^{-1}
BRIGHTON	BBC Transmitter		40000 (3000 prior to 1977)	Conductivity profiles 1985–1991 very similar to pre-1977 Tidal efficiency 40, delay 1.5 hours
	Kingston Middle Road		700 at base	A typical SEC of 100 µS cm^{-1} recorded in 1985
	Kingstone Stoney Lane		400–600	Decrease in resistivity below 170 m indicating elevated Cl in pore water SEC of greater than 1000 µS^{-1} cm recorded in 1987
	Travis and Arnold	<0.5?	40 000	May be affected by harbour locks Tidal efficiency 4, delay 8 hours
	Western Lawns	coast (0.1)	50 000	Lower SEC above 50 m suggests fresh-water flow to sea. Tidal efficiency 20, delay 1 hour
	Pembroke Gardens	0.4	2000	Sharp increase in SEC at 125 m depth Tidal efficiency 3, delay 8 hours
	Goldstone OB	2	500	
	Old Steine	coast (0.1)	500 to approximately 120 m, increasing 1000 below	Dramatic changes in SEC recorded at times of low groundwater levels (e.g. 35 000 µS cm^{-1} in August 1976) Tidal efficiency 40, delay 1 hour
	Victoria Gardens	0.6	650	Little tidal effect. SEC peaks at times of unknown origin. Tidal efficiency 0.1, delay 4 hours
	St Peters Church	1	650	SEC peaks at times of unknown origin
	Preston Park	2.5	450	
	East St. car park	coast	> 35000	
	Roedean	0.5	15 000	SEC increases with depth Tidal efficiency 8, delay 2 hours

Table 11 *continued*

Block	Borehole	Distance from coast (km)	SEC (max) (µS cm^{-1})	Comments
BRIGHTON *continued*	Ovingdean	0.5	700	SEC 500 µS cm^{-1} at top, decreasing to 400 µS cm^{-1} below~600 Tidal efficiency 5, delay 6 hours
	Rottingdean	1	600	1991 — slight increase in SEC at base, coincident with period of low groundwater levels
	Telscombe	3 2 km from R Ouse	500	Occasional increases to ~700 µS cm^{-1}
	Saltdean	1?	15 000	
	Peacehaven	0.7	max 700	SEC decreases with depth. May be increase in pore water salinity below 60 m
	Shoreham Wimpney	2 km <1 km R Adur	500	Mid 1989 onwards increase in SEC up to ~1000 µS cm^{-1} between 145 and 160 m — depth corresponds with significant reduction in groundwater level between 1989 and 1991
	Trafalgar Road	1 km	400–650	Mile Oak South, Trafalgar Road, Greenleas and Mile Oak North all located in same dry valley Occasionally peaks up to 800 µS cm^{-1}
	Mile Oak South	2 km	400	
	Greenleas	2.5	800–950	Slight increase with time — possibly associated with low groundwater levels 1989–91 Elevated SEC for an inland site. Chemical analysis (1988) suggested may be due to agrochemical pollution
	Mile Oak North	3.5	400	
CHICHESTER	Newells Lane		~400	Funtingdon abstraction borehole 2.5 km NE
	Deeside Avenue		~400	Funtingdon abstraction borehole 4 km NE
	Shripney	near coast	20 000 to 100 m increases to 30 000 at 145 m	
	Woodgate	7	~2000	Tidally affected Eastergate and Westergate sources ~3 km N
	Climping	<1 km	>33 000 at >110 m depth	Tidally affected
	South Stoke	0.5 from R Arun	>10 000	Fracture zone at ~70 m
	Church Lane	8		
	Tangmere Road	9		
SEAFORD	Mercury Motel	0.5	25 000	2 stepped increases between 25–40 m and 55–65 m
	Bishopstone	6		
	Bishopstone Deep	6	max 20 000	Many stepped increases to 95 m where SEC increases from 10 000 to 20 000 µScm^{-1}. Depths of increases are both tidally and seasonally affected
	Poverty Bottom	2.5 (2.5 km from Ouse)		Above 82 m, SEC ~200 µS cm^{-1}; below 82 m, SEC 4000 to 5000 increase to maximum of 1500 and 7000 respectively by1991. High SEC probably associated with abstraction from Poverty Bottom
	Norton Top	3.75	500	
	Sutton Drove	8	Upper hole 1500, increasing to 27000 toward base	Interface fluctuates between 60 and 80 m
	Cradle Hill	3	600-800 above 70 m depth, 1000–1400 below 70 m	

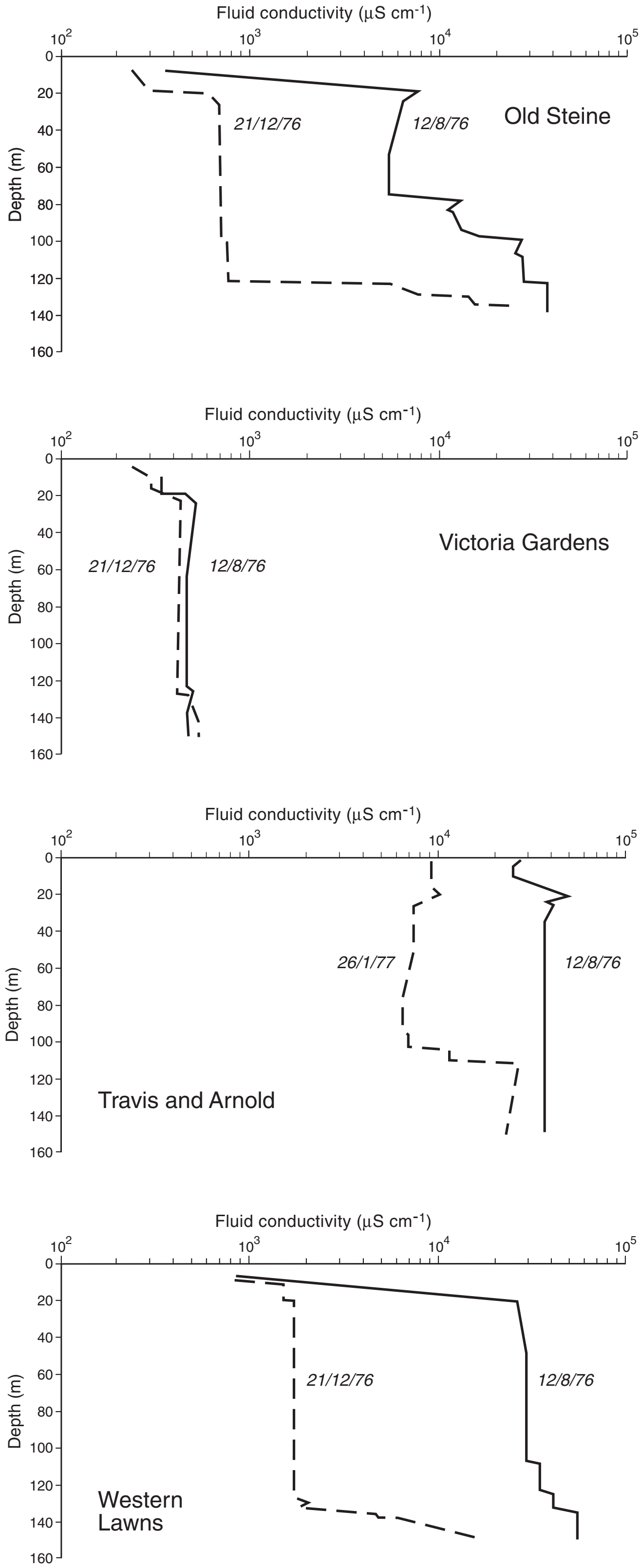


Figure 50 Conductivity profiles at the end of the 1976 drought (12/8/76) and after groundwater recovery (21/12/76): Old Steine; Victoria Gardens; Travis and Arnold; Western Lawns.

water. In chalk areas where the pore water is relatively fresh, the pore water resistivity is constantly high, and the resistivity log is primarily a function of porosity, and thus an indicator of lithology. In saline aquifers, the highly conductive pore waters control the resistivity of the formation, and variations respond to changes in the salinity of the pore water.

However, the water column in the borehole also exerts an influence on the measured resistivity. Thus when both borehole and aquifer contain fresh water, the apparent formation resistivity is high, and it is lower when either contain saline water. In certain cases, for example when there is vertical flow or mixing in the borehole, there may be fresh water in the borehole and saline in the aquifer, or vice versa. This results in intermediate values of apparent formation resistivity.

Temperature and conductivity logging of the fluid column is based on the principle that a borehole drilled through the Chalk connects different fracture systems, with vertical flow taking place in the borehole in response to the different piezometric pressures of these horizons. A temperature log will show variations in temperature due to inflow and outflow, superimposed on the natural geothermal gradient. Fluid conductivity logs indicate changes in conductivity associated with the entry into the borehole of different quality waters through fractures, and do not necessarily bear any relation to the pore water conductivity of the Chalk.

General findings

In the course of the logging carried out by the Water Research Centre it was found that each borehole has its own distinct fluid conductivity profile. This profile generally fluctuated between two outer envelope limits which depended on regional groundwater head. Thus conductivities are generally higher during the summer months, a feature that was particularly noticeable during the droughts of 1973 and 1976, and there is normally a reduction in conductivity commencing soon after the onset of winter recharge. The effects of low groundwater head are exemplified in Figure 50, which shows the conductivity profiles for the Old Steine, Victoria Gardens, Travis and Arnold, and Western Lawns boreholes. The figure illustrates the maximum conductivities which occurred at the peak of the 1976 drought and the much lower conductivities which occurred in December 1976 after three months of heavy rain.

In order to investigate the conductivity variations in boreholes caused by tidal effects, conductivity logs were run in selected coastal boreholes at intervals of 1 hour over a complete tidal cycle. The most dramatic tidal effect was observed at Western Lawns, on the Hove seafront, where the saline interface was found to move down the borehole by 86 m between high and low tide. At Pembroke Gardens, some 500 m inland, the saline interface moved through a distance of only 15 m. At Roedean the saline interface moves up and down the borehole by about 21 m, with a delay (normally) of an hour or more between high tide and the saline interface reaching its peak. Thus the influence of the tide on conductivity in the Chalk is unpredictable, with boreholes at similar distances from the coast showing quite different responses and some showing no response at all. In some boreholes, a small change in conductivity occurs with no movement of the saline interface.

Continuous water level recorders were used to measure fluctuations in water level in the boreholes relative to the tidal fluctuations. Calculated borehole tidal efficiencies varied from a maximum of about 40% to a minimum of about 0.1%. As expected, tidal efficiencies generally decrease with distance from the coast, although this relationship again did not always hold. Those boreholes with high tidal efficiencies generally showed greater conductivity changes in response to the tides.

To investigate seasonal change in conductivity, a number of horizons were selected in each borehole and variations in conductivity plotted against time. For coastal boreholes tidal effects were eliminated by taking readings at the same time relative to high tide on each occasion. Conductivity variations were compared with groundwater levels at inland boreholes (since coastal boreholes show little seasonal fluctuation and are affected predominantly by tidal conditions). Several of the boreholes showed a significant seasonal pattern, with low groundwater levels and high conductivities during the summer and higher groundwater levels and lower conductivities during the winter. Boreholes nearer the coast show a greater variation in conductivity than those further inland.

Abstraction from the Chalk lowers regional groundwater levels and in this way accentuates the seasonal variation in conductivity in the boreholes. In some areas variations in abstraction can be seen to have a direct, short-term effect on borehole conductivity. For example, variations in abstraction from Mile Oak, Mossy Bottom and Shoreham at the west of the Brighton Block, from Balsdean at the east of the Brighton Block and from Sompting in the Worthing Block, appear to directly affect conductivities in the coastal boreholes.

Over the period of the study, the lowest groundwater levels (measured as the average rest water level at Mile Oak, Patcham, Goldstone and Lewes Road) occurred between August and December 1973 rather than during the more severe drought of 1976. Similarly, the maximum conductivities measured during the 1976 drought were similar to or lower than those measured during the less severe drought of 1973. This was largely due to a 15% reduction in consumption at the height of the 1976 drought in response to the introduction of hose-pipe bans and requests to the public to reduce consumption. It is interesting to note that the conductivity peak which occurred in several coastal boreholes in October/ November 1976, reflected consumers relaxing their water conservation measures following the onset of heavy rain in September. If there had been no reduction in demand in 1976, it is clear that conductivities would have exceeded those in 1973 and many pumping stations may have experienced problems with high chlorides.

The investigations also highlighted the existence of large variations in fluid conductivity between boreholes only a short distance apart, reflecting whether the boreholes intercept fractures containing saline water. The extent of saline intrusion is predominantly controlled by the degree of fracturing. Fractures allow saline water to penetrate some distance inland, even though a net outflow of groundwater from the aquifer may be maintained. Thus boreholes equidistant from the coast may have quite different conductivity profiles and boreholes adjacent to the coast may not necessarily indicate the presence or absence of saline water in boreholes further inland.

Detailed examination of borehole logs along the Sussex coast indicated that sharp increases in fluid conductivity and changes in temperature coincided with resistivity minima wherever borehole and aquifer fluid were both saline. At other horizons, although saline water was detected in the borehole, formation resistivity maxima indicated fresh pore water. It was concluded that the resistivity lows were associated with zones of fracturing where saline water had gradually diffused into the pore spaces with time.

Interpretation of recent detailed logging of several of the South Downs boreholes by BGS indicates probable positions of water movement at various chalk horizons. It was evident from this work that there appears to be a consistency of water inflows at specific marl and flint bands (see Table 7). The significance of these horizons in terms of groundwater flow has already been discussed in Chapter 3, although their relevance to the problem of saline intrusion is also of great importance. This is of particular interest in the coastal areas, as mixing of fresh and saline water leads to undersaturation in calcium carbonate (Back et al., 1986), and hence to enhanced dissolution of the Chalk.

Chloride ion distribution

Geophysical logging of observation boreholes indicates the extent of the saline intrusion in those fractures intercepted by the borehole but provides little indication of the regional extent of the saline intrusion. This is best obtained by an analysis of the water abstracted from public water supply boreholes as an integrated sample of the water drawn from the surrounding area. Raw water quality data (Figure 51) from public water supply boreholes in the Worthing and Brighton blocks were obtained for October/ November 1990 (a period of relatively low groundwater levels) and for April/May 1991 (a period of higher groundwater levels). Figure 51 also highlights the significance of the tidal Rivers Arun and Adur in causing saline intrusion into the Chalk. The impact of seasonal variations in regional groundwater levels can also be seen, with chlorides in the autumn of 1990 significantly higher than those in the spring of 1991.

SALINE INTRUSION OF CHALK BLOCKS

Chichester Chalk Block

The Chichester Chalk Block is partly protected from saline intrusion by the Chichester syncline, which provides a low permeability barrier to flow. Consequently none of the public supply boreholes are affected by salinity problems. However, monitoring boreholes in the south-east of the block (Shripney and Climping) south of the syncline show a high degree of saline intrusion, with conductivities of up to 20 000 $\mu S\ cm^{-1}$ in the Shripney borehole at 60 m depth, increasing to approximately 30 000 $\mu S\ cm^{-1}$ at 145 m depth. In the

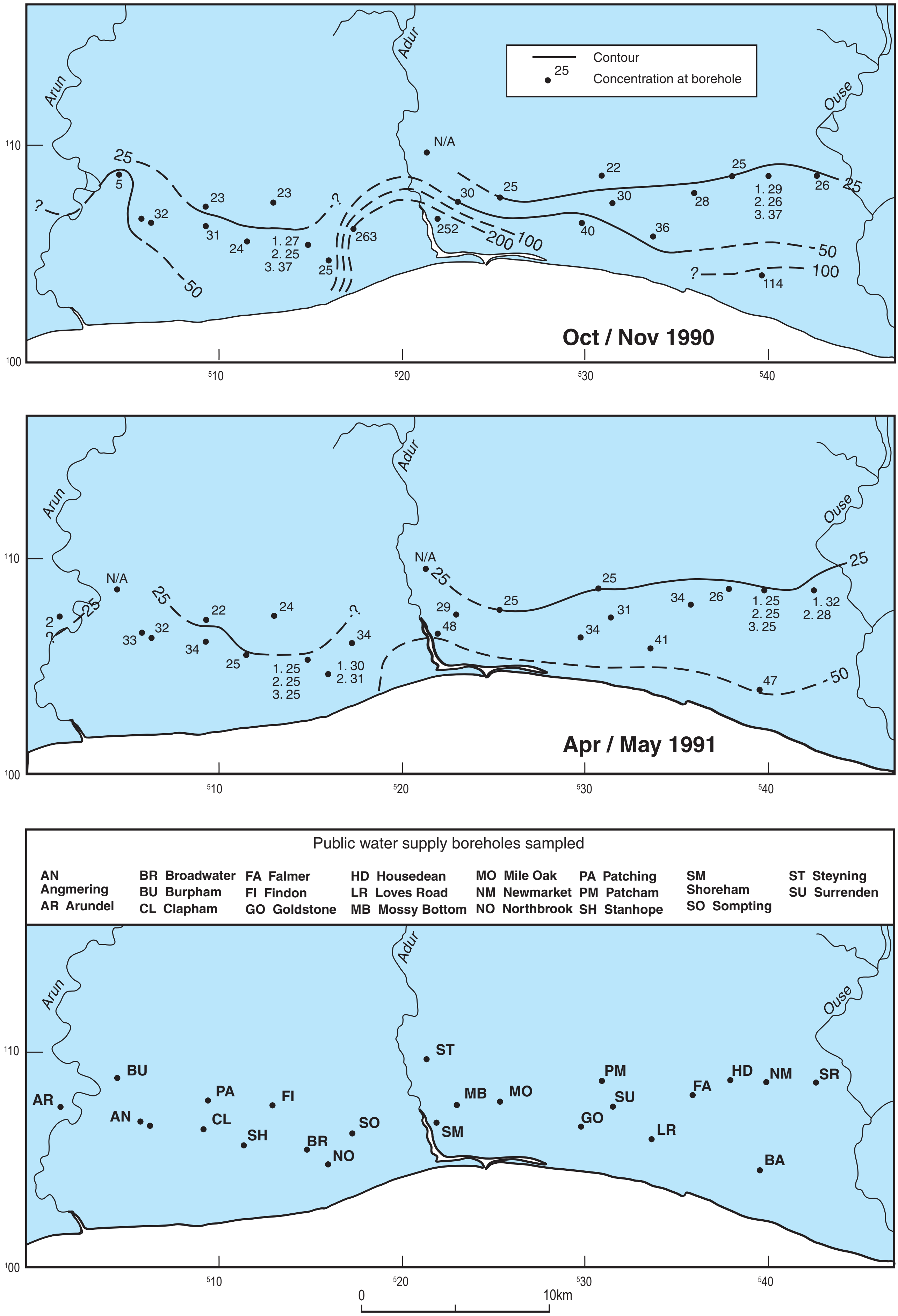


Figure 51 Chloride ion distribution in the Worthing and Brighton blocks (mg l^{-1}).

Climping borehole, conductivities in excess of 33 000 μS cm^{-1} have been recorded below 110 m depth. The high salinity appears to extend inland (at a much reduced level) as far as the southern limb of the syncline, and at the Woodgate monitoring borehole the conductivity is about 2000 μS cm^{-1}, i.e. brackish. The nearest public water supply boreholes (Arundel, Eastergate and Westergate) are more than 5 km to the north, and are not affected by saline intrusion.

The River Arun is a potential source of salinity north of the syncline. However, the source at Arundel, only about 500 m from the river, has no salinity problems (average chloride concentration of approximately 25 mg l^{-1}). This reflects the area of concentrated groundwater flow caused by the adjacent syncline deflecting southerly groundwater flow towards the east. Many springs emerge in this area and the groundwater head is probably sufficient to supply the Arundel borehole and prevent any saline ingress locally. Boreholes on the opposite side of the Arun (in the Worthing Block) are affected by saline intrusion, and in addition, groundwater is saline 1.5 km north of Arundel, at the South Stoke monitoring borehole (also about 500 m from the Arun). The saline water has a maximum conductivity greater than 10 000 μs cm^{-1} and occurs below a fractured zone at about 70 m depth. The formation resistivity decreases from 70 m to the bottom of the hole at approximately 113 m.

Worthing Chalk Block

There are nine groundwater sources for public water supply within the Worthing Block. The western part of the Worthing Block is largely protected from saline intrusion from the sea by the continuation of the Chichester syncline. However, the River Arun in the west, and the River Adur and the sea in the east, are sources of saline water.

In the western part of the block, a major saline incursion occurs to the north of the syncline from the River Arun, and this has a serious impact on abstractions from the Burpham public water supply source. This source is situated about 8 km from the coast, but less than 2 km from the river, and has the largest licensed abstraction of all the Worthing Block sources. Saline intrusion is affected both seasonally and tidally, and abstraction is severely curtailed under conditions of low groundwater level and high tide. Tracer experiments in the 1970s established that the salinity problems resulted from reversal of springs discharging into the River Arun (see Chapter 7). No observation boreholes have been drilled to monitor the extent and behaviour of the intrusion in this area.

The Hammerpot observation borehole, 0.5 km from the Angmering public water supply borehole, was investigated as a result of anomalous conductivity profiles in September 1986 and October 1991 (Southern Science, 1991). The logged profile for December 1985 showed fluid conductivities ranging from 680 to 850 μS cm^{-1} to 62 m depth, at which point there appeared to be a rupture in the borehole casing. Conductivity reduces below this level and ranged from 350 μS cm^{-1} below the rupture, to 400 μS cm^{-1} at the base of the borehole. The two anomalous logs indicated a major increase in conductivity at 84 to 85 m depth, coinciding with a possible fracture horizon interpreted from the caliper log. The highest conductivity in both cases occurred at 104 m depth, although there was no indication of a fracture on the caliper log. Water sampling showed an unusual water chemistry, enriched in dissolved salts, but not characteristic of sea water. It was concluded that these logs represented a localised and periodic condition, related to the confined conditions at this site. It was not possible to rule out contamination, but no obvious source could be identified.

Four monitoring boreholes to the south of the Chichester Syncline (Southfields, East Preston, Glynde Avenue and Victoria Park) all contain brackish water. However, the chloride concentration is not dependant on distance from the coast, since the Southfields and East Preston boreholes show conductivities more than double those at Glynde Avenue and Victoria Park, which are situated furthest from the sea. The geophysical logs from the Southfields borehole show a progressive increase in conductivity with depth, reaching in excess of 10 000 μS cm^{-1} below approximately 105 m depth; no major inflow zones could be detected. At East Preston monitoring borehole, fractures were identified between 98 and 115 m, the latter depth coinciding with the main saline interface. At Glynde Avenue, situated less than 400 m inland, conductivity increases occur at about 62, 79 and 104 m, rising to a maximum of only 4000 μS cm^{-1}. Victoria Park borehole (around 600 m from the coast) showed a conductivity increase between 120 and 150 m bgl, rising to a maximum of over 4500 μS cm^{-1} at the base of the hole.

Formation resistivity logs of the Southfields and East Preston boreholes showed a gradual reduction in resistivity with depth, indicating increasing pore-water salinity. In contrast, logs of the Glynde Avenue borehole indicated a marked transition at approximately 60 m depth, possibly coinciding with fractures. The resistivity profile at Victoria Park is more complex, suggesting some brackish pore water between 58 and 85 m, and increasing salinity with depth from 115 m. However, pore water between these two zones was apparently fresh, possibly suggesting a lack of active fractures between the zones.

To the east of the Worthing Block, saline intrusion from both the sea and the tidal River Adur is possible. The only public water supply source significantly affected is the Sompting source, located about 3 km from the sea, and 3.5 km from the Adur, but which is situated in the area where salinity has penetrated the furthest distance inland from sea or river. This source has fairly high chloride concentrations, particularly during summer months. For example, during the 1976 drought, chloride values at Sompting rose to 216 mg l^{-1}, approximately eight times the normal winter level. It is interesting to note the difference in chloride concentrations between the two production boreholes at Sompting. Chloride concentrations of up to 250 μS cm^{-1} were recorded in Sompting No. 2, and up to 500 μS cm^{-1} in Sompting No. 4 during 1989 and 1990, suggesting that the two boreholes do not intercept the same fracture systems, and that they are not hydraulically connected.

Chloride levels are no higher at Sompting because of the combination of distance from sea and river, and the fact that the Chichester syncline probably diverts groundwater flow eastwards to pass close to the Sompting site. Thermal infrared linescan imagery showed a concentration of spring discharges along the foreshore close to this point (Davies, 1973, Monkhouse and Fleet, 1975).

The monitoring boreholes along the coast, New Salts Farm and Old Salts Farm, show conductivities consistent with sea water in the lower sections of the boreholes. The conductivity at Old Salts Farm varies considerably over short time periods, and is thought to be affected by the pumping of two nearby private sources. Inland, brackish water is found at Daniels Barn (approximately 2500 µS cm^{-1}). At Sompting observation borehole conductivities were generally around 400 µS cm^{-1}, with occasional peaks (up to 800 µS cm^{-1}) associated with low water levels and abstraction from the Sompting source. Logging during the period 1985 to 1991 indicated a general long-term decrease in water quality, with conductivity increasing to approximately 700 µS cm^{-1}, and peaks of up to 2000 µS cm^{-1}.

Pore-water samples were taken from core extracted from a second borehole at New Salts Farm. The pore-water was brackish or saline throughout the Chalk sequence, ranging from 1200 mg l^{-1} to 12 900 mg l^{-1}, with a steady increase from 60 to 90 m, then a slight decrease. There was little correlation between the observed formation resistivity log and pore-water chloride, and it was considered that the formation resistivity was probably being masked by the saline water in the borehole water column (Ellis, 1977). The fact that brackish water was present in the chalk matrix through the whole profile indicates that the chalk in the area has had saline water passing through it for some considerable time. This is not unexpected, considering that the borehole is located within the valley of the River Adur.

Abstraction at Sompting also appears to affect conductivities at the Daniel's Barn, Old Salts Farm and New Salts Farm observation boreholes. For example, a general correlation between conductivity at Daniel's Barn and New Salts Farm, and chloride at Sompting is apparent, and it is possible that increased salinity at Daniel's Barn and New Salts Farm could indicate impending saline intrusion at Sompting. At Daniel's Barn there are four daily peaks in water level, suggesting that levels may be affected by tidal conditions in the River Adur as well as the sea. However, there does not appear to be a change in conductivity over the tidal cycle (here or at New Salts Farm), and monitoring of Old Salts Farm prior to 1977 did not indicate any seasonal change or long-term deterioration at this borehole.

Also in this area, very slightly elevated chlorides occur at Northbrook and Broadwater public water supply sources (32 mg l^{-1} and 27 mg l^{-1} respectively), but these are not sufficiently high to cause any operational problems. The Northbrook borehole is situated closer to the sea than Sompting and the licensed abstraction is only slightly less. The Broadwater source is situated slightly further from the sea than Sompting, but the abstraction is much greater. This again illustrates the variable nature of the Chalk, and the influence that this has on the extent of saline intrusion.

None of the remaining sources in the Worthing Block show signs of saline intrusion, and the average chloride concentrations are generally below 25 mg l^{-1}.

Brighton Chalk Block

The Brighton Block is vulnerable from the sea, and to saline intrusion from the River Adur to the west and the Ouse to the east. There are 18 public water supply sources. Of these, there are serious saline intrusion problems at Shoreham (chloride concentration up to 500 mg l^{-1} in 1989), Balsdean (up to 200 mg l^{-1} in 1989), and Goldstone (up to 75 mg l^{-1} in 1989, but previously as high as 400 mg l^{-1}), with intermediate chloride concentrations at Mossy Bottom (45 mg l^{-1}), Mile Oak (30 mg l^{-1}), and Lewes Road (average of 40 mg l^{-1}). The Aldrington source, which in the past suffered from occasional elevated chloride levels, has been abandoned.

In the western Brighton Block, high conductivities occur at the Shoreham source, about 500 m from the Adur and 2 km from the coast. The salinity rises and declines slowly, possibly indicating transport through rather less permeable horizons than elsewhere. Monkhouse and Fleet (1975) suggested this was due to the occurrence of many small fractures rather than a few major ones, and that saline intrusion was probably slow and on a broad front.

Elevated conductivities also occur at Mossy Bottom and Mile Oak (both approximately 3 km from the coast). The saline intrusion here almost certainly originates from the Adur rather than from the sea.

Monitoring boreholes close to the coast in this part of the block (BBC Transmitter, and Travis and Arnold) intercept water with a conductivity equivalent to that of sea water (approximately 40 000 µS cm^{-1}) whereas 300 m further inland (Kingston Middle Road) the water is relatively fresh (less than 700 µS cm^{-1} at the base of the hole), although in 1985, a conductivity of nearly 1000 µS cm^{-1} was recorded near the base. Some 300 m further inland, at Kingston Stoney Lane, conductivities are slightly lower (in the range 400 to 600 µS cm^{-1}) and a single atypical profile was recorded in 1987, with conductivity greater than 1000 µS cm^{-1}. From the major change in conductivity between the coastal and inland boreholes, it appears that either the saline intrusion is of very limited extent or that the latter boreholes do not intercept fractures containing saline water.

It was noted from the WRC logging that conductivity changes occur in the coastal boreholes (Travis and Arnold, and BBC Transmitter) as a result of changes in the abstraction at Shoreham, Mossy Bottom and Mile Oak. There is little change in the level of the saline interface in these monitoring boreholes during the tidal cycle, although there is a small increase in maximum conductivity, together with a slight rise in water level. The tidal efficiencies in the BBC Transmitter, and Travis and Arnold boreholes are 40% and 4% respectively with delay times of 1.5 and 8 hours. The results from Travis and Arnold are surprising considering its close proximity to the coast; one possible explanation may be its location, inland of Portslade Harbour, which is separated from the sea by a system of locks.

The inland monitoring boreholes generally exhibit conductivities consistent with fresh water, although there are occasional increases, the causes of which are sometimes difficult to identify. At the Shoreham Wimpney borehole situated 2 km from the coast, 1 km from the Adur and 600 m from Shoreham public water supply, increases in conductivity during the period 1989 to 1991 appeared to be associated with low groundwater levels. At Greenleas (2.5 km from the coast), conductivities are in the range 800 to 950 µS cm^{-1}, increasing slightly with time. Although rather high for an inland site, chemical analysis of the water in 1988 suggested this was due to agrochemical pollution, rather than saline intrusion.

Most sources in the central area of the Brighton Block are greater than 3 km inland and not at risk. Sources that are at most risk are those at Goldstone and Lewes Road, both only about 2 km from the coast. Both Goldstone and Aldrington (now abandoned) show significant seasonal variation in chloride concentrations (35 to 80 mg l^{-1} at Goldstone). Historically high chloride concentrations have been recorded at Goldstone (up to 400 mg l^{-1}), and only careful management of abstraction has overcome the problem.

The three coastal monitoring boreholes (Western Lawns, East Street Car Park and Old Steine) all show conductivities consistent with sea water. Conductivities in these boreholes vary both seasonally and in response to variations in abstraction from inland pumping stations. Logging showed a relationship between changing abstraction at inland pumping stations, and conductivity variations at the monitoring boreholes.

Western Lawns in Hove was found to be particularly sensitive to tidal effects. Logging of the borehole showed the highest fluid conductivity (27 500 µS cm^{-1}) occurred approximately one hour after high tide, with the saline interface occurring at 24 m depth. The interface fell to 110 m (1600 µS cm^{-1}), 1 hour after low tide. Inland, at Pembroke Gardens, the interface moved by only 15 m.

Examination of the Western Lawns conductivity logs indicated that saline water enters the borehole at high tide via an enlarged fracture at 130 m depth, probably leaving the borehole via a fracture at 66 m (see Figure 52). Reverse flow occurs during the falling tide, with fresh water leaving via the fractures at 114 and 130 m depth. Seasonal variations are also illustrated in Figure 52. Below 50 m, there are significant seasonal differences in the conductivity profile, with the freshest fluid column being recorded in February 1988 (EC2), when the inland groundwater head was highest after winter recharge. Above approximately 50 m depth, seasonal variation in conductivity is less pronounced than it is deeper in the borehole. Detailed examination of the logs indicated that fresher water inflows are related to caliper enlargements.

There is no apparent correlation between pore-water conductivity and formation resistivity (Ellis, 1977). However, the resistivity logs were obtained using a 16 to 64 resistivity probe which is affected by saline borehole fluid, and it is probable that (as at New Salts Farm) the high salinity of the borehole fluid masked the true formation resistivity changes. Peaks occur in the pore water chloride at depths of 45 to 55 m, 110 m, and 140 to 145 m, the maximum occurring at 143 m below surface. Pore-water chloride concentrations remain above 120 mg l^{-1} down to 151 m, suggesting some diffusion of chloride into the matrix throughout the profile. However, below 151 m, the pore-water is fresh, nowhere exceeding 75 mg l^{-1}, with an average of 35 mg l^{-1}, suggesting an absence of fractures below this level and the effective base of the aquifer.

At Old Steine (about 3 km to the east) there is a complex tidal response, although the range of conductivity values is similar to that at Western Lawns. At East Street Car Park (200 m from Old Steine) there is no measurable tidal effect. Brackish water penetrates further inland from Western Lawns than it does from Old Steine 1 to 2 km inland, although fresh water conductivities are found in all boreholes further inland.

Geophysical logging of the Pembroke Gardens borehole during the 1980s showed a sharp increase in conductivity at about 125 m depth, coinciding with a reduction in formation resistivity. This suggested saline pore water and the base of the aquifer; possibly because saline water has gradually diffused into the matrix from the borehole.

The Old Steine monitoring borehole (100 m from the coast) experiences saline intrusion at low groundwater levels, with fresh groundwater flushing out saline, when groundwater levels rise. Logging of this hole during the 1980s indicated the normal conductivity profile was around 500 µS cm^{-1} to a depth of approximately 120 m, below which there was an increase to 1000 µS cm^{-1}. The effect of low groundwater levels on conductivity is illustrated by logging carried out during times of depressed groundwater levels. During August 1976 there was a striking increase in conductivity to 35 000 µS cm^{-1}, falling to approximately 700 µS cm^{-1} in all but the base of the hole by December of that year. Similarly, early in 1989 a dramatic change in the profile occurred, with saline water apparently entering the borehole at four depths, with conductivity peaks exceeding 10 000 µS cm^{-1}. About a week later the profile had smoothed to an average conductivity of 11 000 µS cm^{-1} throughout the hole; two months later, conductivities had returned to around 500 µS cm^{-1} throughout.

Geophysical logging of the cored borehole in 1974 identified active fracture zones at 97 m and between 118 m and the base of the borehole (Ellis, 1977). Fluid conductivity logging indicated that the lower of these zones contained saline water throughout the year and at all states of the tide, whereas the upper zone contained water ranging from 5% to 95% sea water depending on seasonal and tidal effects. There was a good correlation between the chloride profile and the formation resistivity log (Ellis, 1977) indicating that brackish or saline water within the fractures had diffused into the matrix above and below the fracture zones. In the case of the 97 m level, the chloride peak was observed to be 11 m wide, with diffusion approximately 5.5 m above and below the fracture zone (Ellis, 1977). Between the main fracture zones, the chalk matrix contains fresh water with chloride concentrations of 20 to 40 mg l^{-1}.

Victoria Gardens and St Peter's Church boreholes are located in the same dry valley as Old Steine, but are located 600 m and 1 km respectively from the coast. Over the period 1985 to 1991 average background conductivity values of 500 to 600 µS cm^{-1} were recorded in the Victoria Gardens borehole. During November 1985 and December 1986 conductivity peaks of up to 2000 µS cm^{-1} were observed at various depths. St Peter's

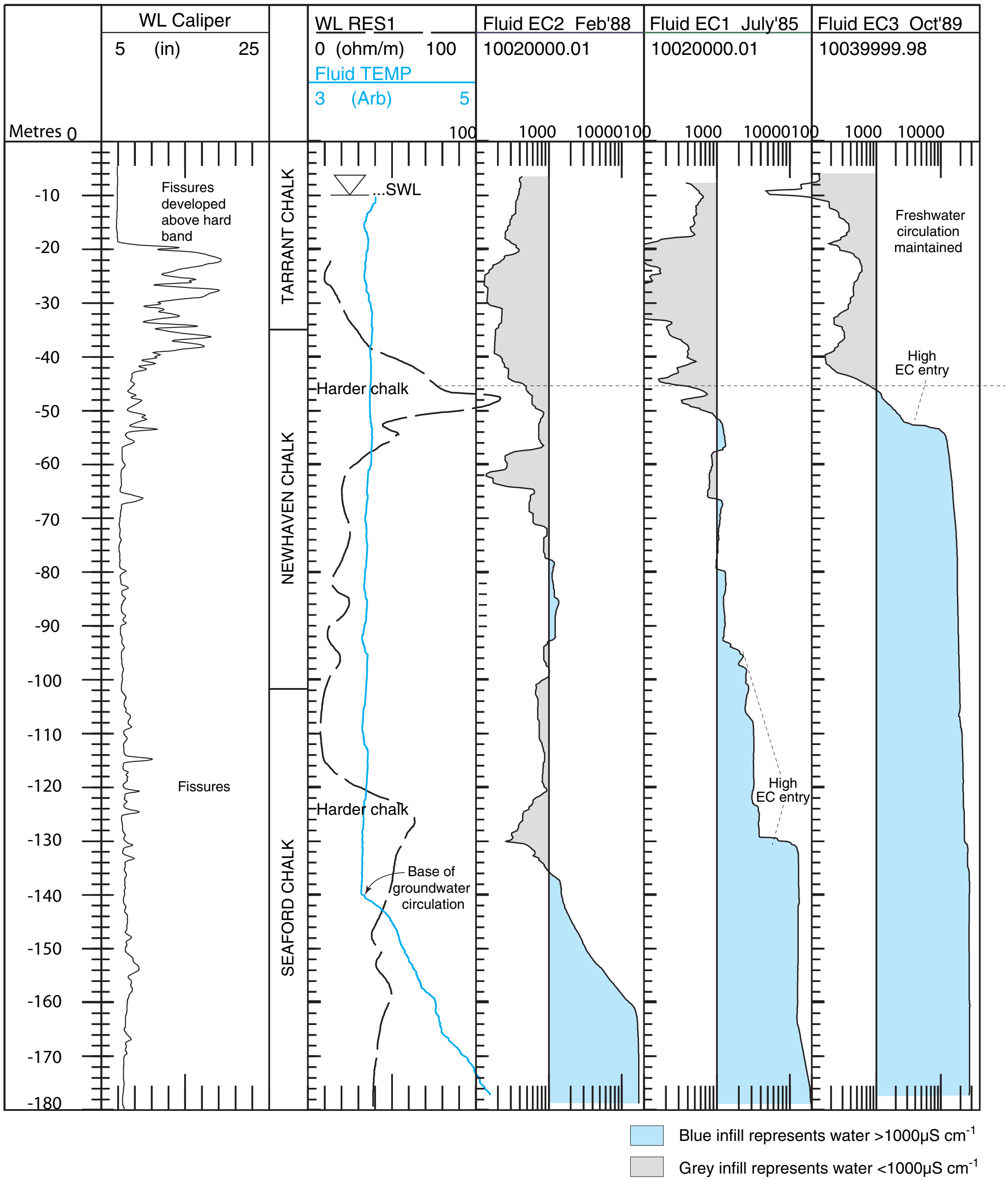


Figure 52 Conductivity variations at Western Lawns observation borehole.

Church borehole, with similar background values to Victoria Gardens, also experienced a peak up to about 1000 μS cm^{-1} during November 1985. These features could not be related to low groundwater levels, or to increases in abstraction, and were accounted for as an intermittent effect of unknown origin.

It is interesting to note that the seasonal fluctuation in conductivity is much greater in the coastal boreholes than the inland boreholes, whereas the seasonal water level fluctuation is greater in the inland boreholes.

In the east of the Brighton Block, the Balsdean source, about 2.5 km from the sea, but controlled by a careful pumping regime, suffers from saline intrusion. The response to pumping is rapid, particularly at high tide, and there may be a direct fracture connection between Balsdean and the sea (Warren, 1967). This source cannot be pumped three hours either side of high tide. During the drought of 1976, a maximum chloride concentration of 126 mg l^{-1} was recorded.

The only monitoring boreholes in this eastern area which intercept saline water are those at Roedean and Saltdean. Conductivities recorded in these boreholes were over 15 000 μS cm^{-1}. The conductivities in both are seasonal, and Roedean is affected by abstraction from Balsdean and other sources in the area. Roedean is also strongly affected by the tide, the saline interface moving 21 m vertically between high and low tide, with the interface reacting twice as fast to the rising tide as to the falling tide. Figure 53 illustrates the variation in conductivity with depth at Roedean 2 hours prior to, and 2 hours after, high tide.

Logging at Saltdean revealed a fracture at the base of the borehole, which acts as a conduit for entry of much of the saline water. Although the water level at Saltdean is affected by pumping at Balsdean, short-term conductivity variations do not appear to be related. However, long-term increases in conductivity at Balsdean do appear to reflect rising conductivities at both Roedean and Saltdean.

Other monitoring boreholes in the eastern part of the block (Ovingdean, Rottingdean and Telscombe) contain relatively fresh water. The variability of the Chalk is illustrated by the different responses of Roedean and Ovingdean, both situated approximately 500 m from the coast, and 1 km apart, but suffering greatly different degrees of saline intrusion.

Seaford Chalk Block

There are three public water supply sources in the Seaford Chalk Block: Cow Wish, Poverty Bottom, and Rathfinny. The block is only 7 km^2 in area, and is at risk from saline intrusion on three fronts: the sea to the south and the rivers Ouse and Cuckmere to the west and east. Transmissivities are high and groundwater gradients flat, providing scope for saline intrusion well inland.

Poverty Bottom public water supply borehole is the largest source in the block, and is located approximately 2.5 km from both the coast and the tidal River Ouse. Very high chloride concentrations have been measured in the past (up to 6300 mg l^{-1}), and there has been a gradual increase in conductivity in both Poverty Bottom and the adjacent monitoring borehole over the past 30 years. The increase cannot be accounted for by a reduction in groundwater head, since there has not been any significant lowering of water levels, but it may reflect abstraction from Poverty Bottom.

The only monitoring borehole in the Seaford Block which shows no signs of saline intrusion is that at Norton Top, close to the centre of the block and approximately 4 km from the coast. Although the borehole elevation is 116 m above OD, groundwater levels are approximately 1 to 2 m above sea level, as the hydraulic gradient is very flat across this block. Logging of other monitoring boreholes in the block (Mercury Motel, Bishopstone Deep, Poverty Bottom, Sutton Drove, and Cradle Hill) reveals stepped increases in conductivity at certain depths, the depths often being tidally and seasonally influenced. The fact that there are such marked increases of conductivity with depth is probably related to the high transmissivity of this block, with flow occurring along well-developed fracture horizons. Other than Poverty Bottom, there does not appear to be any deterioration of water quality with time.

Poverty Bottom monitoring borehole is located adjacent to the Poverty Bottom public supply borehole. The main feature of the conductivity profile is a sharp increase in conductivity at 82 m. Above this depth conductivities were generally about 200 μS cm^{-1} up to 1988, but have increased to a maximum of about 1500 μS cm^{-1} between 1988 to 1991. Below this depth, conductivities have

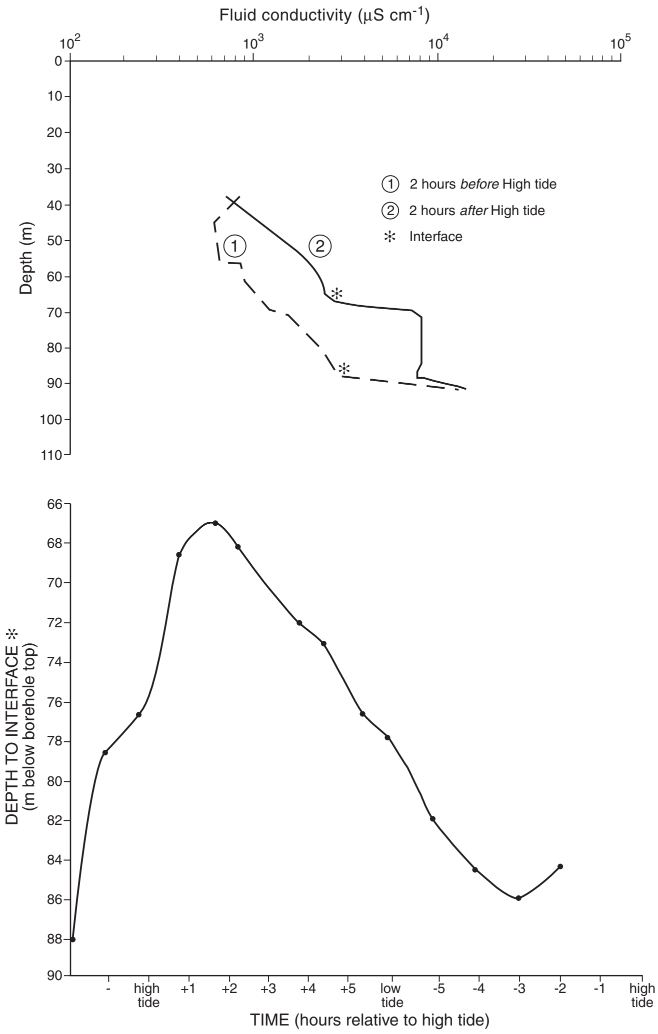


Figure 53 Conductivity variations during one tidal cycle at Roedean observation borehole.

increased from about 4000 to 5000 μS cm^{-1} (prior to 1989), to a maximum of 7000 μS cm^{-1} by May 1991. From this rather limited temporal data, there does appear to be a general increase in conductivity with time. This cannot be accounted for by a reduction in groundwater levels, since the water level in the observation borehole was not significantly lower than in previous years. Conductivities are high for a borehole so far from the coast; this is no doubt partly associated with abstraction from Poverty Bottom, but also with the high transmissivity across the block.

Eastbourne Chalk Block

The base of the Chalk rises progressively eastwards and the basal beds of the Lower Chalk are exposed along the foot of the cliffs from Beachy Head to Eastbourne. As a result, saline intrusion of the Chalk aquifer has not generally been a problem. Chloride is, however, regularly monitored, particularly at Friston, where in 1897 five observation boreholes were constructed between the pumping station and the River Cuckmere to warn of any reversal of hydraulic gradient. These precautions were undoubtedly triggered by the problems encountered at Waterworks Road Pumping Station, Eastbourne, which was eventually taken out of supply in 1899 when chloride exceeded 2000 mg l^{-1}. This source was brought back into supply in the 1950s and engineering work carried out in recent years should ensure that the problem does not recur.

DISCUSSION

The South Downs Chalk aquifer is susceptible to saline intrusion. The aquifer is in direct contact with the sea along much of its length, although it is partly protected by the Palaeogene strata in the west, and the low permeability Lower Chalk in the east.

In a homogeneous coastal aquifer, the Ghyben-Herzberg relationship would apply, with relatively fresh water floating above a lens of saline water, becoming more saline with depth. It is apparent that this relationship does not apply to the dual porosity and dual permeability medium of the Chalk (see Chapter 4), where the size, location and nature of fracture systems is the major influence on the occurrence and extent of saline intrusion, the water moving predominantly through fractured horizons.

Extensive geophysical logging has been carried out in boreholes in the area since the 1970s. The boreholes that have been logged each have a unique conductivity profile, with individual responses to variations in groundwater head, tide and abstraction rates. Even boreholes at similar distances from the coast respond differently due to the complex fracture system of the Chalk. Tidal effects in some boreholes are expressed as a change in groundwater level, in others by a change in the saline interface, and yet in others by a change in conductivity. Variation in conductivity would be anticipated only where there is good hydraulic connection with the sea and where there is an open, active fracture system to transport the water. An example of this is the Balsdean source, which cannot be pumped for a period either side of high tide. As this source is 2.5 km from the coast, there must be an active conduit system that rapidly transports water. Further from the coast, perhaps where the fractures are not as well developed, pressure differences propagate through the aquifer, even though the saline water itself cannot, and the dominant effect is on the groundwater head and/or the saline water interface.

A combination of the resistivity, temperature and conductivity logging provides evidence that saline water moves laterally through the fractures in response to groundwater and tidal hydraulic gradients. In the vicinity of the fractures, saline water gradually diffuses into the pores of the Chalk matrix. In the less fractured and less permeable areas of chalk, resistivity is much higher because the matrix water is fresh relative to the water in the fractures and the adjacent borehole. A borehole intercepting the fractures may provide a means for saline water to move vertically via the borehole. This complicates interpretation of geophysical logs, and is one of the major drawbacks of logging open holes.

Conductivities in most boreholes, particularly those close to the coast, show a significant seasonal effect, related to fluctuations of inland groundwater head. Conductivity variations due to changes in groundwater abstraction are less easy to identify but can be seen in some areas. Tidal fluctuations had a major impact on conductivities in coastal boreholes, the saline interface moving up and down the borehole by up to 86 m between high and low tide. Tidal efficiencies of up to 40% were calculated in the coastal boreholes.

6 Pollution and groundwater protection

INTRODUCTION

One of the major advantages of groundwater for supply purposes is its generally favourable and consistent quality which reduces the need for water treatment. However, urbanisation and industrial growth coupled with widespread intensive agricultural activity has a serious potential impact on groundwater quality, and this is especially significant in the South Downs where groundwater is in great demand. Groundwater is particularly vulnerable to insidious long-term pollution since water movement is very slow; current groundwater quality may reflect pollution events from many years or even decades ago.

If groundwater does become polluted, low flow rates and limited microbiological activity inhibit self purification; rehabilitation is difficult and costly, if not impossible. It is, therefore, important that the groundwater resources are protected, both with regard to aquifer vulnerability and source protection.

POLLUTION

Nature of pollution

Pollution can be divided into two overall types:

- Point source pollution arising from an identifiable incident or point or line source (or series of such). Examples include industrial spillages, fuel handling mishaps, landfills.
- Diffuse pollution which is derived from widespread activities at a low level, where detectable contamination cannot generally be ascribed to any individual usage or application. Examples may derive from agriculture, e.g. nitrate and pesticides, or substances present in rainfall

Plate 13 Typical land use in East Sussex. [A13384].

or mobilised by acid rain. In practice there is a spectrum of intermediate situations. These include leaking sewers in densely populated areas.

The saturated zone of the Chalk aquifer is protected by the unsaturated zone. Rapid transport can take place through fractures, but where diffusion into the matrix occurs, pollutant transport is relatively slow, perhaps only 1 m a^{-1} (Foster et al., 1991). However, it is possible for more rapid flow to occur which effectively by-passes the unsaturated zone; polluting activity which generates sufficient hydraulic surcharge will increase the risk of by-pass flow significantly.

URBAN AREAS

Most urban areas present a complex array of human activities which are potentially polluting to groundwater. Sources of pollution may include leaking sewers, road run-off, sanitary waste disposal, industry 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 change 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 these modern landfills are engineered to minimise the risk of leachate reaching the water table many existing facilities remain a potential source of pollution, particularly at sites located in areas of shallow groundwater tables. The greatest risk occurs where disposal sites are situated directly on the Chalk, whereas Palaeogene or Recent cover may reduce the opportunity for leachate to access the water table. Operational landfill sites and those now closed in the area are shown in Figure 54 and listed in Table 12. Most of these are old sites, and rely on the dilute and disperse principle.

Both the quantity and the composition of leachate (which are related to the origin of the waste) need to be considered when estimating pollution risk. Municipal landfill typically contains high concentrations of organic matter originating from the degradation of organic wastes which then act as a large pool of substrate for microbial activities in the aquifer. The migration of low Eh leachate into the aquifer may lead to the development of a redox zone sequence that ranges from methanogenic conditions close to the landfill, progressively through sulphate, iron, manganese and nitrate reducing conditions and finally to aerobic conditions on the outskirts. Many leachates also have low pH as a result of heavy acidic loading, this greatly increases the mobility of heavy metals. Anaerobic conditions decrease the likelihood of biodegradation of many synthetic organic compounds, although the degradation of some heavily chlorinated compounds appears to be most significant in the zone of iron reduction (Lynekilde and Christensen, 1992). The pollution plume which may occur away from a domestic landfill site, as leachate slowly percolates through the unsaturated zone, provides a wide variety of conditions in which degradation may take place.

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.

An example of the effectiveness of the Chalk in leachate attenuation is at Beddingham, where a landfill is still being developed. The older parts of the site were designed to dilute and disperse, and the refuse was disposed directly onto unlined Chalk. The more modern extensions are fully contained. Elevated levels of leachate

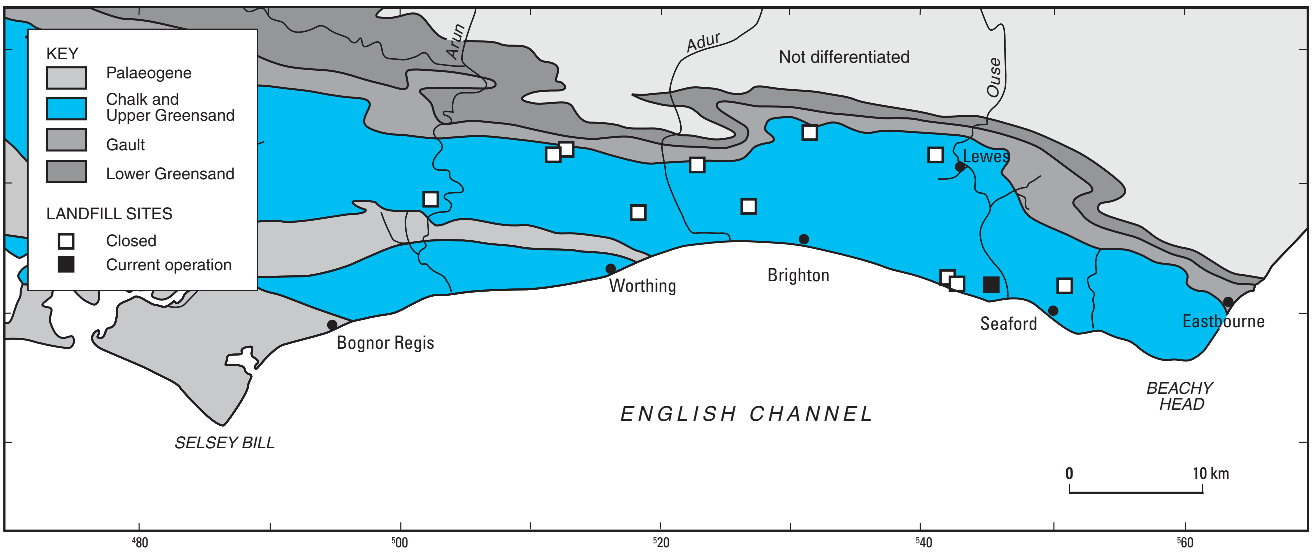


Figure 54 Locations of landfill sites receiving domestic or industrial wastes on the Chalk outcrop of the South Downs.

Table 12 Landfill sites on the Chalk outcrop of the South Downs.
Sites receiving inert materials not included.

Location	Waste type	Date tipping ceased
Beddingham	Domestic	Current
Cradle Hill	Domestic	1982
Elmbourne House	Industrial	1982
Canada Road	Domestic	1973
Mile Oak	Domestic/incinerator ash	before 1970
Offham Road	Domestic	before 1940
Paddock Lane	Domestic	before 1940
Kingston	Domestic	before 1930
Glazeby Road	Industrial	—
Halewick Lane	Domestic	—
Mill Lane	Industrial	—
Room Bottom Valley	Industrial	—

migration have been seen only in monitoring wells situated very close to the site, and there is no evidence that sources in the surrounding area have been affected.

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). Phenols have been detected in one South Downs public supply source which could be directly related to soakaway drainage from a nearby road. The metals considered to pose the greatest threat are lead and copper, due to their solubility and ubiquity. However, most pollution incidents attributed to run-off on the South Downs have been road salt.

Road drainage is a potentially serious risk wherever major roads cross the catchments of public supply sources. The risk is minimised by making every effort to route roads outside the public supply protection zones. Where this is not possible, for example the A27 Brighton bypass, full drainage is 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 a recurring problem and are widely controlled by the application of broad spectrum herbicides. Much of the pesticide is applied to hard paved areas, industrial sites and railways, and may be integrated within rapid runoff events. The possibility of infiltration to groundwater is greatly enhanced where surface drainage is directly to soakaways, bypassing the biologically active soil zone.

The use of weed killers was responsible for the widespread national occurrence of the triazine herbicides, atrazine and simazine in groundwater resulting in the banning of atrazine for non-agricultural use in August 1992. Atrazine is detectable in the South Downs aquifer and is responsible for almost all the pesticide transgressions of the recommended limit. Whilst concentrations of 0.1 to 0.3 $\mu g\ l^{-1}$ are common in raw water there are none above 0.7 $\mu g\ l^{-1}$. The higher concentrations are seen north of Worthing and clustered along the route of the Brighton to Lewes road and railway line. The water from sources with persistently high pesticide concentrations requires treatment or blending before supply.

Industrial impact

Inorganic compounds

Inorganic pollution occurs in many of the major urban areas of the UK where groundwater is unconfined. The dominant contaminants are chloride and nitrate, and high concentrations of nitrate in the Brighton urban area, have, in the past, caused at least one public supply source to be taken out of service.

Organic compounds

Many organic contaminants 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 chief concern are industrial solvents (dense non-aqueous phase liquids) and petroleum hydrocarbons (light NAPLs), which 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.

Results of monitoring show that solvent concentrations are generally lower in the western part of the South Downs aquifer with higher concentrations present to the east, the highest concentrations being found in three boreholes to the north-east of Brighton (fluctuating up to 28 $\mu g\ l^{-1}$ of trichloroethene). All boreholes between the main London to Brighton Road and the Ouse are affected, although none presently approach the recommended maximum concentration in drinking water.

Hydrocarbons are a less serious but potentially more widespread problem. The change to unleaded petrol in the UK over the last ten years has resulted in the identification of a new groundwater contaminant, methyl tertiary butyl ether (MTBE). This is an oxygenate added to fuel at up to 10% by volume. MTBE is very soluble in water and is reported to be non-biodegradable

(Symington et al., 1994). It is rapidly dissolved from spilled petrol into groundwater and moves away from the site, generally being the first indicator of a pollution incident. However, while there is little positive data available on pollution incidents due to petroleum compounds in the South Downs, a particularly serious incident was recorded where diesel from a storage tank was discharged via a corroded pipe into the unsaturated zone of the Chalk directly above the adit of a public supply source.

Low levels of organophosphorous compounds, used as flame retardants, have recently been detected in a few sources to the west of Chichester. The origin of these compounds is unclear.

A case history of pollution of an urban public supply borehole

The pressures on groundwater quality in the vulnerable urban zone of the aquifer are illustrated by the Waterworks Road borehole in Eastbourne (Flude, 1993). This borehole was one of the original supply sources for the town, abstracting shallow groundwater (only 15 m bgl) from the Chalk and Upper Greensand. There are five wells interconnected by a system of adits. Extension of the adits and increased abstraction at the end of the last century led to problems of saline intrusion, and the source was taken out of service in 1899 and the surrounding land sold. The source was brought back into service during the 1950s to meet increasing demand, but has suffered from several pollution incidents, including bacterial, nitrate, herbicide, and oil contamination. It is currently under threat from a new road improvement scheme in the area.

High bacterial counts were thought to come both from leaking sewers which passed close to the wellhead and more generally from connections with surface water during periods of intense rainfall. Extensive drainage and sewerage works were carried out to deal with the bacterial pollution. However, despite extensive investigations they were never eliminated, and the borehole water has subsequently been chlorinated.

In 1967 it became apparent that nitrate concentrations were increasing throughout the Eastbourne Block. This was generally attributed to agricultural activities in the area. However, land adjacent to the Eastbourne Waterworks source was used for agricultural storage and allotments; nitrate concentrations rose to 16 mg l^{-1} NO_3-N with peak concentrations up to 21 mg l^{-1} NO_3-N. The drainage and sewerage works carried out to deal with bacterial problems may have aggravated the situation, as the nitrate concentration has since declined to 8 mg l^{-1} NO_3-N.

In common with many other groundwater sources, low concentrations of triazine herbicides whave been detected. Atrazine in particular, exceeded the limit for the period reported by Flude (1993) in 1992, possibly derived from the allotments or the railway tracks.

The source has also been subject to two documented oil pollution incidents arising from disturbance of land previously occupied by an oil-storage depot. This problem was resolved by sealing the connections between the present pumping well and the older adit system.

AGRICULTURE

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 in the subsurface environment. The most rapid growth in pesticide use is the herbicides isoproturon and mecoprop and the fungicides mancozeb and fenpropimorph for the cultivation of autumn-sown cereals. The greatest threat to groundwater is likely to be 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 use of pesticides in agriculture for south-east England is summarised in Table 13.

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 1^{-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 leached 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 frequently 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 exceed 1 m a^{-1}, and only the most persistent pesticides are able to reach the water table.

However, under certain conditions, rapid by-pass flow may occur. This could permit low- to moderately persistent components to reach the water table relatively rapidly.

Nitrate

The mineralisation of soil organic matter is the major source of nitrate in arable soils in the autumn. Agricultural soils contain several thousand kg N ha^{-1} in organic matter, of which a few per cent is mineralised to nitrate each year. A proportion of this is available to the crop during the main growing season of spring and early summer. However a significant remainder is produced too late in the growing season and remains in the soil until leaching begins in the following autumn. Nitrate is also derived from the direct leaching of nitrogenous fertilisers, which are composed of inorganic nitrogen. The use of organic manures (animal slurry and sewage sludge) is only of limited local importance.

Table 13 Average annual usage of pesticides for south-east England in 1993.

Ranking by wt	Active ingredient	Wt applied (kg)	Ranking by area	Active ingredient	Area (ha)
1	Isoproturon	347 176	1	Chlormequat	277 796
2	Chlormequat	321 103	2	Isoproturon	272 377
3	Chlorotoluron	177 634	3	Fenpropimorph	258 524
4	Sulphuric acid	156 002	4	Cypermethrin	254 932
5	Formaldehyde	150 969	5	Carbendazim	247 544
6	Chlorothalonil	116 941	6	Chlorothalonil	224 051
7	Mecoprop	107 358	7	Propiconazole	199 890
8	Tar oil	104 161	8	Flutriafol	185 322
9	Glyphosate	79 279	9	(-HCH	176 269
10	Fenpropimorph	72 714	10	Fluroxypyr	161 558
11	MCPA	72 499	11	Diflufenican	127 576
12	Maneb	70 273	12	Tridimenol	104 860
13	Mancozeb	67 217	13	Cyproconazole	102 145
14	Methyl bromide	61 737	14	Flusilazole	101 197
15	Sulphur	52 048	15	Glyphosate	95 970
16	Mecoprop-P	50 582	16	Fenpropdin	95 778
17	Carbendazim	42 574	17	Metsulphuronmethyl	92 693
18	Simazine	38 454	18	Prochloraz	89 662
19	Sodium chloride	36 185	19	Mecoprop	88 770
20	Fenpropidin	36 081	20	Maneb	88 077

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 recharging water. Careful management of the land at this time is important to reduce the amount of nitrate which is available to be leached.

In the South Downs, the majority of the Chalk outcrop, excluding urban areas, now forms the South Downs Environmentally Sensitive Area (ESA). This was designated in 1992 with the primary aims of maintaining the characteristic open Chalk downland and important wildlife habitats. The ESA covers some 51 000 ha, of which about 20% has presently been entered into the scheme. Farmers participating in the scheme, which is voluntary, receive grants in exchange for following the ESA Guidelines for agricultural land (MAFF, 1992). No form of cultivation of existing chalk or dry river valley grassland is allowed, including any ploughing, reseeding or application of fertilisers or pesticides. The stocking density for grazing is regulated to maintain sward height within the range 0.5 to 1.5 adult cattle ha^{-1} or 3 to 10 sheep ha^{-1}. The reversion of arable land to downland is also covered and similar guidelines apply. Although the restrictions on nitrate and pesticide application are intended as a means of maintaining the Chalk downland environment, they must also play a role in restricting nitrate leaching to groundwater.

The remainder of the arable land is farmed using moderate input/output methods typical of low productivity soils. Development of more hardy cereal strains has permitted the introduction of autumn sowing to the high downland. Fertiliser application rates are somewhat lower than the national average (Table 14).

An estimate of the mass of potential nitrate leaching to groundwater can be made from the land use data. Areas which have the highest intensity of arable land are on the outcrop to the NW and NE of Brighton and on the drift around Chichester. Tilled land constitutes about 30% of the outcrop area. Given average annual recharge of 337 mm and the assumption that all the applied nitrogen is leached, then the nitrogen concentration in recharge is not likely to exceed 16 mg l^{-1} NO_3-N. This is of course a simplistic estimate since nitrogen from other sources including grazed land is not included.

Extensive (unpublished) work was carried out from 1978 onwards, into the movement of nitrate below experimental agricultural plots on the Chalk at Deep Dean, in the Eastbourne Block. This work showed an annual nitrate pulse being carried downward by winter recharge through the unsaturated zone at rates of between 1 and 2.5 m a^{-1}. Nitrate leaching under permanent grassland was low, in the range 0 to 10 kgN ha^{-1} a^{-1}. However, ploughing released between 200 and 300 kg-N ha^{-1} for each of the first two years. This contrasts with leaching from arable land, which was in the range 50 to 150 kgN ha^{-1} a^{-1}.

Trends

Nitrate concentrations in South Downs public supply boreholes are between 4 and 7 mg l^{-1} NO_3- N (Figure 55). It is likely that this derives solely from agriculture since abstraction tends to be concentrated up groundwater gradient of major urban areas. Nitrate concentrations are increasing in about 40% of sources and these are predominantly located in areas of more intensive arable agriculture.

Table 14 Nitrogen fertiliser applications to arable land on the South Downs.

Crop	Area (%)	Nitrogen applied (kg ha^{-1} a^{-1})
Winter wheat	50	200–215
Winter barley	30	125
Spring barley		100–115
Oilseed rape	20	190
	Average	180

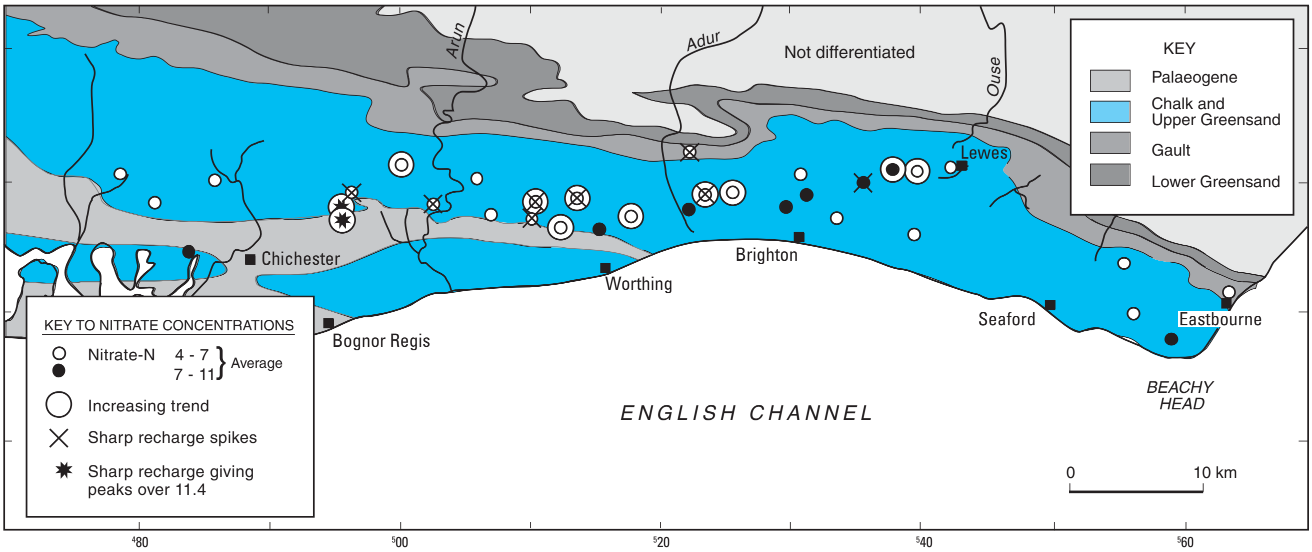


Figure 55 Behaviour of nitrate concentrations in public supply sources.

Superimposed on these long-term trends is the rapid response to the onset of winter recharge which creates sharp nitrate peaks in many sources (Figure 56). This response is most pronounced in the eastern part of the Chichester Block; recovery of water levels at the end of the drought in late 1993 resulted in a sharp increase in nitrate followed by a more steady decline to the original concentration. Subsequent winter recharge has produced greater peaks which transgress the drinking water limit in a few cases (Figure 56a). In many places elsewhere, nitrate concentrations show little seasonal variation. A rapid response to recharge is more frequently seen in

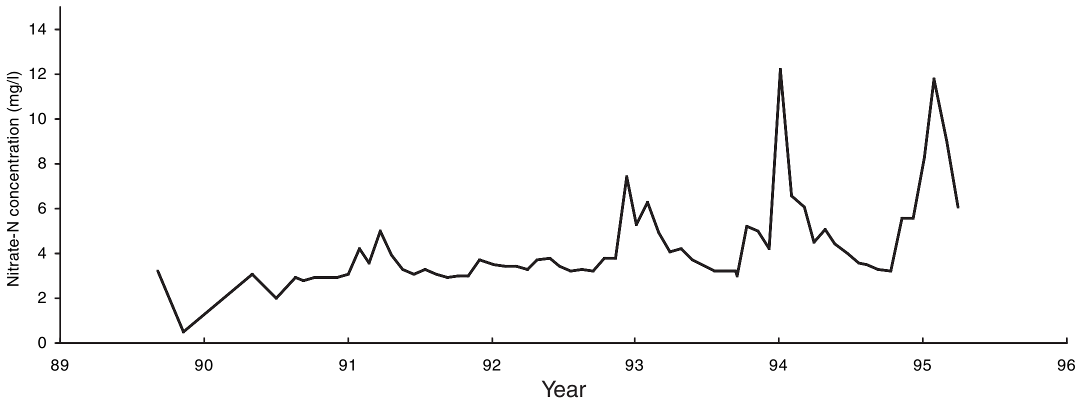


Figure 56a Nitrate concentrations in Chichester Block.

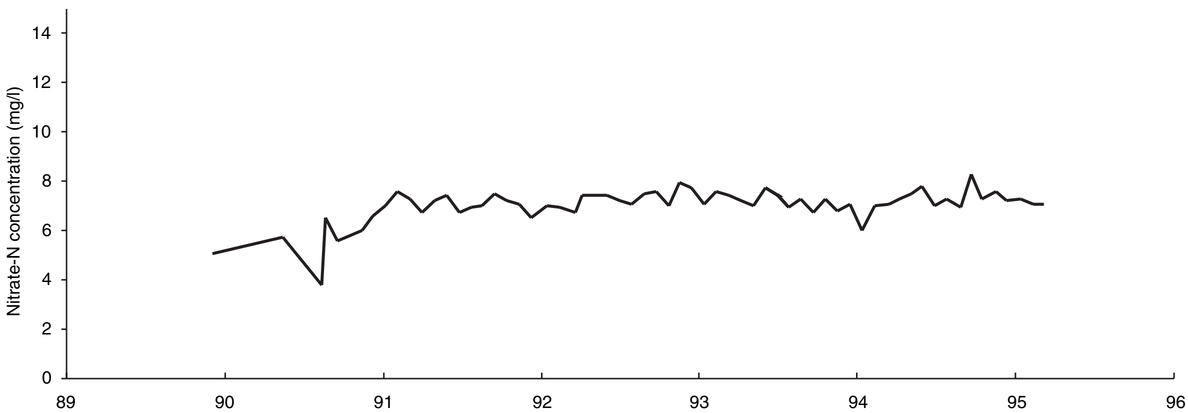


Figure 56b Nitrate concentrations north-east of Brighton.

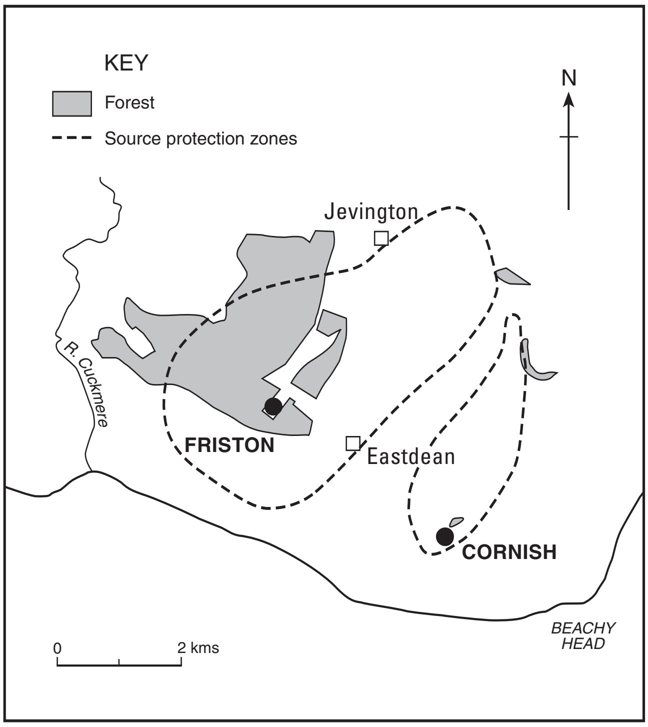


Figure 57 Afforestation within Friston and Cornish catchments.

boreholes which are continuously and heavily pumped. Many of the more peaky sources are located in areas with substantial depth to the water table, and this response cannot necessarily be related to the damping effect of a thick unsaturated zone.

The lower concentrations are probably due to a combination of factors, including:

- the thick unsaturated zone, greater than 40 m under much of the area, which increases rapidly away from river valleys,
- moderate inputs from agriculture, including changes in land-use practice,
- far-sighted protection policies implemented initially by Brighton Corporation and subsequnetly extended by Southern Water Authority.

Impact of land-use control in the Eastbourne block

The impact of land use on nitrate concentrations in groundwater can be seen in two contrasting sources operated by the former Eastbourne Waterworks Company (EWWC). The Friston source provides a large part of the supply for Eastbourne. About 30% of the present catchment is under commercial forestry (Figure 57). The majority of nitrogen to the catchment is assumed to be derived from agricultural land in the Jevington valley to the north. Nitrate concentrations have remained moderate at between 4 and 6 mg l^{-1} NO_3-N since 1954.

In contrast, the former Eastbourne Waterworks Company suffered for many years with problems of high nitrate in its groundwater source at Cornish (Green and Walker, 1970). Nitrate concentrations rose from 5 mg l^{-1} NO_3-N in 1954 when the source was developed to 8 mg l^{-1} NO_3-N in 1968, and by 1969 were fluctuating at concentrations of up to 16 mg l^{-1} NO_3-N (Figure 58). They remained high until 1972 when, after a period of fluctuation, they fell to approximately 8 mg l^{-1} NO_3-N.

The catchment for this source extends over about 400 ha of intensively farmed arable land with limited grazing. The EWWC had been successful in agreeing a management plan in 1952 with Eastbourne Borough Council who directly managed or leased all the land in the catchment. Three farms straddle the catchment to the Company's pumping station at Cornish. Two are under the direct management of Eastbourne Borough Council's agricultural advisors and the other is operated under a tenancy agreement with the Council. The farm which is operated under the tenancy agreement occupies 70% of the catchment and has 70 ha of unploughed permanent pasture with the remainder being farmed on a 7-year rotation of grass, winter wheat, winter barley and spring barley. Stubble-sown turnips provide winter grazing for 1000 sheep. This agreement allowed only 'approved' artificial fertilisers to be used in defined zones of the catchment.

EWWC and the Council first drew up an agreement on use of fertiliser in 1952 which restricted application rates to 63 kg ha^{-1} in an inner zone and 75 kg ha^{-1} in an outer zone. Fertiliser applications were reviewed in 1968 and the revised rates have been maintained since this time. The quantity of nitrogenous fertiliser applied in a restricted area was limited to 37.5 kg ha^{-1}, and to 63 kg ha^{-1} over the remainder of the catchment. Soluble fertilisers were to be replaced where possible with slow release formulations and applications of gas liquor were prohibited.

Recent data from the two sources shows that both have stablilized, although Cornish remains over 7 mg l^{-1} NO_3-N. It was not possible to match directly the pattern of fertiliser applications with the observed nitrate levels at Cornish. However, this agreement can be seen as an important example of the cooperation which is possible between water undertaker and land owner to control activities which are prejudicial to water quality.

GROUNDWATER QUALITY PROTECTION

History of groundwater quality protection in the South Downs

One of the main reasons for the generally high quality of Chalk groundwater in the South Downs is the early

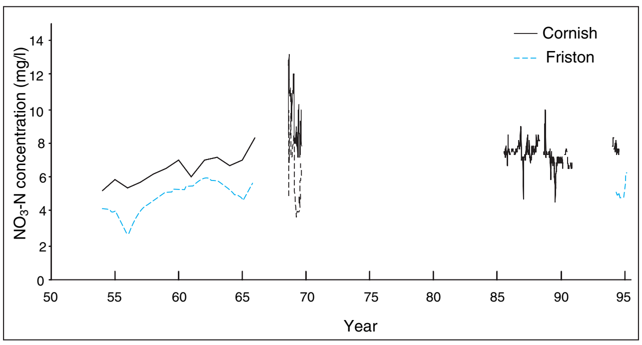
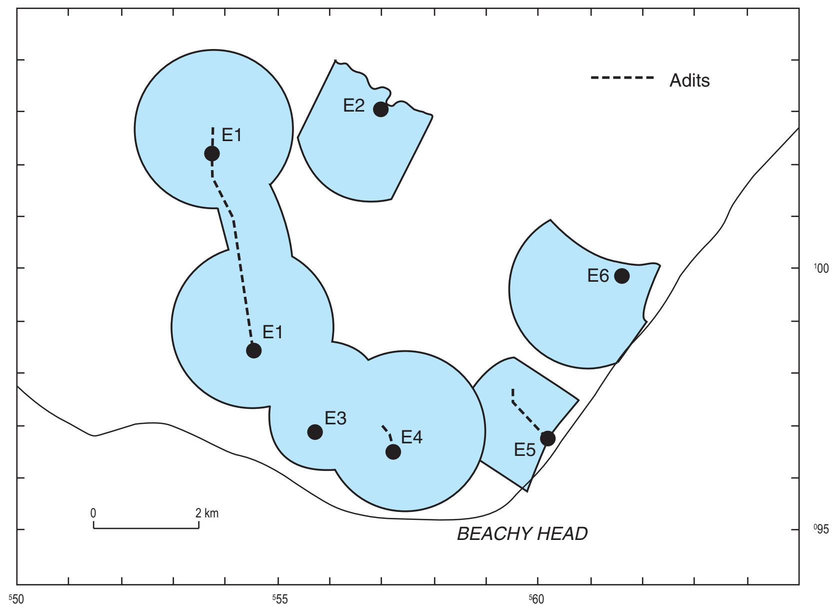


Figure 58 Nitrate concentration in Cornish and Friston sources.

Figure 59 Source protection zones designated as a result of Southern Water Authority's Aquifer Protection Policy (1985).



realisation that surface activities could constitute a threat to groundwater integrity. As far back as the 1920s, groundwater protection was practised in the South Downs area. In 1924 and 1936 the Brighton Corporation obtained Acts of Parliament enabling bylaws to be enforced over approximately 5000 ha of downland to prevent pollution of groundwater. The Corporation also pursued a policy of buying land to control land use (Green, 1955). Further, bylaws passed by the Corporation in 1970 made use of a facility in the Water Act 1945 to protect groundwaters against potential pollution. Under Section 18 of this Act, Brighton passed bylaws which made it an offence to discharge sewage into underground strata within a distance of approximately 3.2 km from each pumping station. As a consequence, regular emptying of septic tanks and cesspools was carried out at a nominal charge. The policy of buying farms on the gathering grounds was continued in orders to control discharges into the Chalk.

1985 Aquifer Protection Policy

In 1978 the Southern Water Authority adopted Aquifer Protection Guidelines which became its Aquifer Protection Policy in 1985 (Southern Water Authority, 1985). Southern Water recognised the need for a clear aquifer protection policy for several reasons:

- With over 70% of public water supplies in the region derived from underground strata, as well as many private supplies for agriculture and industry, there was a clear need to protect aquifers and groundwater from pollution, whether from chemicals, organic wastes, oils or micro-organisms.
- The region was large, covering several water undertaking and county council areas. A common approach was essential in setting standards for pollution control and for responding to proposals and enquiries.
- While the Control of Pollution Act (1974) at that time provided powers to prosecute certain activities causing pollution, these were not all-embracing. It was preferred to avoid the use of legal powers and sought to protect its aquifers through normal planning controls and consultation.

Southern Water Authority's Aquifer Protection Policy (Southern Water Authority, 1985) adopted five protection zones, (see example Figure 59) four of which were based on the vulnerability of the strata in the region, of which that for the Chalk was the greatest, while a fifth (Zone 1) provided special protection to water supply sources:

Zone 1 provided the highest level of protection to all public and the larger private water supplies (see Box 5). It comprised 15% of the area.

Zone 2 covered the Chalk and underlying Upper Greensand which are hydraulically linked, as well as a narrow strip of Chalk below the overlying Palaeogene

Zone 1 areas

Southern Water Authority adopted the international practice of affording 50 days travel-time protection around individual sources of supply against microbiological contamination. Use of a mathematical model showed that for typical ranges of aquifer hydraulic parameters, the 50-day travel-time distances ranged from 110 to 410 m for granular aquifers, and from 370 to 2200 m for the Chalk. Based on these calculations. a set of conservative but technically based uniform zones were drawn up. For Chalk sources these ranged in size from 1.0 km to 2.5 km for abstraction rates varying from less than 5 Ml d^{-1} to over 15 Ml d^{-1}. For granular aquifers, where borehole yields do not generally exceed 5 Ml d^{-1}, a protection zone of 0.5 km was adopted with an additional 0.5 km buffer zone applied. Springs only had a protection zone 'up-stream', since no pumping cone of depression is induced by them.

strata where there is less than 7 m thickness of impermeable cover. Research had shown that this was sufficient to substantially retard the rate of downward movement of pollutant. 18% of the region lay in this zone.

Zone 3 covered the most important granular aquifers such as the valley and beach gravels and the Lower Greensand aquifers and made up 20% of the region.

Zone 4 made up the less-important granular aquifers, such as the Palaeogene sand formations, the plateau gravels, and the Tunbridge Wells Sand and Ashdown Beds. 22% of the region fell into this zone.

Zone 5 comprised the impermeable clays where activities were only prohibited or measures only required where there was a risk of pollution of surface waters.

For each of these five zones the Policy specified acceptable and unacceptable activities under the seven headings of: domestic and non-hazardous waste; difficult waste; general development; manufacture and storage; mineral and energy exploration and exploitation; agriculture; and sewage sludges and cesspool contents disposed to agricultural land. The constraints sought on these activities became more rigorous moving from Zone 5 to Zone 1.

The Aquifer Protection Policy was found to be over-cautious in two respects. The first related to the acceptability or otherwise of septic tanks, while the second related to the insistence on the use of ductile iron pipes, rather than glazed clay pipes, for small sewerage schemes. With regards to septic tanks an algorithm was developed which had regard to the size of the proposed development, whether the aquifer was fractured or granular, whether a soil layer existed below the point of discharge, as well as the thickness of the unsaturated zone. Use of this algorithm overcame many of the difficulties then being encountered in responding even-handedly to proposals.

Problems had also been encountered in requiring developers to use ductile iron pipes instead of glazed clay pipes for sewers in its Zone 1 areas. For example, a small sewerage scheme, crossing the margin of an aquifer zone 'down-gradient' of a source of supply, and where vulnerability was reduced by soil conditions or unsaturated aquifer thickness, was likely to pose a minimal risk to the source. Consequently, a second algorithm was adopted which had regard to similar factors to those above and it provided a choice in the use of glazed clay pipes as close as 50 m from the source. Again this approach worked well.

1992 Aquifer Protection Policy

The 1985 Aquifer Protection Policy (Southern Water Authority) was superseded in 1992 by the Groundwater Protection Policy (National Rivers Authority). The latter specified a series of policies for all activities which could give rise to groundwater pollution, and defined the measures which would be adopted in applying them. The policies themselves were drawn from the statutory duties, powers and regulations then available. They are largely consultative in nature and advise developers, local authorities and others of the response which they can expect to receive to proposals which they put forward which can impact on groundwater quality.

The Policy was based on two independent elements:

- Aquifer vulnerability; division of the land surface on the basis of aquifer pollution vulnerability.
- Source protection: special protection areas for individual sources, in which, various potentially polluting activities are either prohibited or strictly controlled.

Aquifer vulnerability

The factors which together define the vulnerability of groundwater resources to a given pollutant or activity are: the presence and nature of the overlying soil; the presence and nature of drift; the nature of the strata; and the depth of the unsaturated zone. However, the concept of 'general vulnerability' has serious limitations, and in rigorous scientific terms 'general vulnerability to a universal contaminant in a typical pollution scenario' has no precise meaning (Foster and Hirata, 1988; Adams and Foster, 1992). For this reason some authors (e.g. Anderson and Gosk, 1987) propose that vulnerability mapping should be carried out for individual contaminants and specific pollution scenarios.

However, even if the required data were available, an atlas of maps would be required for any particular region, and the issues would be too complex for general land-use planning purposes. Thus the former NRA (1992) adopted a more pragmatic approach based on available soil and geological information. They produced a nationally reliable map at the most detailed scale currently possible (1:100 000, the South Downs is covered by Sheet Numbers 45 and 46.). Three geological classes (Major, Minor and Non Aquifers) were recognised and for the Major and Minor aquifer classes, three soil classes were identified (High, Intermediate and Low Leaching Susceptibility) (see Table 15).

Quaternary deposits forming aquifers are included in the 'Minor Aquifer' group, except where they are in hydraulic contact with 'Major Aquifers' when they are then classified as 'Major Aquifers' themselves. 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. Such deposits may effectively protect underlying aquifers but their integrity and effective thickness are not adequately understood and site-specific evaluation is, therefore, essential.

Source protection

The NRA policy provided for three protection zones, inner, intermediate and outer, around all private and public groundwater sources of potable water. The zones are defined by 50 and 400 days time of travel through the saturated zone, and the whole catchment respectively. The objective of the inner protection zone is to protect against the effects of pathogenic pollution, the 50 day travel time being based on the time it takes for biological contaminants to decay. The outer protection zone is based upon the time necessary to provide delay and/or attenuation of slowly degrading pollutants. The presence of adits, extended horizontally away from boreholes creates difficulties when attempting to model source protection zones.

Table 15 Classification of aquifers and soil leaching susceptibility for nitrate vulnerability mapping.

Soil leaching classification

Rating	Class	Typical soil characteristics
Extreme	1	Deep permeable sandy soils, some affected by fluctuating groundwater levels in winter; shallow loamy soils over sandstone and medium loamy soils over limestone 1.0–2.5% organic carbon*
High	2	Deep permeable, light and medium loamy soils some affected by fluctuating groundwater levels in winter 1.5–2.5% organic carbon*
Moderate	3	Deep moderately permeable silty and medium loamy soils; moderately permeable clayey subsoils 2.0–4.0% organic carbon*
Low	4	Weakly permeable loamy, loamy over clayey soils; clayey alluvial soils 2.0–4.0% organic carbon*

*Typical value for arable topsoils

Geological classification type

Class	Characteristics
Type 1	Aquifer outcrop without Drift cover or with cover of permeable Drift (sands and gravels)
Type 2	Aquifer outcrop covered by less permeable Drift (thin lacustrine clays, peat), or by thin and/or patchy glacial till
Type 3	Aquifer outcrop covered by impermeable Drift (glacial till)

Groundwater vulnerability classification

Aquifer classification type	Soil leaching class			
	1	2	3	4
1	EXTREME	HIGH	MODERATE	LOW
2	HIGH	MODERATE	LOW	LOW
3	LOW	LOW	LOW	LOW

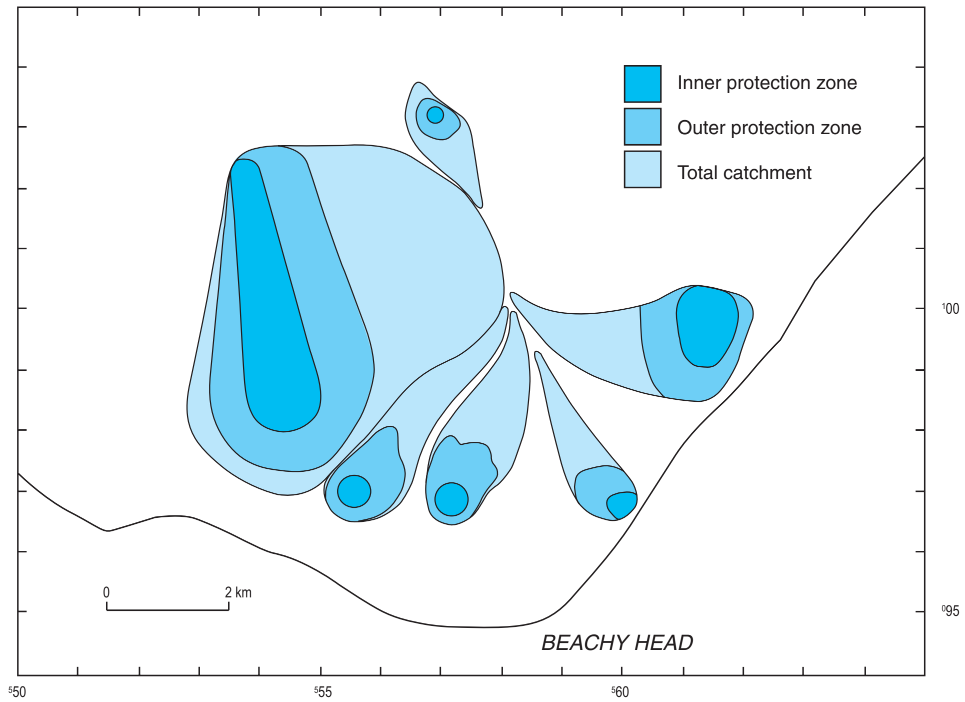


Figure 60 Source protection zones designated as a result of the National River Authority's Groundwater Protection Policy (1992).

The methodology developed to define these Source Protection Zones used steady-state groundwater models. Zones were defined and made public using the best available data, and represent the first pass. The Environment Aency recognise that consideration may need to be given to the redefinition of zone boundaries in the light of additional investigations carried out prior to particular developments, or due to land-use changes.

An example of the Source Protection Zones developed for a production borehole in the South Downs is shown in Figure 60. This is the same source as shown in Figure 59, it is interesting to compare the two sets of zones. The Zone 1 protection zones of the 1985 aquifer protection policy are significantly more conservative than the 50 day (or Inner) Source Protection Zones defined following publication of the NRA's Groundwater Protection Policy.

Control of activities

A series of special protection areas exist for individual sources, in which various potentially polluting activities are either prohibited or strictly controlled. Such activities include: control of groundwater abstractions; physical disturbance of aquifers/ groundwater flow; waste disposal to land; contaminated land; disposal of liquid effluents, sludges, slurries to land; discharges to underground strata; diffuse pollution of groundwater; and additional activities or developments which pose a threat to groundwater quality

The Environment Agency has direct powers over only a limited number of activities falling into the above eight categories. Over others, the Environment Agency generally, but not always, has indirect powers as a statutory consultee.

Nitrate vulnerability mapping

Due to the existing and potential problems of nitrate pollution, a series of Nitrate Vulnerability Maps (three county sheets) had previously been published by the NRA Southern Region. These maps were produced at a scale of 1:100 000 and were also combined into a single 1:250 000 composite map of the entire region (SSLRC and BGS, 1992). It was recognised that they were insufficiently detailed for studies at the field scale, their intended use being as a strategic guide to the nitrate vulnerability of groundwater for general planning and resource management purposes.

The methodology used for the compilation of these maps had been developed for a series of the (then) Severn–Trent (SSLRC/BGS, 1987) and Anglian (SSLRC/BGS, 1988) Water Authorities. Three types of aquifer and four classes of soil were identified, see Table 15 (from Robins et al., 1994). The soil classification was based on leaching risk derived from an indexation system utilising the following factors: topsoil and subsoil texture, porosity, soil water regime and lithology of the underlying strata. The classification was tested against data from field monitoring programmes and assessments of nitrate loss derived from a computerised soil-leaching model (Addiscott, 1977).

The geology and soil classifications are combined via a matrix to provide four categories of risk, see Table 15. Land with an extreme risk of nitrate leaching includes (unsurprisingly) shallow permeable loamy soils over Chalk. Conversely, a low risk of nitrate leaching occurs where the aquifer is covered by impermeable drift deposits irrespective of soil type, or where there are slightly permeable clayey soils or deep moderately permeable clayey soils along river valleys.

The vulnerability classification was of course specifically designed for the leaching of nitrate from soils through the unsaturated zone to groundwater. The behaviour of other potential sources of diffuse pollution (e.g. herbicides and pesticides) may be significantly different.

DISCUSSION

Despite the high population, extensive groundwater utilisation, and widespread agriculture across the South Downs, incidents of groundwater pollution are rare. Nitrate pollution has not, historically, been a problem, although in recent years, some boreholes have shown increasing concentrations. There may be several reasons for the low nitrate concentrations observed:

- In some areas, such as the Seaford Block, high transmissivities ensure that water is rapidly transported out of the aquifer.
- Agriculture may be less intensive, and therefore fertiliser application rates lower, than in other Chalk areas. Arable agriculture is dominant across the Brighton and Seaford blocks, although across the Worthing and Eastbourne blocks, arable agriculture alternates with grazing. The Chalk Downs are dominated by forestry in the Chichester block.
- The groundwater protection policies practised by both Brighton Corporation and Southern Water Authority, particularly since the 1970s, probably played a significant role, not only in the low levels of nitrate recorded, but also in the rare occurrence of other groundwater contaminants.

Although the Environmentally Sensitive Area has only recently been established, and the restrictions imposed have probably had little impact in reducing nitrate and pesticides in groundwater, this may become significant in future years.

7 Resource management

MANAGEMENT OF THE GROUNDWATER RESOURCES OF THE SOUTH DOWNS

The South Downs Chalk aquifer has a long history of careful management, due to intensive demand and the risk of saline intrusion. The more recent history includes the assimilation of the small water companies into larger water supply undertakings, the abstraction policy for the Brighton Block, the South Downs Investigation as well as a description of water management through the 1988 to 1992 drought.

Many of the original sources in the South Downs were drilled close to the coast, and became brackish; these were abandoned in favour of new boreholes located further inland. The replacement of Saltdean by Balsdean, east of Brighton, in the early 1930s, and the abandonment of a well at Bognor in 1879 in favour of new sources at Westergate and Eastergate, between Arundel and Chichester, are good examples of this. This 'trial and error' approach was the first step in the management of the South Downs aquifer.

WATER SUPPLY: A HISTORICAL PERSPECTIVE

The first attempt to provide piped public water supplies from the Chalk was in the early part of the nineteenth century. This was in response to increasing concern over problems of water supply, sanitation, and drainage in the urban areas then being developing. There were several occurrences of cholera at that time.

Green (1955) and Mustchin (1974) described the history and development of Brighton's water supply. The Brighton, Hove and Preston Waterworks Company was founded in 1834. The original intention was to take water from the chalk springs at the base of the northern scarp slope of the Downs particularly those near Poynings, and transfer the water by gravity through a tunnel in the Chalk to Brighton. The scheme did not proceed, probably because of the high capital cost of the tunnel, but later a well was sunk near the Lewes Road at Hollingdean, Brighton, about 2 km from the sea. Water was supplied for only two hours per day, and this unsatisfactory outcome was resolved by the formation of a new company, the Brighton, Hove and Preston Constant Service Waterworks Company in 1853. This absorbed the earlier company and was the foundation of the Brighton Corporation Water Undertaking which is now part of the Southern Water Group.

The Lewes Road well was extended in 1853 by the addition of adits which were driven outwards from the base of the well. This work was carried out on the advice of James Easton, who had observed that fresh water issued from the base of the local Chalk cliffs and who concluded that this could be tapped by driving tunnels parallel to the shoreline roughly at the low tide level to intersect water-bearing fractures. He had successfully applied the same technique at Ramsgate in north-east Kent during 1834.

This approach was pursued for over 100 years in the Chalk of the South Downs, and adits continued to be driven until the mid-1950s. The adits are typically 2 m high and 1.7 m wide with a drainage trench along one or both sides. The floors of the adits are at either 5.4 m above OD, at OD, or 6.1 m below OD (Mustchin, 1974). The chalk is self-supporting, no brick or concrete support being necessary. The Brighton Corporation Water Undertaking had a total length of about 12 km of adits.

The Portsmouth Water Company obtains part of its supplies from the large springs at Havant and Bedhampton in the west of the Chichester Block. Early steps to provide a public supply were taken in 1741 when Thomas Smith, the Lord of the Manor of Farlington, obtained authority by Act of Parliament to use springs in Farlington Marshes but the initiative came to nothing. The Farlington Waterworks Company was then established in 1809 and it took over the powers obtained by Smith to develop a pumping station in Farlington Marshes and provide a supply from springs starting in 1811. The Portsea Island Waterworks Company was also formed in 1809 under the name Portsmouth and Farlington Waterworks Company, but this company failed to extend the available works because of lack of resources, and in 1857 it was bought up by the Borough of Portsmouth Waterworks Company. The company continued to use the Farlington Springs and soon bought some of the springs at Havant which were used as an additional source of water from 1860 onwards. Other springs at Havant and Bedhampton were purchased from time to time eventually creating the waterworks as they exist today, and which supply some 40 000 $m^3 d^{-1}$. The main sources are now at Bedhampton and Havant where 28 springs issue along a 1.5 km east–west line. Twenty four of the springs are impounded, the spring water being collected by gravity in surface basins. The average flow for the entire group of springs is about 113 000 $m^3 d^{-1}$ (Whitaker and Reid, 1899; Thompson, 1925; Day, 1964).

Well sources in the Chalk were also developed to supply Worthing in 1857, Chichester in 1874, Bognor Regis in 1874, Littlehampton in 1888 and Seaford in 1896. Some of the older wells such as those at Eastbourne, were sited too near the coast and became saline. The gradual extension of the sources of supply to the coastal towns has been reviewed by Headworth and Fox (1986).

The Eastbourne Waterworks Company was formed in 1859 out of a pre-existing private company by Act of Parliament. The initial supply was from wells and adits in the Upper Greensand, but these were abandoned in 1899 when they became saline. After several trial boreholes, a shaft and an adit was constructed at Friston in 1896 (Whitaker and Reid, 1899). Subsequently further sources in the Chalk have been developed and some 30 000 $m^3 d^{-1}$ are now supplied from the aquifer.

PRESENT-DAY MANAGEMENT OF THE AQUIFER

Brighton Chalk Block

Abstraction policy

Prior to the introduction of the Brighton abstraction policy in the late 1950s, groundwater abstraction had been largely piecemeal and disconnected. The summers of 1949 and 1956 were particularly dry, and this caused severe problems for Brighton, with water levels at Mile Oak and Lewes Road close to the level of the adits at sea level. This, coupled with increasing demand for water and the risk of increasing salinity at a number of pumping stations led to the need for a new approach and a careful review of the way in which the sources were operated.

From 1957, preference was given to using the coastal pumping stations in winter to maximise interception of the seaward outflow from the aquifer. At the same time reduced abstraction from inland pumping stations conserved aquifer storage and promoted recovery of water levels. In the summer months abstraction from the coastal sites was reduced and preference was given to the inland sites such as Mile Oak, Patcham and Falmer. Seasonal output from the coastal sites was maintained until chloride started to rise. This policy allows greater use to be made of inland pumping stations to meet the high summer demand, and helps in coping with drought years.

The coastal and inland sources were termed ‘leakage and storage stations’ respectively by the Brighton water engineers; the former intercepting winter outflows from the Chalk, and the latter abstracting groundwater from the centre of the Chalk Block. There is a clear distinction between the leakage sources (e.g. Shoreham, Balsdean, Goldstone and Southover) and the storage sources (e.g. Mile Oak, Patcham, Falmer). The former exhibit very small, if any, groundwater level recoveries during the year, while the latter exhibit normal water-level fluctuations.

Growth in abstractions

At the turn of the century, the total amount of water abstracted in the Brighton Block was 10 300 megalitres per annum (Ml a^{-1}) from five sources. By 1950, the output from these sources had doubled. The 1957 abstraction policy put greater emphasis on the leakage stations, and these supplied 65% of the total by the early 1960s (see Figure 61). Several new sources have been established since then and these allow abstraction to be spread more evenly across the aquifer. In 1980, twelve pumping stations met the demand of 26 930 Ml a^{-1} with 63% per cent taken from storage stations and 37% from the leakage stations. In 1993, 54% of the 29 200 Ml a^{-1} came from the leakage stations and the remainder from the storage stations.

Individual sources

Southern Water Services operates 12 groundwater sources in the Brighton Chalk Block, plus one at Steyning, north of the scarp of the South Downs. In addition, South East Water abstracts from five small scarp springs (See Table 16).

Goldstone is a semi-leakage, semi-storage station, situated 2 km from the coast in Hove. It has a small annual water level range of around 3 m. When it was first constructed in 1872 it yielded brackish water when pumped heavily for long periods. As production approached 27 Ml d^{-1}, chloride could build up to 600 mg l^{-1}. This problem lessened when additional stations were commissioned in and around Brighton between 1900 and 1910, although it became severe again during the summer of 1949.

Figure 61 Leakage and storage abstractions from the Brighton Chalk Block.

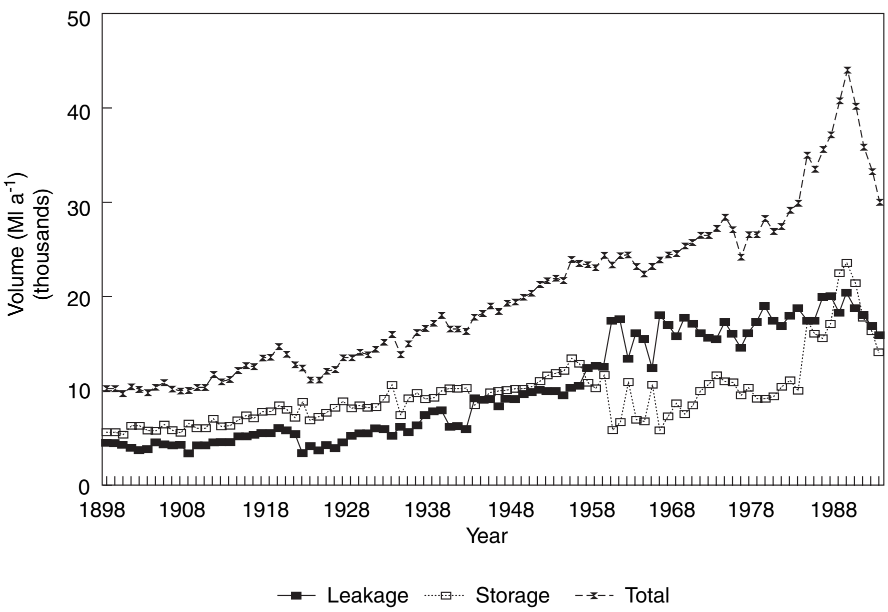


Table 16 Public water supply sources in the Brighton Block.

Source	Autumn drought output (Ml d^{-1})	Licensed quantities (Ml a^{-1})	
SOUTHERN WATER			
Steyning	0.7	2.3	596
Shoreham	5.5	10.0	grouped 38 000
Mossy Bottom	3.8	4.5	
Mile Oak	7.5	17.5	
Goldstone	19.3	20.0	
Patcham	7.5	17.5	
Surrenden	3.3	7.6	
Lewes Road	5.8	7.0	
Falmer	7.5	22.0	
Housedean	6.7	6.7	
Newmarket	14.8	14.8	
Balsdean	13.5	34.0	
Southover	17.0	25.0	
SOUTH EAST WATER			
Saddlescombe	1.1	2.4	grouped 1659
Clayton	1.1	2.5	
Whitelands	0.3	1.0	
Coombe Down	0.3	0.9	
Offham	0.6	2.3	

Balsdean pumping station, which was introduced in 1936, had similar difficulties. This leakage station is 2.5 km from the sea, but the maximum water levels is only 3.7 m above OD, with minimum annual minimum levels of between 0.3 and 1.2 m above OD. Balsdean was developed as a major new source in the early 1930s once the nearby source at Saltdean had become saline. Most of the water at Balsdean derives from a single large fracture at 21 m depth, and during the summer the salinity increases as the sea tide rises. For several months of the year pumping is avoided for two hours each side of high tide, but the year 1949 was particularly bad and chloride concentrations reached 400 mg l^{-1}. Later studies of groundwater flow in the boreholes showed that the chloride concentrations exhibited a cyclic pattern which reached a peak during spring tides whenever groundwater levels were low (Warren, 1962; 1972).

Southover is located close to the flood plain of the Ouse near Lewes. Although it is classified as a leakage station, it has never become saline. This reflects the substantial groundwater flow down the Winterbourne valley from Falmer, which prevents saline water migrating far from the Ouse.

Mile Oak and Shoreham, in the west of the Brighton Block are used in conjunction in 'storage and leakage' sources. Mile Oak has been an important inland storage station from which abstraction gradually increased during the first half of the century to 3800 Ml a^{-1}, but Shoreham was not much used until the Brighton abstraction policy was implemented in 1957. The output from Shoreham was then increased to 2500 Ml a^{-1} and that at Mile Oak severely cut back to 1200 Ml a^{-1}.

Shoreham, although less vulnerable to saline intrusion than Balsdean, can suffer salinity ingress from the Adur estuary during the summer months. In most years, abstraction does not need to be cut back, but if in a dry year the chloride concentration reaches 100 mg l^{-1}, then the main pumping load is transferred to Mile Oak. This occurred in 1959, 1964–65, 1972–1974 and, more recently in 1988–1992, with abstraction from Mile Oak increasing to 57% of the combined Mile Oak and Shoreham output, while in the three years previous to 1988 it made up only 47%. The wide variations in pumping levels which have occurred in the last 25 years at Shoreham reflect its use as a leakage station for which maximum use is made. Water levels at Mile Oak have risen by 6 m as a result of the changed abstraction regime, although they were drawn down to -3.4 m above OD in 1989 during the prolonged 1988–1992 drought in order to compensate for the reduced pumping at Shoreham (see Figure 62).

From the end of the last century the three stations at Mile Oak, Patcham and Falmer, situated across the centre of the Chalk block, have been key sources of supply. In 1905 they met 63% of the total demand. Between 1900 and 1957 their combined output trebled to 13 000 Ml a^{-1}. It was then severely reduced to an aggregate abstraction of between 4000 and 6000 l a^{-1} (see Figure 63). This cut back has led to a significant rise in pumping and rest water levels at these sites. Prior to 1957 the average minimum annual pumping levels, for these three stations, was generally 0 to 4 m above OD, but it has since risen to 5 to 8 m above OD.

A clear indication of the extent of the post-1957 rise in levels in these sources can be obtained by comparing them with natural groundwater levels recorded at Chilgrove, near Chichester, (see Figure 63). Comparing minimum annual groundwater levels using a double mass plot shows that the average levels in these three stations are now 5 m higher than they would have been if the pre-1957 rates of abstraction had been maintained. Similar comparisons using annual mean water levels shows an improvement of 4.4 m over 1957 conditions.

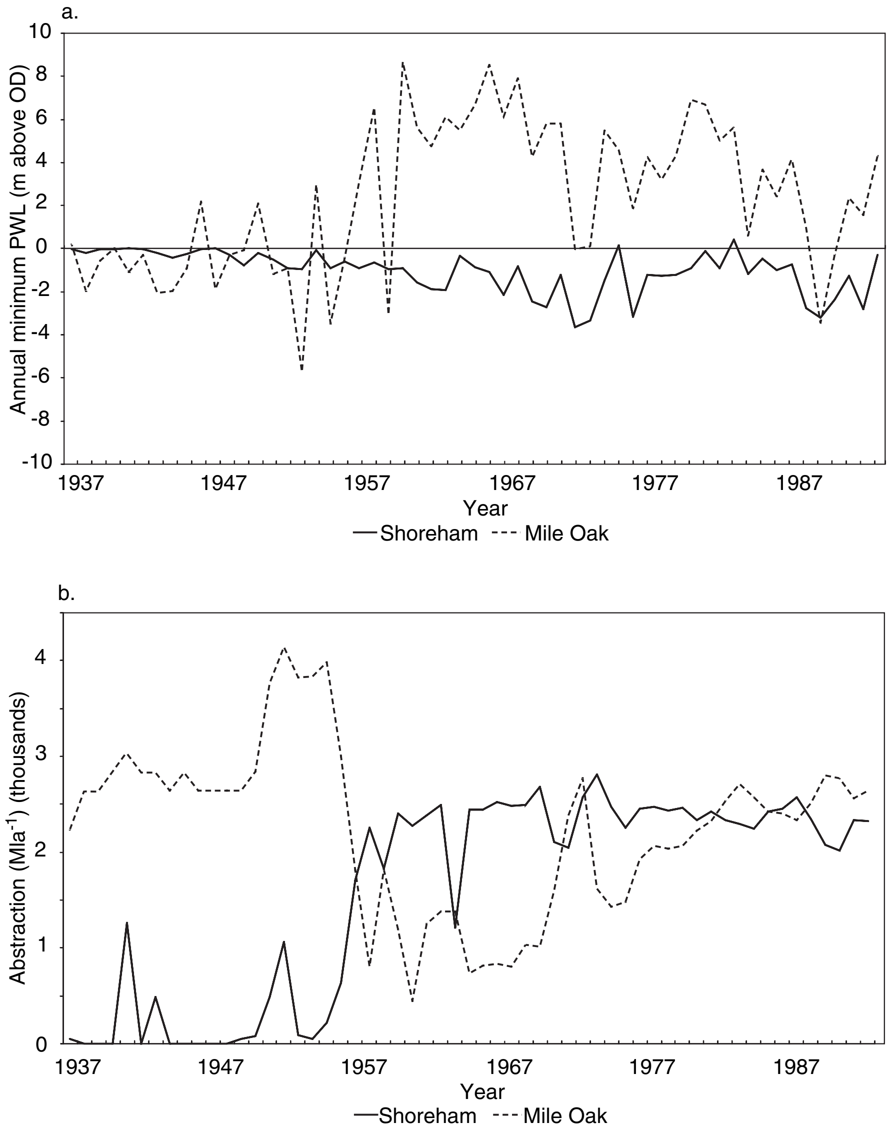
SUCCESS OF THE BRIGHTON ABSTRACTION POLICY

The effectiveness of the abstraction policy allowed increased abstraction whilst maintaining acceptable levels of salinity. However, there are significant costs in lifting large amounts of water from pumped groundwater levels to service reservoirs high on the Downs, as

Figure 62 Mile Oak and Shoreham public abstraction boreholes.

a. Average annual minimum pumped water level (PWL).

b. Total abstraction.



well as pumping it over long distances. As a consequence, abstraction schedules are now designed to minimise pumping costs as well as to conserve groundwater storage and an all-pervading 'storage and leakage' pattern of abstraction is not clearly apparent across the block. Three factors contribute to the success of the policy (Headworth, 1994):

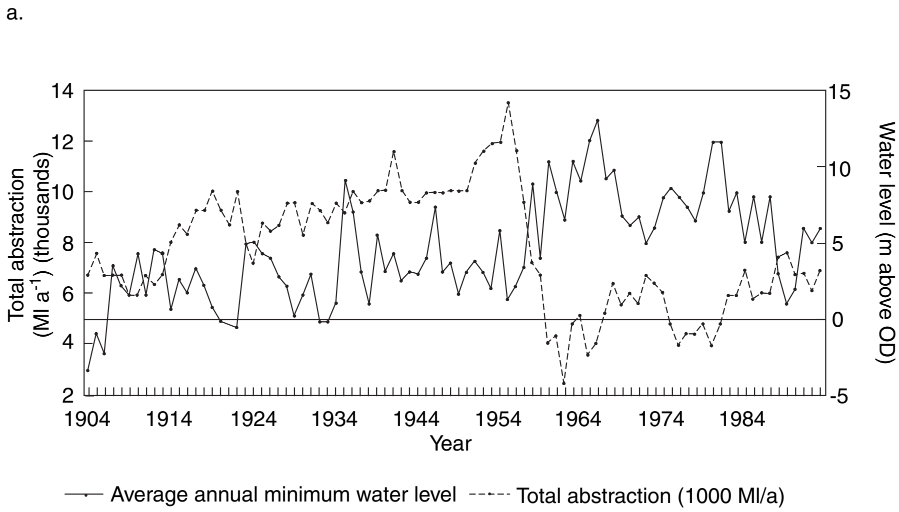
- The very close control of service reservoir levels, pumping levels, abstracted quantities and daily pumping regimes which is practised by Southern Water using sophisticated central telemetered control.
- The number of sources added since 1972 which has allowed the abstraction load to be better distributed.
- The small number of private abstractors, permitting comprehensive aquifer management.

An objective assessment of the overall improvement in aquifer groundwater levels since 1957 was carried out in 1972 using a two-dimensional finite-difference numerical model (Nutbrown, 1975; Nutbrown et al., 1975) and which was subsequently modified and recalibrated. The model used the conventional successive over-relaxation method of computing water levels over a 1 km square grid. The results of the modeling show that for steady-state conditions, groundwater levels, when averaged over the whole of the 193 km^2 area of the Brighton Block, are 0.6 m higher than they were in 1953, despite a 33% increase in total output since then (Headworth and Fox, 1986). If no increase in pumping had occurred since 1953 the difference in mean water level would have been 1.6 m.

However, much of Brighton Block comprises the coastal or estuarial margin where groundwater levels are influenced more by the sea and tidal rivers than by inland pumping. For the central part of the aquifer, where most of the active aquifer storage exists, the numerical model shows that for steady-state conditions the present average groundwater levels are 1.9 m higher than those which occurred under 1953 conditions. Moreover, if the present-day output had been achieved in 1953 with the abstraction regime then in force, the average improvement in levels in the central area of the block could have been 4.3 m.

Figure 63 Annual minimum water level and total abstraction.

a. Mile Oak, Patcham and Falmer public abstraction boreholes.
b. Annual average water level at Chilgrove borehole.



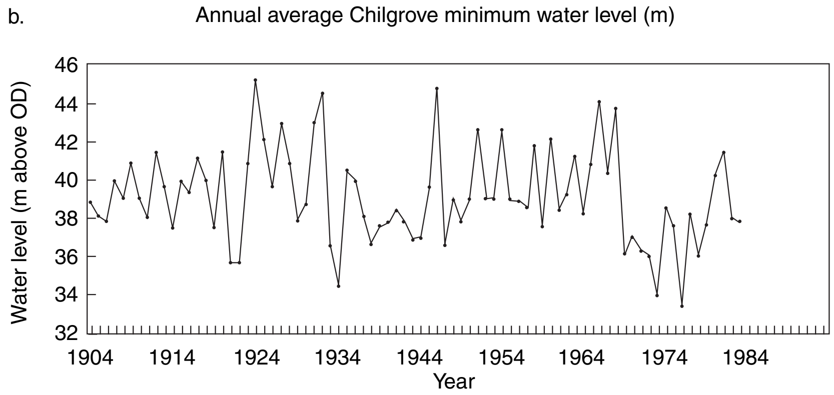


Plate 14a The River Lavant at Mid Lavant: normal wet winter (GS 638).

Plate 14b The River Lavant at Mid Lavant: normal summer (GS 637).

Plate 14c The River Lavant at Mid Lavant: flooding on 24 January 1994 (GS 636).

Worthing Chalk Block

Southern Water Services operates nine groundwater sources in the Worthing Chalk Block. These are grouped into a single abstraction licence for which each source has its own daily maximum authorised quantity but for which there is a single annual maximum (See Table 17). The Company's two sources at the eastern end of the Chichester Block at Arundel and Madehurst are included in this licence for operational convenience.

The 'storage and leakage' abstraction policy has not been applied in the Worthing Block, because it is largely protected from saline intrusion by the eastward extension of the Chichester syncline. The Worthing Block is narrower than the Brighton Block and any winter gain in aquifer storage is mobilised less readily. There are also fewer sources, and none in the upper part of the block, with which to facilitate storage manipulation. Nevertheless, the two pumping stations situated on the

Table 17 Public water supply sources in the Worthing Block.

Source	Autumn drought output (Ml d^{-1})	Licensed quantities (Ml a^{-1}) daily (Ml)	Licensed quantities annual (Ml)
Burpham	3.0	25.0	
Angmering	3.5	4.0	
Patching	5.0	9.0	
Clapham	3.5	4.5	total
Stanhope Lodge	6.5	7.0	19430*
Findon	6.0	11.5	
Broadwater	13.0	22.5	
Northbrook	7.0	7.0	
Sompting	7.5	11.5	

* Southern Water's Worthing group license totals 26 000 Ml a^{-1} and includes Madehurst for 4927 Ml a^{-1} and Arundel for 1643 Ml a^{-1}.

west and east flanks of the block at Sompting and Burpham, display the leakage characteristics of low groundwater levels and periodic elevated salinities. Sompting lies 4 km west of the tidal River Adur and 3 km from the coast, but is adjacent to a stretch of coast which is not protected by the overlying Palaeogene clay. The copious chalk springs which discharge at Honeyman's Hole, near Shoreham Airport, may suffer reverse flow in winter leading to occasional increases in salinity at Sompting.

Southern Water's pumping station at Burpham is located 5 km north-east of Arundel and 2 km from the tidal River Arun. This source is subject to saline, bacteriological and turbidity contamination and treatment is now provided to remove occasional suspended matter. In the 1970s extensive work was carried out to detect the origin of the contamination, and several dye tracing surveys established that the salinity and turbidity contamination arose from the reversal of springs in the Burpham Loop, a sharp bluff on the left bank of the tidal Arun, 1.3 km south-west of Burpham. Later, attempts were made to close off these reversing springs with sheet piling, but these were not successful. The extent of this contamination severely reduces the reliable yield of the source in the late summer and autumn months, particularly at times of spring tides.

Chichester Chalk Block

Portsmouth Water plc operates nine groundwater sources in the Chichester Block which is contiguous with the Hampshire Downs to the west where the Company also has several other sources, including the Havant and Bedhampton Springs. Southern Water Services operates two sources at the eastern end of the Chichester Block at Arundel and Madehurst (Table 18).

The Chichester Chalk Block, like the Worthing Block to the east, is protected on its south side by the Chichester syncline. Flow gauging and chemical analysis of the streams draining the central part of the block indicate that outflows are blocked by low-permeability chalk. In consequence, groundwater flows are directed eastwards towards Arundel and westwards towards Chichester. Major springs at Arundel have an average discharge of 50 Ml d^{-1} and are used for amenity and conservation purposes.

The syncline is pierced by several tidal creeks near Chichester. These may be located above arching along the axis of the syncline which promotes numerous spring discharges. The springs to the west of Chichester, partly intercepted by Portsmouth Water at its borehole source at Fishbourne, have flows of between 13 and 36 Ml d^{-1}. There is scope for further resource exploitation of the Chichester Block in this area; at present it is exploited less than the other four Chalk blocks.

The centre of the Chichester Block is drained by a large ephemeral stream, the Lavant, which has no perennial source and dries out for long periods. Flow is very flashy and ranges up to 7.9 cubic metres per second (685 Ml d^{-1}), a maximum which caused the severe and prolonged flooding of Chichester in the winter months of 1993/94. Increased pumping from the existing station at Lavant, close to the river, would have proved detrimental to amenity and conservation interests and in the mid 1970s a new satellite source utilising summer aquifer storage was developed in a tributary valley at Brickkiln Farm, 4 km from the existing station. Licensed only for summer use, the combined abstraction from

Table 18 Public water supply sources in the Chichester Block.

Source	Autumn drought output (Ml d^{-1})	Licensed quantities (Ml a^{-1}) daily (Ml)	Licensed quantities annual (Ml)
PORTSMOUTH WATER COMPANY			
Walderton	31.7	36.4	9955
Woodmancote	3.0	4.6	1364
Funtington	5.0	8.0	2920
Lavant and Brickkiln Farm	20.0	32.0	9950
Fishbourne	8.0	13.6	3741
Westergate, Eastergate and Slindon	31.0	31.0	10 358
SOUTHERN WATER			
Arundel	4.0	4.5	6570* (Arundel and Madehurst combined)
Madehurst	9.1	13.5	

* these sources are included in Southern Water's Worthing group licence.

Brickkiln and Lavant permit full use of groundwater resources in this central part of the Chichester Block with minimum effects on stream flows. This development constitutes a good example of 'summer outstation' development.

The Arundel pumping station is situated on the edge of the flood plain of the Arun valley, but is not subject to salinity problems, due largely to the Chichester Syncline concentrating groundwater flow in an easterly direction. Nevertheless, it suffers from contamination from a filamentous algae and water requires micro-filtration. Nearby, Swanbourne Lake derives most of its flow from the Blue Spring, and there have been a number impact studies investigating the pumping regimes at both Arundel and Madehurst.

Seaford Chalk Block

There are three public water supply sources, all operated by South East Water (Table 19), in the Seaford Block, the smallest of the five blocks. The block possesses unusually high transmissivities which give rise to very rapid groundwater outflows and groundwater retention time in the aquifer is short. This is not conducive to the conservation of storage by seasonal abstraction. Poverty Bottom is the largest of the sources, but chloride concentrations have been gradually rising during the last thirty years: from 40 mg l^{-1} in 1967, to 60 mg l^{-1} in 1977 and as high as 6300 mg l^{-1} more recently, although the abstraction licence specifies cessation of pumping when the chloride concentration exceeds 150 mg l^{-1}.

In the early 1980s, the former Eastbourne Waterworks Company developed and tested a new source at Rathfinny which is located towards the centre of the Seaford Block and in what was then their statutory supply area. Derogation of Poverty Bottom prevented the then Southern Water Authority from licensing the source and in consequence the Mid Sussex Waterworks Company acquired Rathfinny. Poverty Bottom is now used mainly in the winter to make fullest use of winter outflows from the aquifer, and Rathfinny is used mainly in the summer to make maximum use of the little aquifer storage that exists in the block.

Eastbourne Chalk Block

There are seven public water supply sources in the Eastbourne Block, all operated by South East Water (Table 20). Lower Chalk is exposed along the coastline of the Eastbourne Block, and as a result of its low permeability, saline intrusion in this area has not generally been a problem (see Chapter 5). However, early problems did occur at Waterworks Road pumping station, which had to be taken out of supply in 1896 when chloride concentrations exceeded 2000 mg l^{-1}. The station was brought back into supply in the 1950s following engineering work to ensure that the problem does not recur.

THE SOUTH DOWNS INVESTIGATION

While operational developments and innovations saw the introduction of the Brighton abstraction policy in 1957, many developments came about from the investigations in the South Downs between 1968 and 1985 by the Southern Water Authority and its predecessors, in cooperation with the Water Resources Board (WRB), and later the Central Water Planning Unit (CWPU) and Water Research Centre (WRC).

The South Downs investigation started in 1968 following a resources assessment by Sussex River Authority. The study was originally only concerned with the Brighton and Worthing blocks of the South Downs. However, in 1974 the Southern Water Authority was formed, and became responsible for the investigation which was then extended to include the whole of the area (Southern Water Authority, 1984). The aims were to obtain a better understanding of the hydrogeology of the South Downs, and to calculate the optimum location of boreholes to maximise yield and minimise contamination of groundwater resources by saline intrusion. This included development of resources

Table 19 Public water supply sources in the Seaford Block.

Source	Autumn drought output (Ml d^{-1})	Licensed quantities (Ml a^{-1}) daily (Ml)	Licensed quantities annual (Ml)
Poverty Bottom	16.4 (combined)	20.5	7467 (combined)
Cow Wish		7.3	
Rathfinny		10.0	

Table 20 Public water supply sources in the Eastbourne Block.

Source	Autumn drought output (Ml d^{-1})	Licensed quantities (Ml a^{-1}) daily (Ml)	Licensed quantities annual (Ml)
Friston and Deep Dean	12.9	23.6	6632
Filching	27.1 (combined)	2.7	675
Waterworks Road		9.0	3285
Holywell		4.3	900
Cornish		9.0	1980
Birling Farm		3.6	985

beneath the higher dry valleys of the Downs, which are less permeable, but are remote from the coast. Downhole geophysics, aerial thermal infra-red linescan surveys, and mathematical modeling were all utilised (Nutbrown, 1976a).

Borehole drilling and testing

Several sites were selected for drilling and aquifer testing during the investigation, and some were subsequently developed for public water supply (see Table 21). At each site, two, or more commonly three, 250 mm diameter exploratory boreholes were drilled in a configuration which best suited the site conditions. The boreholes were drilled to a depth about 50 m below the water table, and if bailer tests were promising, acidisation followed. The boreholes were then tested for several hours and discharged overground. Any promising boreholes were redrilled to larger diameter (610–760 mm), and the others in the group retained for observation. If none were developed, one was retained as a long-term observation borehole and the others filled in. This proved to be affective exploratory procedure, although there were occasional problems with running sand or turbidity with the full-diameter production boreholes.

Downhole geophysics

Numerous deep observation boreholes were drilled along the Brighton frontage from Portslade to the Steyne (see Chapter 5; Monkhouse and Fleet, 1975). Their purpose was to determine the presence, extent, character and movement of the saline front and to act as long-term salinity monitors for the inland sources. They showed that:

- There is no conventional Ghyben-Herzberg wedge between fresh groundwater and saline water.
- Each borehole has unique salinity features; some show a simple increase of salinity with depth which rises and subsides with the tide, others show complex salinity profiles with the saline front moving in rapidly on the tide along strong fractures, and dissipating equally rapidly on the falling tide.
- The pattern of saline intrusion cannot be easily predicted; a borehole inland may have greater salinity problems than one near the coast.
- Monitoring boreholes along the axis of a dry valley away from a pumping source cannot necessarily be used as a monitor for the pumping source.
- On the rising tide, saline water can move quickly inland along discrete fractures which, on the ebb tide act as conduits for escaping groundwater.

Thermal infra-red aerial survey

In 1973 the former Water Resources Board organised a thermal infra-red aerial linescan survey along the Sussex coast to try to locate offshore springs. The survey was

Table 21 Sites selected for drilling and aquifer testing: South Downs Investigsation.

Site	Grid Ref.	Comments
BRIGHTON BLOCK		
Surrenden Gardens, Withdean	TQ 302 075	Developed as an auxiliary source to Patcham
St Mary's Farm, Balmer Down	TQ 347 105, TQ 346 104	Negligible yields, neither developed
Housedean Farm, Falmer	TQ 362 093	Developed as new source
Housedean Farm, Falmer	TQ 393 102	Not developed, modest yield
Benfield Valley, Portslade	TQ 262 080, TQ 262 083	Running sand, not developed
Mossy Bottom, Mile Oak	TQ 221 077	Developed as new source
Ladies Mile, 1, 2, 3	TQ 317 094	Not developed, very poor yield
WORTHING BLOCK		
Angmering 1 and 2	TQ 058 069, TQ 064 065	Developed as new source
Clapham	TQ 090 060	Developed as new source
Findon No 2	TQ 127 079	Screen replaced in 1994
Findon No 3	TQ 12 10	A proposed site north of Findon; was never investigated
Myrtle Grove, Clapham	TQ 080 082	Not developed, negligible yield
Tolmare Farm	TQ 106 086	Test hole enlarged to full diameter and step tested
Annington Farm, Coombe	TQ 172 095	Not developed, negligible yield
Lychpole Farm, Sompting	TQ 155 077	Not developed, negligible yield
Warningcamp	TQ 046 074	Recently drilled and tested and will be operated with Burpham treatment plant when licensed
CHICHESTER BLOCK		
Madehurst 1 and 2	SU 981 094, SU 981 100	Developed as new source
Park Bottom, Arundel	TQ 005 070	Good yield but too environmentally sensitive to permit development
Brickkiln Farm (Portsmouth WC)	SU 836 124	Developed as a new source
Tortington	SU 983 072	Drilled and tested in 1993/94, awaiting licensing

run between Bognor Regis in the west and Eastbourne in the east during February when groundwater outflows were near their highest and when the temperature difference between sea water and groundwater was at its greatest (Davies, 1973; Brereton and Downing, 1975). The survey was moderately successful and spring discharges were found at Lancing, Hove, Brighton and Saltdean, but navigation problems prevented good results being obtained further to the east. Over-beach sheet flow observed at Lancing reflected the deflection of groundwater from the Palaeogene strata of the Chichester syncline.

Mathematical modeling

The first mathematical model of the South Downs (both Brighton and Worthing blocks) was constructed between 1971 and 1973 (Nutbrown, 1975; Nutbrown et al., 1975). Later, in 1975/76, this was recalibrated (by WRC) using extended and improved recharge data, and again reworked by the Southern Water Authority.

The use of the model for practical decisions on groundwater management is hindered by the limited dataset because evenly distributed aquifer properties information is required for the construction of a reliable model in a fractured aquifer. Furthermore, as the relationship between abstraction and saline intrusion is a key management issue, the model must be able to forecast cause and effect. So far this has not proved possible. Nevertheless, the model represents the general behavoir of the aquifer satisfactorily. For example, use of the model in the early 1970s clearly showed that intensive development of groundwater in the Winterbourne and Patcham valleys of the Brighton Block was likely to affect groundwater levels down to the coast. It also illustrated the development of steep hydraulic gradients to the north of these areas because of the lower permeabilities in the higher areas of the Downs (Nutbrown et al., 1975).

Operational models

Several attempts have been made to model the water supply system of the Brighton Block with the intention of using it to assist day-to-day operations. Unfortunately none of these were successful. This is no doubt because of the complexity of the water supply system of the Brighton area, which includes:

- 12 separate sources
- 16 booster stations
- 33 service reservoirs
- six separate pressure zones
- four different electrical tariffs.

Chichester Block mathematical model

This was constructed by the Southern Water Authority as a conventional finite-difference model based on a 1 km grid. A significant feature is the incorporation of a very low permeability zone of chalk at the south-east end of the block (approximately between Arundel and Westergate). This was required to prevent southward flow since the Rifes study had shown that very little chalk water contributed to the eastern rifes. It was also needed to account for the very large flows which discharge from the block around Arundel (from Swanbourne Lake, Park Bottom, the Mill Stream and Black Rabbit Sluice).

The presence of this low-permeability zone in the corner of the block is important to the understanding of the available resources and their future development. It is probably caused by a deepening of the Chichester Syncline which inhibited the development of fractures in the Chalk during late-glacial times when sea levels were much lower.

The Chichester rifes

Water resource balances for the Chichester Block present a problem because of the large number of outflows which exist around its margins. The small steams (or rifes as they are called locally) which occur between Arundel and Chichester present a major problem because they are numerous and difficult to measure.

As part of the South Downs investigation both the chemistry and the flows of the rifes were studied. Major ion chemistry (Mg, Ca, Na, K, Cl, SO_4, NO_3) was examined using trilinear plots to distinguish different types of water. These proved of only moderate value in the case of the Chichester rifes but, nevertheless, showed that only the rifes at the western end of the block (Bremere, Pagham and Oving) possess any significant chalk groundwater component, while those to the east (Aldingbourne and Binsted), contain little or none. This knowledge was very useful when it came to constructing the mathematical model for the Chichester Block.

THE 1988–92 DROUGHT

The 1988 to 1992 drought illustrated the importance of both resource and water supply management. The four-year period from October 1988 to October 1992 was unusually dry: rainfall was 16% below average, while for the six-monthly winter periods, total rainfall was 20% below average (Miles, 1993). The winters of 1989/90 and 1991/92 experienced rainfall 39% below average (Figure 64). By October 1989 groundwater levels in the South Downs had fallen to record levels.

The low groundwater levels caused increased salinity. Chloride concentrations in South Downs Chalk groundwater peaked at almost 200 mg l^{-1} in central Sussex in the summers of 1988, 1989 and 1990, and the very strong correlation between chloride levels and groundwater head (Figure 64), illustrates the influence of groundwater level on saline intrusion.

Southern Water was obliged to introduced a series of measures of increasing severity. These started in January 1989 with a publicity campaign in local newspapers and on local radio to 'use water wisely'. In May 1989 a hose pipe ban was introduced and this was followed in July and October by two drought orders which permitted restrictions on certain uses of water (e.g. car washes). Recharge during the following winter allowed the restrictions to be lifted, but it was necessary to reintroduce them again in 1990, and they remained in force until February 1991 even though very low groundwater levels continued to persist for the next 18 months. Southern Water was confident that the public would continue to respond and 'use water wisely' as, indeed, it had done in the previous drought of 1976. Moreover, the Company's continued success in reducing water losses through its leakage control programme meant that the amount of water in supply had fallen (Figure 64) and the company remained confident it could maintain supplies as the drought continued. This proved to be the case.

RECENT INFLUENCES

The policies adopted recently in the South Downs have been directed by the strategies introduced by the former National Rivers Authority and more recently by the Environment Agency. These include:

- Sustainable development — the need to ensure there is no long-term systematic deterioration of the water environment due to water resource developments and water use.
- Precautionary principle — the need to err on the side of caution in making decisions on potential developments where there is uncertainty over likely effects on the water environment.
- Demand management — the need to manage the total quantity of water taken from the environment (by all users) using measures to control waste and consumption.

In the specific context of the South Downs these translate into:

- A presumption against licensing additional consumptive abstraction from the Chalk — this recognises that a relatively large proportion of the natural resource had already been licenced.
- Where possible, favouring redistribution of existing water resources rather than development of new sources, thereby maximising use of existing licenced quantities.
- Promotion of water efficiency by industry, commerce, agriculture and in the home — particularly leakage reduction and metering.

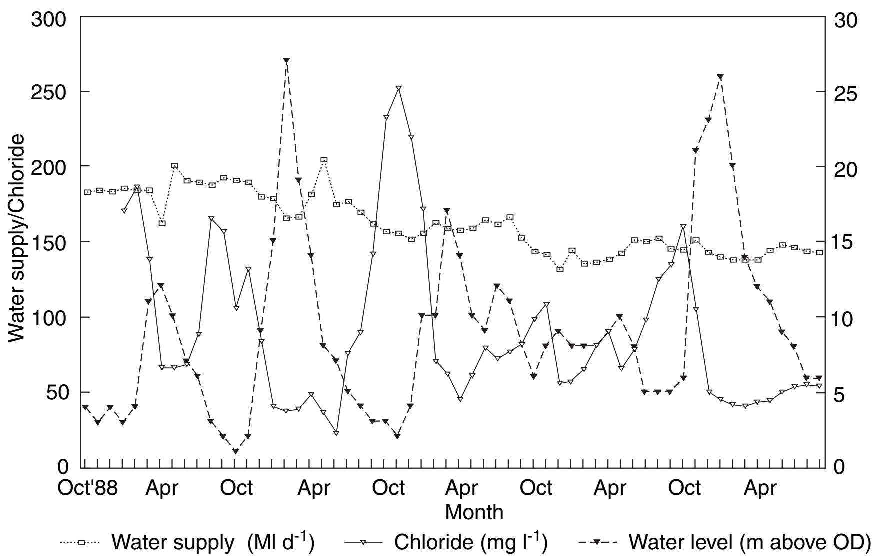
Until recently, operational policy for the Brighton and Worthing supply area hinged upon the use of high-yielding sources satisfying local demand. In 1996, however, Southern Water commissioned a new trunk main linking its Hardham source, (which is licenced to draw from both the River Rother and the Lower Greensand) into the Worthing distribution system. This has improved flexibility, and maximised the use of available resources within existing authorised limits.

Scope for similar supply transfers between other sources across the five South Downs Chalk blocks will depend on cooperative ventures between the three water companies involved. This is under consideration as part of an overall resource assessment currently being carried out for the Environment Agency in collaboration with the water companies.

THE FUTURE OF RESOURCE MANAGEMENT

The policy for the management of groundwater in the South Downs is essentially that of local resources for local demands. High-yielding wells have been developed in areas of favourable permeability in the principal dry valleys and on the coastal fringe. The aquifer responds rapidly to abstraction from these wells because of high permeability and low storativity but this induces rapid changes in the hydraulic gradient (Nutbrown et al., 1975). This rapid response towards the coastal saline boundary has limited the full development of the resources and led to the seasonal emphasis on coastal and inland wells described above. Groundwater

Figure 64 Drought management in central Sussex: water supply and water level.



storage below the less permeable upland regions is utilised to a much lesser extent.

The detailed study of the Brighton and Worthing blocks, carried out in the l960s and 1970s, included drilling and test pumping boreholes in the higher dry valleys of the Downs in an attempt to develop the resources in the less permeable parts of the aquifer, remote from the coast. The investigation was only partially successful, because groundwater development in these areas requires many small yielding sources which are difficult to integrate and expensive to operate. In the early 1980s the Southern Water Authority reviewed the results from all the wells drilled in the high dry valleys and concluded that the project should be abandoned; a significant proportion of the sites had very low yields, for example Balmer Down, Lychpole and Annington.

The emphasis on local resources to meet local demands means there is very little transfer of water between the various blocks and the resources available in the blocks are not utilised equally. It is preferable that future management policy should attempt to operate all the five blocks as a single water resource unit: switching abstraction according to conditions in the aquifer and centres of demand. It is a policy that would require exploitation of all the blocks to the same level, expressed, for example, as a fraction of the average annual recharge (Nutbrown, 1976a). Such integrated use would allow greater overall abstraction with less risk of saline intrusion, but it would require significant volumes of water to be exported from the Chichester Block to the Worthing and Brighton blocks. This is, however, in keeping with current policy of the Environment Agency which favours *transfer of bulk supplies* to areas in need as an attractive alternative to the development of new resources.

Theoretically, groundwater in the Chalk could be developed in conjunction with the surface water resources available in the Wealden rivers, either directly or by way of artificial recharge. In the latter case, an unconfined aquifer in contact with the sea, is constrained by the volume of storage in the aquifer at the end of a summer period (Nutbrown, 1976b). Artificial recharge of even a small volume, say 10 000 $m^3 d^{-1}$ of water, at sites remote from the coast over a six-month winter period, could increase the minimum storage above sea level at the end of a summer recession by about 10% or 10 Mm^3 (Nutbrown, 1976a). At present economic factors preclude the serious consideration of such proposals.

The availability of future groundwater resources may be influenced by global warming. Temperatures could rise in the UK by 1 to 2°C by the middle of the next century and long-term rainfall could decrease in southern England. Winters may be wetter but the summers may be drier and more prolonged. Consequently, autumn soil moisture deficits are likely to be higher than at present and groundwater level recession will extend, i.e. the recharge season would be curtailed.

The impact of climate change on groundwater storage has been investigated by simple aquifer models (Wilkinson and Cooper, 1993). In a rapid response aquifer, such as the Chalk, a small reduction in the length of the recharge season reduces the volume of groundwater storage in the late summer and autumn; a reduction to 4 months could reduce the groundwater stored above the outflow base level by as much as 55% which is particularly significant in a coastal aquifer. Furthermore, increased evapotranspiration could also have a marked affect on groundwater recharge (Cooper et al., 1995). In the event that these changes occur, the management of the South Downs aquifer would assume great importance.

OVERVIEW OF AQUIFER MANAGEMENT

Efficient management of a coastal aquifer such as the South Downs, which is vulnerable to saline intrusion, requires several prerequisites:

- sound knowledge of available resources
- control of private abstractions
- close monitoring of abstractions, water levels and the salinity of groundwater along the coast
- sound water supply management through a clear abstraction policy
- predictive capability

Knowledge of the availability of resources is fundamental. In a fractured aquifer the major uncertainty is the degree to which theoretical resources can be utilised for abstraction. In Britain, during the last 20 years it has become customary to design groundwater abstraction schemes on the basis of the availability of available resources with a return period of one year in 50, and it has been considered prudent to apply this criterion to the South Downs as the standard for resource development.

Abstraction control, monitoring and the acquisition of hydrometric information facilitate the adoption of a sound abstraction policy. This is aided further if the public water supply sources in each catchment are operated by a single water undertaking, as is largely the case in the South Downs. Over the last 37 years in the Brighton area, the policies for intercepting coastal outflows and the ‘leakage and storage’ abstraction policy have contributed to a 33% increase in abstraction with a concurrent rise in average groundwater levels of 1.6 m. If the increase in abstraction had not occurred then the predicted rise in groundwater levels could have been 4.3 m.

This same abstraction policy is now also followed in the Seaford Block where the Rathfinny and Poverty Bottom sources are utilised in combination to maximise the limited resources. The policy is not in use in the Worthing Block because the coastal margin is protected by Palaeogene strata. In the Chichester Block interception of large spring discharges is likely to be the main target for future groundwater development, subject to environmental considerations.

Control and monitoring of private abstractions under the licensing provisions of the Water Resources Act 1991 is also essential to the proper management of resources. Private abstractions are few in number in the South Downs; there is little industrial development, and the light chalky soils are well suited to the growth of arable crops which require little or no irrigation. The proportion of private abstraction, therefore, is generally small and not likely to expand significantly in the future.

Careful monitoring of seasonal and long-term changes in the salinity of groundwater is essential. Regular geophysical down-hole logging of differential temperature and fluid conductivity are used for regular monitoring of seasonal and long-term changes in salinity (Chapter 5).

Water supply management, including demand management are also part of the overall management scheme. Water supply management requires control of sources on a real time basis, to respond to fluctuating demand, varying electrical tariffs, pumping levels and aquifer salinities. This is achieved by Southern Water in the Brighton and Worthing areas by fully telemetered control from one centre.

Aquifer management is, of course, largely the anticipation of problems and their alleviation. The complexity of the water supply system in the Brighton area has so far defied attempts to create an operational model. The linking of such a model with an aquifer model, would provide a powerful means of testing different aquifer and water supply scenarios during a drought event. This desirable objective should be pursued.

8 The present and the future

PRESENT-DAY SITUATION

The new stratigraphical framework of the Chalk of the South Downs (Bristow et al., 1998) has shown that the chalk is neither uniform nor homogeneous. Fracture frequency, and openness are related to a combination of tectonic and geomorphological processes on the different lithologies. The chalk of the South Downs is generally harder than its equivalent in the North Downs. This, together with the extent and nature of the sediments overlying the Chalk, and the degree of exposure of the Chalk to Quaternary weathering, has undoubtably influenced the development of the aquifer properties in this area which include karstic features.

A preliminary geological model for chalk in the saturated or unsaturated zones needs to take account of both the range of lithologies present on a large and small scale; and the potential for karst development in relation to geomorphological setting, cover sediments, fracturing and lithology.

Fractures of tectonic origin extend through much of the Chalk sequence, and they act as extensive preferential groundwater flow routes. All these lines of weakness have been selectively developed and enlarged by weathering processes including solution, contraction and expansion through freeze–thaw cycles, the relaxation of stress in the rock as erosion proceeded, and as the post-Palaeogene landscape was created. They have been further modified by groundwater flow and dissolution.

However, the question remains as to which factors control the development of the aquifer properties of the Chalk. Lithology, or more precisely lithological contacts, appear to be the most significant factor, as evidenced from borehole logging investigations, although there also appears to be some alignment of water inflows according to elevation. This illustrates the influence of groundwater circulation on the development of dissolution-enhanced fractures, although flint bands are also important with respect to groundwater flow.

Topography is also an important factor: although attempts have been made to model transmissivity there are insufficient data for calibration, and a more representative data set is required, including information from interfluve sites. In the absence of a more sophisticated data set, the topography of the South Downs is a good regional indicator of transmissivity, although local transmissivity is enhanced close to Palaeogene deposits, above flint and marl bands, and in hardgrounds such as the Melbourn Rock.

Borehole temperature logs indicate that most groundwater movement takes place in the uppermost 100 m of the aquifer. Close to the coast, water movement may occur at greater depths, commonly as deep as 130 m bgl, but this relates to earlier and lower base levels.

The South Downs Chalk aquifer is in direct contact with the sea along much of its length, and problems of saline intrusion have been recorded for many years. In the west it is protected by the Chichester Syncline, and in the extreme east, by the lower permeability of the Lower Chalk. The Ghyben–Herzberg relationship does not apply to the dual porosity and dual permeability medium of the Chalk. The size, location and nature of fracture systems is the major influence on the occurrence and extent of saline intrusion.

Extensive geophysical logging has been carried out in the area to monitor saline intrusion. The boreholes tend to exhibit unique conductivity profiles, showing individual responses to variations in groundwater head, tide and abstraction rates. Even boreholes at similar distances from the coast have quite different responses, due to the complex fracture system.

A combination of the resistivity, temperature and conductivity logs provides evidence that saline water moves laterally through the fractures in response to groundwater and tidal hydraulic gradients. In the vicinity of the fractures, saline water gradually diffuses into the chalk pores, but a borehole intercepting the fractures may allow saline water to move vertically in the borehole, greatly complicating the interpretation of the geophysical log.

Despite high population density along the coastal fringe, extensive groundwater utilisation, and the agricultural nature of much of the South Downs, groundwater quality is generally good and incidents of groundwater pollution rare. Nitrate has not, historically, been a problem, although in recent years, some boreholes have shown increasing concentrations.

Over recent decades the policy of intercepting seasonal coastal outflows and adopting the practice of 'leakage and storage' abstraction in the Brighton area have contributed to a 33% increase in abstraction with a simultaneous rise in average groundwater levels of 1.6 m. If the increase in abstraction had not occurred then the predicted rise in groundwater levels would have been 4.3 m, a statistic which is used to highlight the success of the adopted strategy. This abstraction policy is now also adopted in the Seaford Block but is unnecessary in the Worthing Block where the coastal margin is protected by Palaeogene strata. In the Brighton Block the further interception of large spring discharges, some offshore, is likely to be the main target for future groundwater development.

While sound management of groundwater resources and protection against groundwater pollution are two of the essential ingredients for aquifer management, of equal importance is water supply management, including demand management. Aquifer management requires anticipation of problems.

The Chalk of the South Downs is one of the major aquifer units in England. Its outcrop covers an area of more than 600 km^2. Assuming a specific yield of 1%, the upper 50 m of the saturated aquifer contains 300 million m^3 of water — *more than the capacity of Kielder Water*. In 1993, the Chalk of the South Downs provided an equivalent yield of over 220 Ml d^{-1}. Although this represents only 25% of the average recharge, it is over 60% of the recharge during a drought year, highlighting its susceptibility to drought. The nature of the aquifer, with its permeable dry valleys, also makes it susceptible to saline intrusion, and some seaward flow of groundwater must be maintained to control the extent of the intrusion.

THE ISSUES

One million new houses are planned for the south-east of England, and the county of Sussex is targeted as a major development area; climate change may cause a reduction in effective rainfall, and could rejuvenate the tourist industry. Together, these diverse factors conspire to maintain an ever-increasing demand on a potentially diminishing resource.

Some of the groundwater management issues have been identified and successfully addressed. Not least among these are the abstraction/saline intrusion problem, and land zonation for restriction on land use to control pollution. Other issues have neither been adequately recognised nor properly addressed. The most significant of these is the determination of the resource potential of the South Downs aquifer as a whole rather than the sum of the five Chalk blocks. This issue is only now arising, because our more detailed understanding of the hydrogeological processes in the Chalk is revealing shortcomings in our current conceptual models.

The other significant issue now facing the aquifer is economics. Now that the water undertakings have become profit-making companies, the pressure for maximising return on investment and minimising operational costs has been intensified. It is no longer appropriate for hydrogeologists to promote groundwater management schemes in isolation, and an integrated approach to the use of all available resources (including bulk transfer) needs to be addressed.

FUTURE WORK PLAN

Although it has been convenient in the past to consider the South Downs aquifer as five discrete blocks each separated by a no-flow boundary, future pressure on the available resource requires that the aquifer be considered as a single hydrogeological unit. This idea is not new, and was first mooted by Nutbrown (1976b), although operational requirements and the need to source water locally for economic reasons have so far prevented progress. Notwithstanding, there is an urgent need to develop a single regional digital groundwater model of the South Downs, and use it to sustain the optimum development of the aquifer on a regional rather than a local scale. This model may then form a component of a GIS-type data assembly whereby demand, distribution and operational constraints can be matched with resource potential.

A key to establishing greater control over the development of the aquifer lies with the creation of a more comprehensive conceptual model. The new lithostratigraphy of the Chalk enables greater control to be put on aquifer geometry and the detailed hydraulics of the aquifer. However, the conceptual model requires an improved evaluation of features such as, for example, the role of the karstic horizons on groundwater flow within the chalk, and the interconnection between rivers and groundwater.

Together these studies will provide a better indication of the resource potential of the South Downs aquifer. Although the Environment Agency is responsible for calculating resource potential as part of its groundwater abstraction licensing activity, knowledge of the overall resource is as yet incomplete and much remains to be done to establish a reliable resource potential figure, and a scheme for the optimum utilisation of the resource.

As time goes on, and demand potentially outstrips resource, or rather our current estimate of resource, it will be necessary to revisit the possibility of diverting surface waters from the Weald for injection as artificial recharge to the Chalk. Arguments against this technique stem from inadequate available storage volumes versus regional head increases without incurring loss to the sea, and considerable effort will be required to match recharge areas with abstraction boreholes. Contemporary developments in aquifer storage and recovery may assist in seasonal import of surface water from the Weald.

Current resource management practise in the South Downs derives from two sets of constraints. One is the formal management strategy developed in recent decades for the optimum exploitation of groundwater according to the season, and the other is the operational constraint of supplying water at the most economical cost to the operator, and thus also the consumer.

Reluctance to move water in bulk is dictated by economics. However, as water is likely to become a more scarce commodity in the future, the options may begin to include bulk transfer. These options have been discussed elsewhere (NRA, 1994; NRA Southern Region, 1994) and they provide further combinations for conjunctive use with the available groundwater. The role of the precautionary principle is clearly a key to regulating and safeguarding the resource, but it needs to be kept in step with technological developments, not least the vastly increased power of interactive models. Nevertheless the important role of source and aquifer protection in safeguarding groundwater from pollution by restricting land use in selected zones illustrates the importance of the precautionary principle in other areas.

Much work has been carried out already on the South Downs aquifer, but much more will need to be done. The future demands on the aquifer will require a more rigourous and integrated source and demand model which will in turn require a far greater understanding of the hydraulics of the aquifer as a whole. Although the South Downs groundwater management record provides interesting reading to date, it is by no means a finished story.

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Selected glossary of terms

Bypass flow	The process, by which, percolating water moves through only a small volume of the total porosity (referring to the unsaturated zone)
Doline	A steep-sided, circular depression, through which surface drainage recharges the aquifer; occurs in limestone areas
Fault	A fracture where displacement of originally adjacent points across the discontinuity is not negligable compared to fracture length
Fracture	Any planar or curviplanar parting where the relative displacement of the two surfaces is unknown or is of no interest or consequence
Griotte chalk	Type of nodular chalk, with a structure comprising 'augen' of chalk enveloped by marl
Hardground	A hardened layer of chalk, formed by progressive synsedimentary cementation in shallow water areas; reflects reworking of the chalk
Macrofracture	A relatively large fracture (nominally >10 m in length)
Matric potential	Total negative pressure potential, denoting the total effect resulting from the affinity of the pore fluid to the rock or soil matrix
Mesofracture	A fracture intermediate in size between a macrofracture and a microfracture
Microfracture	A relatively small fracture, generally of limited aperture
Nodular chalk	Result of partial synsedimenatry cementation of the chalk; first stage of formation of a hardground
Talik	Layer of frozen ground, above, within, or beneath permafrost; occurs in regions of discontinuous permafrost; may be permanent or temporary

Appendix 1 Data sources

Aquifer properties	Environment Agency/BGS (Aquifer Properties Database)
Regional water levels	Southern Science
Chilgrove House water levels	BGS
Climatological data	MORECS
Chemistry	Environment Agency/BGS (Aquifer Properties Database) Environment Agency South West Water Portsmouth Water Co.

Appendix 2 List of boreholes for which geophysical logs were examined

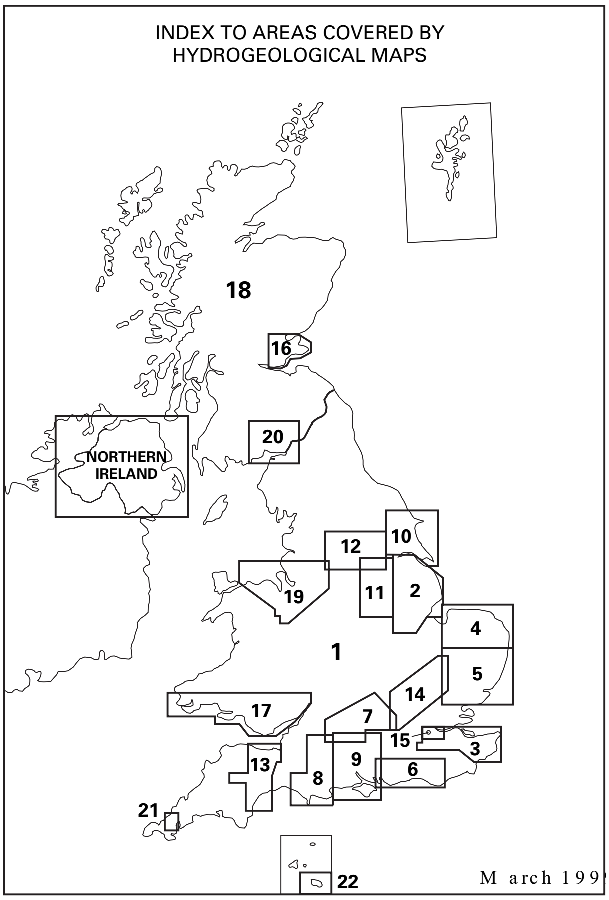
(Boreholes geophysically logged during this study are shown in bold)

Borehole	BGS Registration number	NGR
Abbotstone	300/459	SU 5589 3487
Angmering bh. 2 (obs well)	**TQ 00/28B**	**TQ 0643 0653**
Axford 1B	284/295(c)	SU 6105 4295
Bradley 2B	300/429(a)	SU 6263 4196
Brickiln Farm	—	SU 836 124
Clapham obs bh. 2	**TQ 00/165**	**TQ 0916 0612**
Cornish Farm, Birling Gap	**TV 59 NE23**	**TV 5762 9688**
Dankton Lane, Sompting A, 1	**TQ 10 NE42A**	**TQ 1660 0634**
Duncton 2	SU 91 NE24	SU 9613 1623
Duncton 1	**SU 91 NE23**	**SU 9520 1576**
East Preston No. 97	**TQ 00 SE03**	**TQ 0707 0273**
East Dean, Oxendown	**SU 91148**	**SU 9270 1440**
East Street Car Park, Brighton	—	TQ 311 039
Eldridge Pope brewery, Dorchester	SY 69 SE21[1]	SY 6923 9013
Faircross		**SU 6974 6326**
Findon Ps	318/447	TQ 125076
Halnaker	**SU 90/107**	**SU 9191 0880**
Hammerpot New Barn, Water Lane, Angmering	**TQ 00 NE63**	**TQ 0754 0520**
Kingston Middle Road, Hove		TQ 234 054
Lewes South Street	—	—
Pagham 1	SZ 89 NE17	SZ 8840 9803
Park Bottom Arundel		TQ 005 076
Poverty Bottom	**TQ 40 SE28**	**TQ 4675 0223**
Roedean	—	TQ 358 035
Sandhills 1	SZ 49 SE3	SZ 4571 9085
Shripney Southern Cross Trading Centre	**SU 90 SW68**	**SU 9416 0114**
St Peters Church, Brighton	**TQ 30/51**	**TQ 3145 0491**
Stoughton, Bow Hill	**SU 81/65**	**SU 8135 1047**
Sutton Drove, Seaford	**TV 49 NE17**	**TV 4865 9952**
Tangmere	**SU 90 NW140**	**SU 9140 0620**
Tarring Neville, Lewes	—	TQ 44 5035
Tortington (layby bh.)	**SU 90/10**	**SU 9835 0727**
Totford	300/249(c)	SU 4696 3801
Victoria Park West Worthing	**TQ 10 SW/52**	**TQ 1419 0290**
Victoria Gardens, Brighton	**TQ 30 SW98**	**TQ 3137 0447**
Warningcamp W100	**TQ 00/164**	**TQ 0402 0706**
Westburton Hill	**SU 91/42**	**SU 9890 1320**
Wield Road 2A, Preston Candover	300/428(a)	SU 6152 4049
Winterborne Kingston	SY 89 NW1	SY 8470 9790

1 BGS Keyworth borehole number
2 BGS Wallingford hydrogeology number

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 BGS.



1:625 000
1 England and Wales, 1977
18 Scotland, 1988

1:126 720
2 North and east Lincolnshire, 1967
(out of print, available as a colour photographic print)
3 Chalk and Lower Greensand of Kent, 1970
(two sheets)

1:125 000
4 Northern East Anglia, 1976 (two sheets). Flat only
5 Southern East Anglia, 1981 (two sheets)
17 South Wales, 1986

1:100 000
6 South Downs and part of 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
12 Southern Yorkshire, 1982
13 Permo-Trias and other aquifers of SW England, 1982
14 Between Cambridge and Maidenhead, 1984
16 Fife and Kinross, 1986
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Hydrogeology of Scotland. N S Robins, 1990
(ISBN 0 11 884468 7)

Long-term hydrograph of groundwater levels in the Chilgrove House well in the Chalk of southern England, 1990. Poster

Long-term hydrograph of groundwater levels in the Dalton Holme estate well in the Chalk of Yorkshire, 1992. Poster

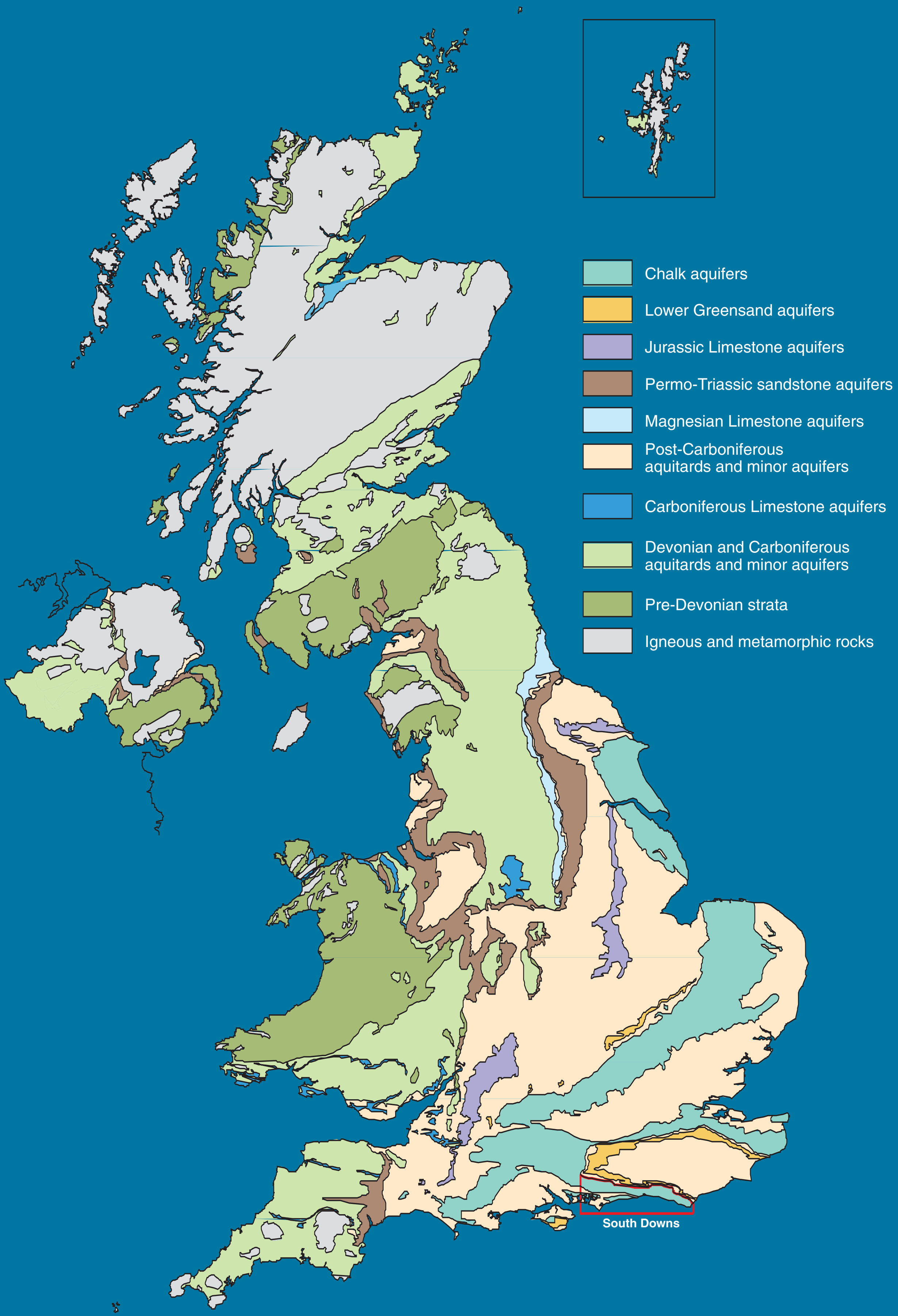
Hydrogeology of Northern Ireland. N S Robins, 1996.
(ISBN 0 11 884524 1)

The physical properties of major aquifers in England and Wales. D J Allen et al., 1997. WD/97/34

The hydrogeological behaviour of the clay-with-flints of southern England. B A Klink et al., 1997. WE/97/5

BGS

THE CHALK AQUIFER OF THE SOUTH DOWNS



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