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The Chalk aquifer of the North Downs

Research Report RR/08/02



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View south-east from the Middle Chalk of the North Downs scarp face at Albury Downs, Surrey (P212885).

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The Chalk aquifer of the North Downs

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Preface

This report is a product of the National Groundwater Survey (NGS), a component part of the British Geological Survey's (BGS) Groundwater Management Programme. The NGS aims to provide strategic scientific underpinning for groundwater resources management and protection. The survey is carried out through studies of major aquifer blocks, which focus on describing and quantifying the occurrence of groundwater in British aquifers, its movement and natural quality as well as the processes controlling solute and contaminant transport and degradation. These descriptions are based on review of existing knowledge and data, supported by collection and interpretation of new data as well as undertaking relevant research of generic or regional significance. Advisory panels at both the national and regional levels have been established to ensure that the development of the programme, within the overall objectives, reflects the needs of the user community.

This study of the Chalk aquifer of the North Downs was carried out in collaboration with Environment Agency (Thames and Southern Regions), Southern Water, Thames Water, Mid Kent Water, Folkestone and Dover Water Services and Sutton and East Surrey Water. An advisory panel involving members of these organisations ensured that the work is relevant and is based on best

available knowledge. Members of the advisory panel also contributed much valuable information and acted as reviewers. Thus, this report brings together information from published and unpublished sources written by, and reviewed by hydrogeologists with extensive experience of development and management of the aquifer, from quantity, quality and groundwater protection perspectives. The editor also acknowledges the reviews and comments of other Environment Agency staff which provided updates on several of the models and management projects discussed in this report. It therefore aims to summarise the current understanding of the hydrogeology of the Chalk aquifer of the North Downs and provide a foundation on which further work can be based.

The report is in a series providing comprehensive descriptions of major blocks of the Chalk aquifer in the UK. The relevance of this work has been brought into sharper focus recently by the need to characterise groundwater bodies in order to meet the requirements of the European Water Framework Directive. In addition the series will provide a starting point for improving our understanding of this and other blocks of aquifer as changing demands are made on resources, storage capacity and environmental needs in response to societal and climatic change.

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Executive summary

The North Downs of south-east England are a prominent feature of the landscape forming the northern limb of the Wealden anticline and the southern margin of the London Basin. They extend from the Hog's Back near Farnham in the west to the white cliffs of the Kent coast in the east. The Chalk dips in a broadly northerly or north-north-easterly direction eventually dipping below Palaeogene and superficial cover into the London Basin. The Chalk aquifer of the North Downs is one of the most intensively developed in the British Isles and comes under the jurisdiction of both the Thames and Southern Regions of the Environment Agency providing a resource for six water companies.

Recharge is dominated by winter rainfall and occurs over the majority of the Chalk outcrop area. Low permeability cover tends to deflect rainfall as run-off to its edges which results in a high degree of solution activity in the Chalk due to the relative acidity of the soils associated with Palaeogene deposits and the clay-with-flints; this not only tends to enhance recharge but also results in minor (but significant) karstification of the underlying Chalk.

Groundwater flows in a broadly northerly or north-north-easterly direction and tends to develop permeability by solution. It would appear that current recharge could probably be dissipated within a relatively thin interval close to the water table. Variations of sea level, particularly during the Pleistocene, have provided a range of base levels for groundwater flow from the Chalk in this region. This has resulted in the development of several permeable horizons at levels associated with former water tables down to a depth of about -130 m OD. Groundwater flow will generally follow one of these permeable horizons down dip for a certain distance, but will then step up via fractures and faults to the nearest outlet where it can discharge to surface water, developing permeability *en route*.

Springs and surface flows occur where the water table intersects the land surface. Consequently, the heads of Chalk streams tend to migrate up and down gradient seasonally as the water table rises and falls in response

to recharge — the typical bourne behaviour recorded in Chalk catchments. Springs are also found on geological contacts, such as that between the Chalk and the Palaeogene. At the coast, seasonal fluctuations are less pronounced and springs are an important element of the marshland environment of this area.

Where the aquifer is unconfined, the natural groundwater quality is good. However, the groundwater is vulnerable to pollution as shown by the high nitrate concentrations (mainly from diffuse agricultural sources) and the occasional detection of pesticides and organic solvents. Significant point source pollution occurred between 1907 and 1974 with the discharge of highly saline mine water from the Tilmanstone and Snowdon collieries. As the aquifer becomes confined below the Palaeogene cover it is better protected from pollution, but the generally more reducing conditions and longer transit times lead to deterioration in the natural quality.

The heavy demands put on the aquifer for public supply can conflict with important environmental demands such as baseflow to rivers and spring flow to the north Kent marshes (much of which is protected by international conventions and/or European legislation). Perhaps the most widely publicised of such conflicts occurred in the Darent valley where groundwater abstraction was blamed for the drying up of the river in the early 1970s and again from 1989. A joint project by Thames Water and the National Rivers Authority (forerunner of the Environment Agency) resulted in the Darent Compensation Scheme which effectively maintains flow in the river.

The North Downs has a long history of water supply development which has concentrated mainly on the Chalk aquifer. It is likely that the future impact of climate change processes will only exacerbate the existing conflict between supply and demand. The future for the Chalk aquifer of the North Downs will unfold within a framework of increasing national and EC legislation aimed at environmental protection and enhancement which will demand increasingly stringent control over water abstraction, use and reuse.

1 Introduction

1.1 LOCATION AND DESCRIPTION OF THE NORTH DOWNS

The North Downs are the prominent physiographical feature of outcropping Chalk which extends from the Hog's Back in the west [SU 4870 1480], to the east coast of Kent as far south as Folkestone and including the White Cliffs of Dover. The Chalk hills of the North Downs form the northern limb of the Wealden anticline, and the southern margin of the London Basin, see Figure 1.1.

The Chalk aquifer within this area extends from the base of the escarpment northwards beneath the Palaeogene and superficial cover on the dip slope of the Downs and within the London Basin. Folding brings the Chalk to surface again near Erith, Purfleet and Tilbury within the confines of the London Basin and again on the Isle of Thanet in east Kent. The northern margin of the study area roughly equates to the axis of the London Basin Syncline which trends east-north-eastward from the Camberley area through Westminster towards the Essex coast between the rivers Blackwater and Crouch. To the south, the aquifer is underlain by a few metres of Upper Greensand in the south-west of the region, but this thins towards the north, and east of Sevenoaks where it is replaced by Gault Clay. Clay-with-flints covers the Chalk on many of the

interflaves, while head deposits and alluvium are present in the valleys. The southern limit of the area of interest in this report is defined by the base of the scarp slope of the Chalk of the Downs, see Figure 1.2.

In terms of the proportion of the resource committed for all water supply purposes, the Chalk of the North Downs ranks as one of the most intensively developed aquifers in the British Isles. It provides a resource for six water companies and lies within both the Thames and Southern Regions of the Environment Agency.

1.2 TOPOGRAPHY AND GEOMORPHOLOGY

The North Downs area is dominated by the dissected plateau-like dip slope of the Chalk escarpment. Figure 1.1 shows the topographical elevation and river network of the area. East of Guildford the Chalk outcrop broadens into the North Downs proper forming an escarpment with its steep scarp facing south over the Weald. The main escarpment trends east-north-east from Guildford towards Maidstone at which point it swings to the east-south-east towards the coast at Folkestone. Between Farnham and Guildford in the west the scarp slope is far less prominent than elsewhere and the outcrop is narrow due to the

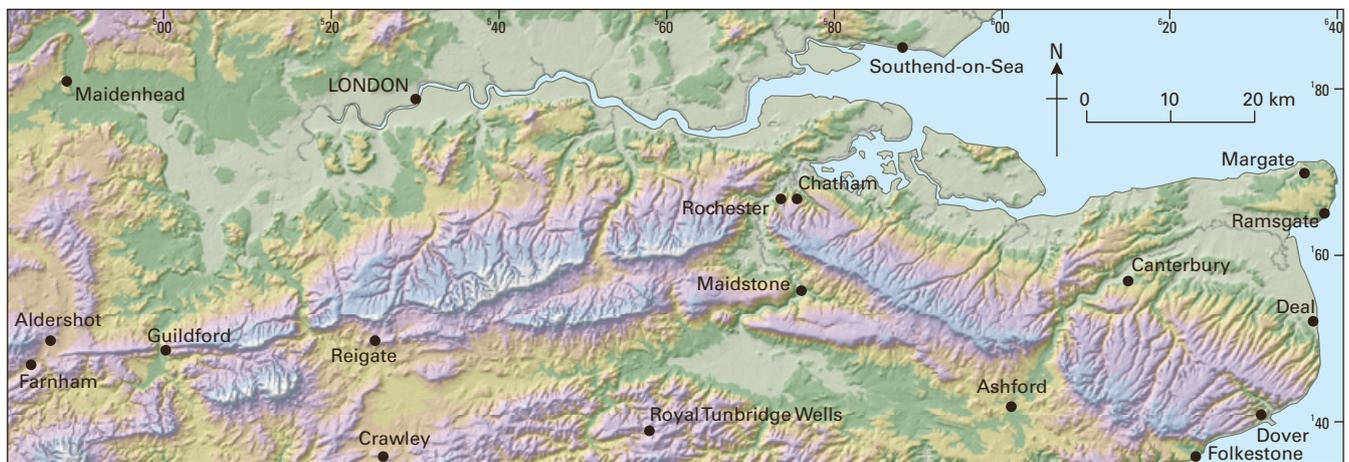
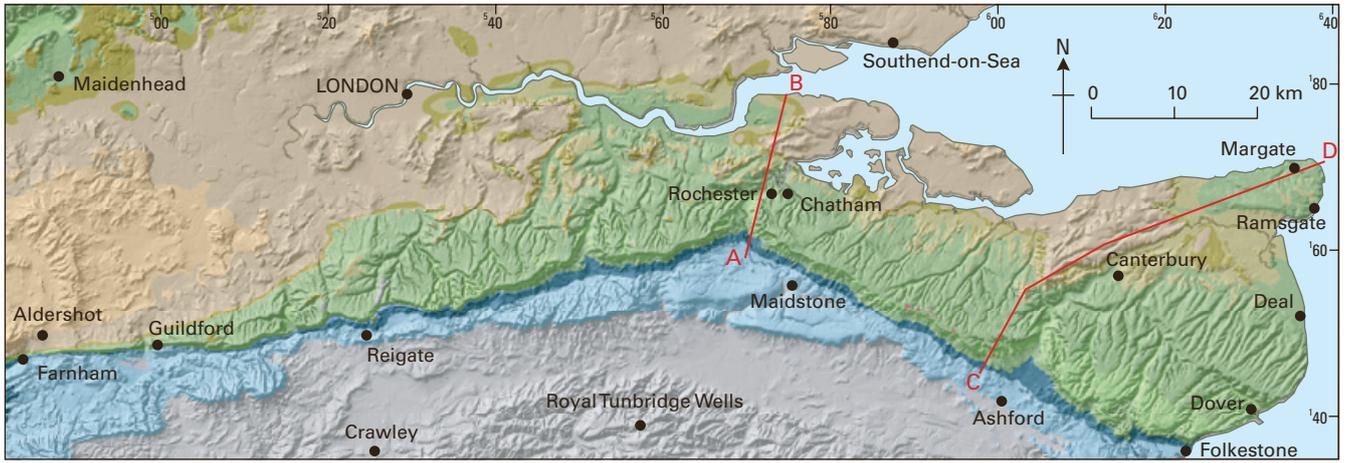


Figure 1.1 Topographical map of the North Downs.



Geology

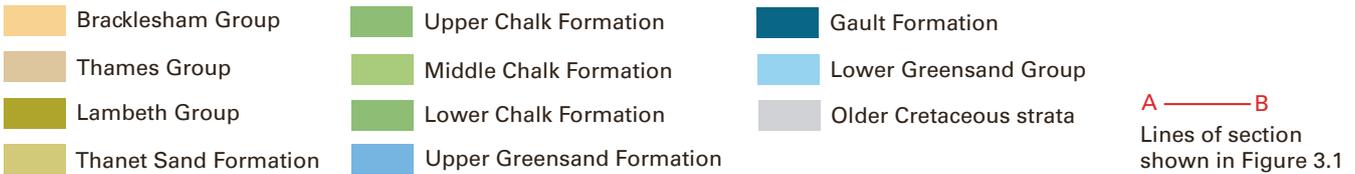


Figure 1.2 Geological map of the North Downs.

steepness of the dip of the beds to the north. In fact, in this part of the North Downs the dip slope and scarp slope are almost equal and the narrow ridge is known as the Hog’s Back, which, to the south, is bounded and accentuated by a fault system trending roughly west to east. Immediately to the north of the Hog’s Back is a broad gently undulating plain founded on Palaeogene strata.

From Guildford eastwards the scarp slope is far more pronounced, rising sharply from 120 m in East Kent to 180 m north of Maidstone, reaching a maximum height of 267 m at Botley Hill [TQ 396 553] to the west of the Darent. Northward from the crest of the escarpment the ground slopes gently and the Chalk is progressively buried beneath superficial and Palaeogene deposits (up to 200 m) within the London Basin Syncline.

A number of river gaps and high-level ‘wind’ gaps cut the escarpment. From west to east the major gaps are formed by the rivers Wey, Mole, Darent, Medway and

Great and Little Stour which divide the Downs into distinct geomorphological segments (Figure 1.3). The rivers flowing northwards from the High Weald rise on sandstone hills and cross clay vales before cutting gaps in the Chalk. Throughout the greater part of their courses they flow with the dip. The cutting of the gaps was obviously started before the beds south of the Chalk had been reduced below the level of the uplands. The present relief and the lowering of the gaps resulted from the more rapid removal of the softer beds along the length of their outcrop, assisted by the growth of subsequent streams.

The Chalk dips to the north at an average angle of about 2°, although in the south-west in the area of the Hog’s Back the dip can be as much as 55° to the north, as a result of the reactivation of deep faults (Hopson, 1999). The general dip is modified by gentle folding, parallel to strike, and by a number of minor displacements perpendicular to strike (Allen et al., 1997). Much of the area is heavily dissected

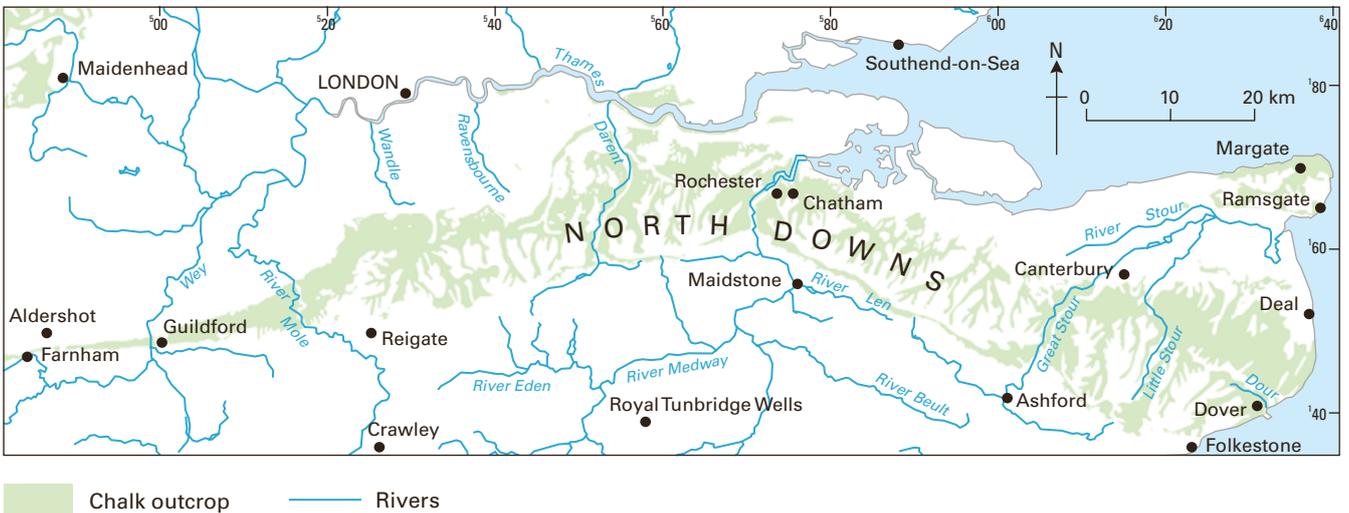


Figure 1.3 The main geomorphological segments of the North Downs.

by a network of dry valleys trending south-west to north-east, which are thought to be structurally controlled. Detailed studies in east Kent have shown that the main conjugate joint set directions are 60° and 120°. Regional groundwater flow in the North Downs is generally to the north or north-east, reflecting the geological and topographical controls. It is likely that preferential solution and groundwater flow was concentrated along the joint-set to the north-east, and this may account for the trend of the dry valleys (Folkestone and District Water Company, 1991).

Pleistocene clay-with-flints and plateau gravels cover the interfluvial, and head deposits and alluvium are found in the valleys and to the east of the area. Dominant soil types grouped according to the hydrologically based classification, HOST (Boorman et al., 1994) are shown in Figure 1.4. The original data consists of 29 classes which have been grouped into five main classes for illustrative purposes. The most common soil type across the North Downs is a mineral soil with the groundwater or aquifer present at greater than 2 m depth.

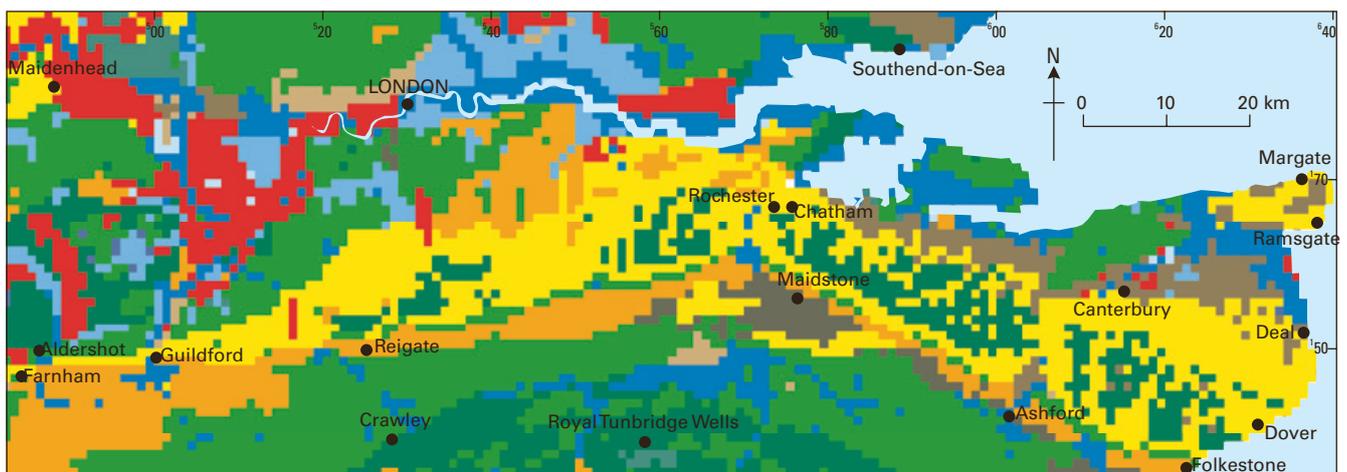
1.3 CLIMATE

The prevailing climate in the North Downs area is temperate and is moderated by the influence of the sea to the north and east. Winters are generally mild and

summers are warm. The distribution of rainfall across the area is controlled in a large part by relief, and annual rainfall totals increase gradually with rising topography, although rainfall also reflects the degree of exposure to south-westerly winds. Average annual rainfall ranges from less than 530 mm to over 800 mm across the area (Holmes, 1981; Southern Water and Mid Kent Water Authority, 1989; Folkestone and District Water Company, 1991). Average annual rainfall distribution is shown in Figure 1.5. The average annual potential evapotranspiration is estimated at between 500 and 550 mm, nearly 80% of this occurring between April and September. Actual evapotranspiration depends largely on vegetation and crop type, but on average is probably about 10% less than potential values (Holmes, 1981).

1.4 DRAINAGE

Six major rivers cross the North Downs, all flowing in valleys which trend from south to north or south-west to north-east. These are the Wey, the Mole, the Darent, the Medway, the Great Stour and the Little Stour (Figure 1.3). Across much of the rest of the Chalk outcrop, except for interfluvial areas covered by low permeability Pleistocene deposits, there is no real surface run-off. Almost all effective rainfall infiltrates and recharges the aquifer (Holmes, 1981).



HOST CLASS NO.	SUBSTRATE HYDROGEOLOGY	MINERAL SOILS				PEAT SOILS
		Groundwater or aquifer	No impermeable or gleyed layer within 100 cm	Impermeable layer within 100 cm or gleyed layer at 40 – 100 cm	Gleyed layer within 40 cm	
1	Weakly consolidated, microporous, by-pass flow uncommon (Chalk).	Normally present and at >2m	X			
3	Weakly consolidated, macroporous, by-pass flow uncommon.		X			
5	Unconsolidated, macroporous, by-pass flow very uncommon.		X			
6	Unconsolidated, microporous, by-pass flow common.		X			
8	Unconsolidated, microporous, by-pass flow common.	Normally present and at <2m		X		
9	Unconsolidated, microporous, by-pass flow common (Integrated air capacity <12.5).				X	
10	Unconsolidated, microporous, by-pass flow common (Integrated air capacity >12.5).				X	X
11	Unconsolidated, microporous, by-pass flow common.					X
16	Slowly permeable	No significant groundwater or aquifer	X			
18	Slowly permeable			X		
24	Slowly permeable				X	
25	Impermeable (soft)				X	
98	Surface Water					

Figure 1.4 Dominant soil types grouped according to a hydrologically based classification, HOST (after Boorman et al., 1994).

Dry valleys are a significant feature of the area, and often form parallel series running consequentially down the dip slope of the Chalk. Most of these consequent valleys are captured or diverted by subsequent valleys running nearly parallel to the strike of the Chalk, e.g. the Dour valley in the south-east of the region. Although perennial rivers are generally confined to the subsequent valleys, many of the dry consequent valleys have intermittent streams under present climatic conditions (Worssam, 1963; Folkestone and District Water Company, 1991). In the unconfined aquifer considerable annual fluctuations in the water table occur, and during periods of high recharge characteristic migratory springs may form. Throughout the dip slope of the North Downs springs may migrate laterally for several kilometres, giving rise to seasonal streams or 'winterbournes', which flow along parts of their reaches (Day, 1996).

The vertical location of springs is dictated by the elevation of the water table, while flow from springs is determined both by the amount of groundwater in storage

in the spring catchment and, therefore, by recharge to the catchment, and by aquifer permeability (Folkestone and District Water Company, 1991). Peak spring flow tends to coincide with the timing of peak groundwater levels, and hence storage, in late spring or early summer. To the south of London there are many springs which are geologically controlled, where the Chalk abutts Palaeogene deposits.

1.5 LAND USE

The main land-use types across the area are managed grasslands and arable farm land, with a number of small woodlands, see Figure 1.6. There are significant areas of urbanisation, particularly the southern outskirts of London, Gravesend and the Medway Towns. The region is environmentally sensitive, and conflicts have arisen between development and conservation. Communications between London and the coast, including the Channel Tunnel Rail Link, have also given rise to important protection issues with regard to the Chalk aquifer.

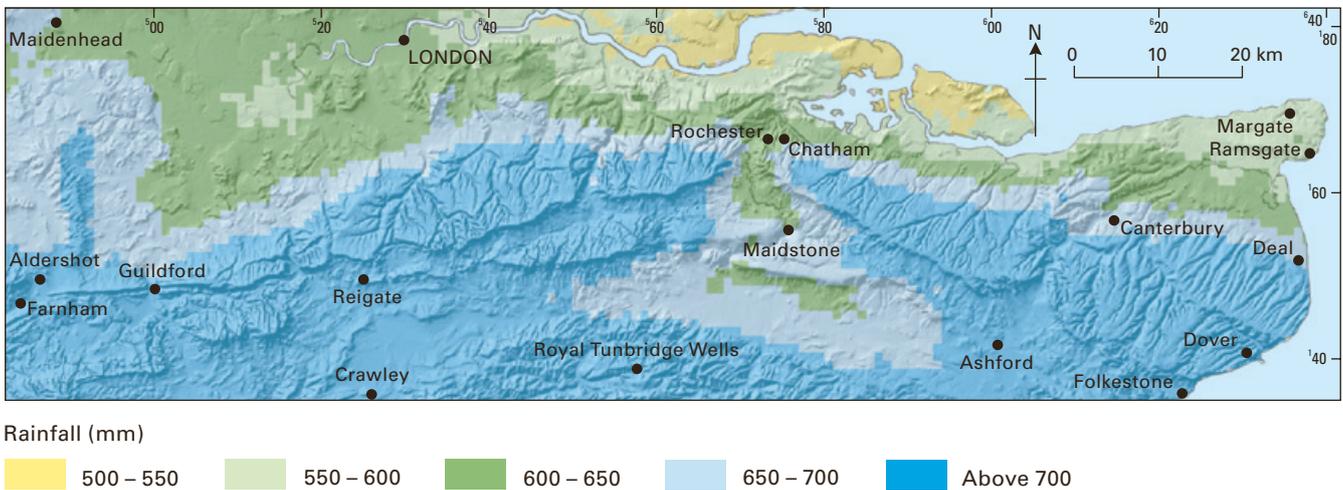


Figure 1.5 Long-term (30 year) average annual rainfall for the period 1961 to 1990. Includes material based on Meteorological Office data, © Crown copyright.

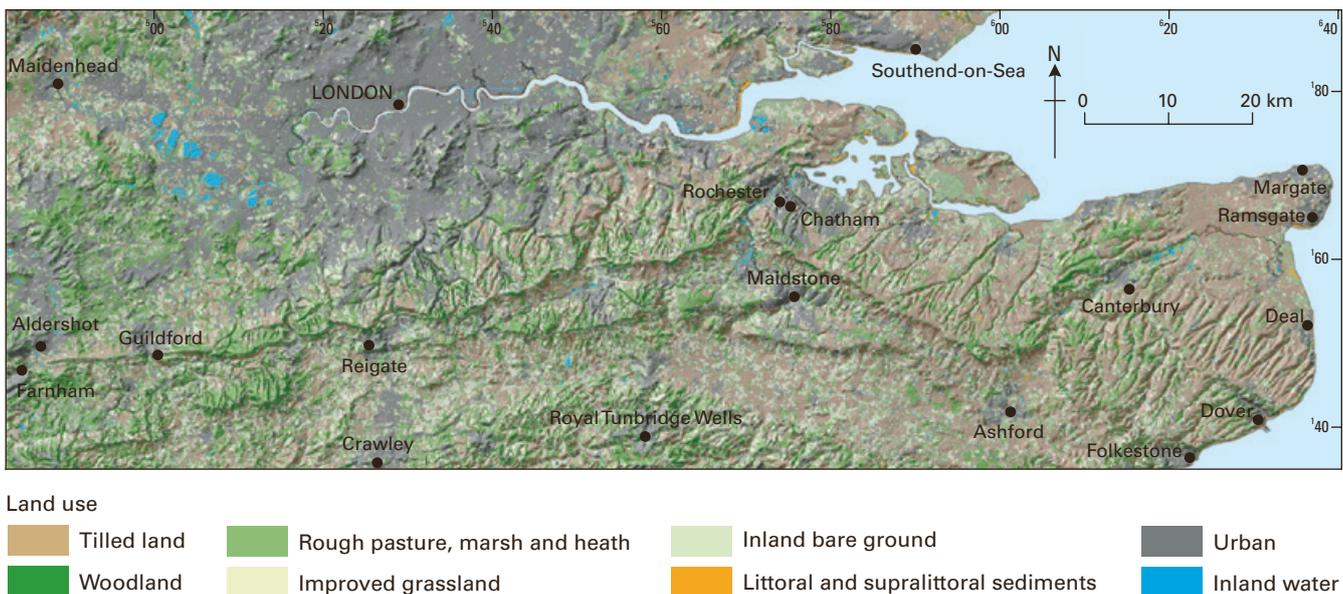


Figure 1.6 Land-use cover. Based on digital spatial data licensed from the Centre for Ecology and Hydrology, © Centre for Ecology and Hydrology.

2 Geology and structure

2.1 INTRODUCTION

This chapter describes both the Chalk at crop and that buried beneath the Palaeogene, as well as the Palaeogene cover itself. This cover thickens (up to 200 m) northwards toward the axis of the London Basin Syncline. The syncline, whose axis trends east-north-eastward from the Camberley area through Westminster and on to the Essex coast between the rivers Blackwater and Crouch, is the result of Miocene (Alpine) compression inverting a pre-existing high represented by the London Platform.

The cliffs of the coastal section, from Folkestone and Dover to the Isle of Thanet, have formed the basis for description and argument within the Chalk since the early 19th century. Inland, Chalk sections are infrequent, often limited to valley-side exposures below a plateau frequently covered by younger Palaeogene and Quaternary deposits. Moreover, many exposures described in the literature from the early part of this century are now lost for study.

2.2 GEOLOGICAL SEQUENCE IN THE NORTH DOWNS

2.2.1 Lower Cretaceous

Whilst there is a significant thickness of Lower Cretaceous formations below the Chalk of the North Downs, those below the Gault Clay Formation are not of direct interest to the hydrogeology of the Chalk aquifer as the clay acts as an aquiclude between the Chalk and the Lower Greensand.

GAULT CLAY FORMATION

The Gault consists mainly of pale to dark grey, fissured, soft, silty clay with scattered phosphatic nodules up to 15 mm across. In general the darker hues of grey predominate in the Lower Gault. The weathered profile of natural exposures shows a gradation up into very soft, pale yellow-brown, plastic clay beneath the active soil layer. Northward from the outcrop the Lower Gault becomes progressively condensed and in the Thames valley region rarely exceeds 10 to 15 m in thickness. In total, the Gault is about 39 to 45 m thick on the coast at Folkestone and beneath the Chalk of East Kent. The formation thickens westward to 68 m north of Maidstone and up to 85 m in Surrey.

The Gault acts as an aquiclude between the Chalk and Lower Greensand aquifers throughout the North Downs area.

UPPER GREENSAND FORMATION

This formation consists of pale yellow-brown, pale grey and greenish grey bioturbated siltstone and silty very fine-grained sandstone with variable amounts of mica and glauconite. The beds show a characteristically wispy-bedded structure due to small lenses of clay and sand. The Upper Greensand forms a distinct scarp along its outcrop; the formation is 35 m thick at its maximum around Guildford but thins eastward and is absent east of Sevenoaks.

2.2.2 Upper Cretaceous

CHALK GROUP

On BGS published maps of the area (with the exception of the new maps for Dartford and South London and digital maps for the whole area — DigMap50) the lithostratigraphical scheme is 'traditional' with three 'formations' (Lower, Middle and Upper) within the Chalk 'Group'. In addition numerous named 'units' which can be either individual beds or sequences of beds are noted on the maps and in the descriptive memoirs. A brief description of the lithology of the Chalk is given in Box 2.1 and its diagenesis is described in Box 2.2.

The scheme used on BGS maps over much of the north Kent area, and described within the memoirs, is essentially a combination of litho- and biostratigraphical data. The base of the Lower Chalk is taken at the base of the Glauconitic Marl ('Chloritic Marl' in some of the older memoirs). The base of the Middle Chalk is taken at the base of the Melbourn Rock (in some memoirs discussed in terms of the top of the immediately preceding Plenus Marls). In east Kent this horizon was not considered well enough defined on lithological grounds and in the early memoir for Ramsgate and Dover (White, 1928) the term 'Grit Bed' (about 10 m thick) was used as originally defined by Price (1877). In the subsequent memoir (Shephard-Thorn, 1988), the Melbourn Rock is considered to be the direct equivalent of the Grit Bed (also the 'Melbourn Rock Beds' of Robinson, 1986) but this is still significantly thicker (at 10.8 m in Robinson, 1986) than the Melbourn Rock in West Kent and Surrey. In the Chatham area for example the name Melbourn Rock is reserved for the 1.8 to 4.6 m of intensely hard and massive chalk at the base of a sequence of 'brittle white chalk with nodules and marls' that is a

BOX 2.1 CHALK LITHOLOGY

The Chalk comprises predominantly soft white to off-white very fine-grained and extremely pure homogenous microporous limestones (the white chalk, massive chalk or featureless chalk of various authors) with subordinate hardgrounds and beds of marl, calcarenite and flint (Hancock, 1975; Scholle, 1974). Chalk is composed largely of the microscopic calcareous skeletal remains of haplophycean planktonic algae (coccoliths) (Black, 1953, 1980; Hancock and Kennedy, 1967). In general the Chalk is thoroughly bioturbated (Bromley and Gale, 1982) and has a high porosity on average (about 32% according to Allen et al., 1997). Other coarser carbonate material derived from foraminifera, ostracods and calcispheres together with entire and finely comminuted echinoderm, bryozoan, coral and bivalve debris, notably disaggregated prisms of inoceramids, is present, sometimes in rock building proportions (e.g. the Totternhoe Stone of the Chilterns, the Cast Bed found throughout most of southern England, and the Hay Cliff Member of Robinson, 1986).

BOX 2.2 DIAGENESIS OF CHALK

Two distinct phases of diagenesis can be recognised in the Chalk. Firstly, an early stage associated with interruptions of sedimentation and affecting initially unconsolidated sediment at or just below the sea floor. Secondly, a late modifying stage associated with deeper burial, compaction, silicification and carbonate dissolution.

Early diagenesis of the Chalk in response to changing water depth, deposition rates and erosion gives rise to a variety of bedding surfaces and associated lithologies. These range from horizons demonstrating simple non-deposition (omission surfaces) to complicated scoured, burrowed and mineralised surfaces (hardgrounds) overlying lithified chalk (chalkstone) and provide a framework of lithological markers in the Chalk sequence. The fact that many of these surfaces and lithologies are the result of basin-wide changes in depositional conditions has permitted the detailed intra- and inter-regional correlations of the modern literature (e.g. Mortimore, 1986, 1987; Bromley and Gale, 1982; Robnson, 1986).

Carbonate dissolution as the result of deep burial and compaction has produced a variety of effects. In hard chalks, microstylolites are common, but in the softer chalks stylolites are absent and anastomosing residual clay seams are widespread. Where dissolution has been extensive, the softer chalk takes on a 'flaser' appearance with 'augen' of white chalk enveloped by greyish marl. The 'flaser'-like limestones described by Kennedy and Garrison (1975) seem to be the same as the 'griotte' chalks described in Mortimore (1979).

Silicification is the most conspicuous diagenetic process in the Chalk, its major product being flint which is considered to have resulted from the segregation of silica, presumably derived from dissolution of siliceous organisms, in layers parallel to the sea floor. Most prevalent in the Middle and Upper Chalk, these usually bedding-parallel flint seams are extremely important for correlation. Later stage silicification and remobilisation of silica is demonstrated by sheet-like bodies that line some joints and faults.

further 6.1 to 9.1 m thick. The definition in the Chatham memoir accords more accurately with the concept of the Melbourn Rock as defined in the Chilterns (see discussion in Hopson et al., 1996) and with the definition proposed by Mortimore (1986) for the South Downs area.

The base of the Upper Chalk is taken at the base of the Chalk Rock indicated by the co-occurrence of hard nodular chalk and a fauna characterised by the ammonite *Hyphantoceras reussianum*. At this level there are at least three known hard nodular chalk seams which contain this fauna and similar lithologies without the fauna are known both below and above this level. In consequence the mapable boundary across the North Downs is probably not taken everywhere at a consistent level, although the base of the Upper Chalk should not vary by more than 5 m from west to east.

Detailed truly lithostratigraphical schemes for the Chalk of the 'southern province' were established in 1986 for the North Downs (Robnson, 1986) and the South Downs (Mortimore, 1986). Mapping of the western South Downs, east Hampshire and Wiltshire/Dorset areas by the British Geological Survey in the 1990s established a close correlation between units mapable across these areas with the scheme devised by Mortimore and a unified lithostratigraphy for the mapping of the Chalk was published by Bristow et al. (1997). The current nomenclature, as adopted by the Geological Society Stratigraphic Commission (Rawson et al., 2001 and Hopson, 2005), is a development of these earlier schemes, (Figure 2.1) and it will be possible to use the unified nomenclature in the North Downs as geological sheets come up for revision.

Such a revision mapping exercise was carried out for the region between the River Medway and the River Great Stour as part of the development of a 3D geological model of the area using the new stratigraphy (Farrant and Aldiss, 2002). This exercise also included a correlation and lithostratigraphical interpretation of selected borehole geophysical logs (Woods, 2002). For the current report, resistivity log profiles of a further selection of boreholes have been interpreted and classified in terms of the new stratigraphy, at least provisionally. The more detailed subdivision permits the structure to be better determined, and the horizons of groundwater movement to be better

located. With a few notable exceptions, geophysical logging performed in the North Downs area has provided a characterisation of the Chalk in the subsurface at isolated points, and the results of logging have not generally been related to adjacent boreholes to provide correlations of the subsurface. The notable exceptions include the work of Murray (1982) who showed correlations across the London Basin based on resistivity log profiles and that of Woods (1995) who examined and stratigraphically classified resistivity logs of 125 boreholes both north and south of the River Thames as part of the BGS London Basin Project and mapping for the Dartford sheet. The work of Woods (2002) to correlate and provide lithostratigraphical interpretations for 40 boreholes between the rivers Medway and Stour as part of an exercise to develop a 3D geological model of the area (Farrant and Aldiss, 2002) has been noted above. The logs were interpreted in terms of the new Chalk stratigraphical units. Further to the east, geophysical logs run in several relatively deep boreholes drilled for the North Kent Investigation for Southern Water in the 1980s have been interpreted and correlations made. Geophysical logging performed as part of investigations at Reculver and Venson Farm by the BGS in the 1990s provides some detailed information on water inflows and extends the correlations eastwards.

Whilst the unified Chalk stratigraphy is now well established, there is, as yet, no significant body of work on the hydrogeology of the North Downs utilising this nomenclature. Therefore, within this report, the traditional subdivisions of Lower, Middle and Upper Chalk will be used when summarising work carried out before 2001.

2.2.3 Palaeogene

Following uplift and erosion of the Chalk in response to early 'Alpine' basin compression, the early Palaeogene deposits (Thanet Sand Formation) were laid down in a shallow southward extension of the expanding North Sea Basin. A short period of regression, represented onshore in south-east England by the fluvial and estuarine deposits of the Lambeth Group, was followed by a major transgressive event (with smaller scale transgressive/regressive fluctuations) represented by the Thames and Bracklesham groups. An appraisal of the lithofacies within

Stage	Foraminiferal zones*		Macrofossils		Traditional southern England subdivisions #	North Downs Robinson (1986)	South Downs Mortimore (1986)	Shaftesbury Bristow et al. (1995)	Southern England Bristow et al. (1997)	Southern England Rawson et al. (2001) Hopson (2005)			
	1980 UKB	BGS	Zones	Subzones									
Campanian (pars)	B3 (pars)	18 (pars)	<i>Belemnitella mucronata</i> s.l. (pars)	post <i>A. cretaceus</i> beds <i>Applinoocinus cretaceus</i> <i>Hagenowia blackmorei</i> 'abundant <i>O. pilula</i> ' <i>Echinocorys depressula</i>	Upper Chalk	Margate Member	Portsmouth Chalk Member	Studland Chalk Portsmouth Chalk	Portsmouth Chalk Formation	Southern England Rawson et al. (2001) Hopson (2005)			
	B2	17	<i>Goniotentaculites quadrata</i>								Culver Chalk Member	Spetisbury Ck Tarrant Chalk	Culver Chalk Fm Tarrant Chalk Member
	B1	16	<i>Offaster pilula</i>								Newhaven Chalk Member		Newhaven Chalk Formation
Santonian	B1	15	<i>Uintacrinus anglicus</i> <i>Marsupites testudinarius</i> <i>Uintacrinus socialis</i>		Blandford Chalk	Upper Chalk	Upper Chalk	Margate Chalk Newhaven Chalk	Seaford Chalk Formation	Southern England Bristow et al. (1997)			
		14	<i>Micraster coranguinum</i>								Seaford Chalk		
		13	<i>Micraster cortestudinarius</i>								Lewes Nodular Chalk		
Coniacian	B1	11	<i>Sternotaxis plana</i>		St Margarets Member	Upper Chalk	Lewes Nodular Chalk	Lewes Nodular Chalk	Lewes Nodular Chalk Formation	Southern England Bristow et al. (1997)			
		10	<i>Terebratulina lata</i>										
		9	<i>Mytiloides labiatus</i> s.l.										
Turonian	B1	9	<i>Neocardioceras juddii</i> <i>Metioceras gestinianum</i> <i>Calyoceras guerangeri</i> <i>Acanthoceras jukesbrownei</i> <i>Acanthoceras rhodomagense</i> <i>Cunningtoniceras inerne</i> <i>Mantelliceras dixoni</i>		Dover Chalk Fm	Middle Chalk	New Pit Chalk	New Pit Chalk	New Pit Chalk Formation	Southern England Bristow et al. (1997)			
		8	<i>Turrillites acutus</i> <i>Turrillites costatus</i>								Holywell Nodular Chalk		
		7	<i>Mantelliceras saxbii</i> <i>Sharpeiceras schlueteri</i> <i>Neostriogoceras carcitense</i> <i>Araraphoceras briceensis</i> <i>M. (D.) pernilatum</i> <i>M. (M.) rostratum</i>								Holywell Nodular Chalk		
Cenomanian	B1	14	<i>Stoliczkaia dispar</i>		St Margarets Member	Lower Chalk	Zig Zag Chalk	Zig Zag Chalk	Zig Zag Chalk Formation	Southern England Bristow et al. (1997)			
		13											
		12											
Upper Albian (pars)	B1	11			St Margarets Member	Lower Chalk	West Melbury Chalk	West Melbury Chalk	West Melbury Chalk Formation	Southern England Bristow et al. (1997)			
		10											
		9											

Traditional Chalk subdivisions after Jukes-Browne and Hill (1903, 1904, for example). UGS = Upper Greensand; s.l. = sensu lato
* Foraminiferal zones after Carter and Hart (1977), Swiecicki (1980), Hart et al. (1989) (UKB zones) and Wilkinson (2000) (BGS zones).

Figure 2.1 Stratigraphy of the Chalk of southern England.

Not to scale

the Thanet Sand Formation and Lambeth Group which superpose the Chalk is given in Figure 2.2. Table 2.1 summarises lithological and hydrogeological information on the formations which make up the Palaeogene succession of the North Downs.

2.2.4 Neogene

Although late Eocene, Oligocene and Miocene deposits are known from the nearby North Sea Basin no deposits of this time are found onshore in south-east England. Arid climate combined with pedogenic processes resulted in near-surface silicification of Palaeogene strata creating the 'sarsens' commonly seen as 'stranded' blocks on the present land surface. The timing of this process during this long interval of non-deposition is uncertain.

Deposits of ferruginous sand and gravel with casts of marine molluscs are known from high on the North Downs at Lenham (the Lenham Beds) and at Netley Heath (the Netley Heath Beds) where they are commonly preserved in solution pipes in the Chalk. They include fossils which suggest equivalence with the Coralline Crag and Red Crag deposits of East Anglia, respectively.

2.2.5 Quaternary

About 40 million years is estimated to have elapsed between the deposition of the youngest preserved Palaeogene and the oldest Quaternary deposits in this district. During this time younger Palaeogene and Neogene strata were deposited across much of southern

Britain, and subsequently removed following uplift along the Wealden axis (as part of the general inversion of the Wessex Basin). During the Quaternary, a further significant break in deposition occurred after the accumulation of the clay-with-flints and before the deposition of the younger Pleistocene drift.

Sea level rose and fell according to the quantity of water locked up in ice caps during the Pleistocene. At times of glacial maxima, a periglacial environment was established in this district. There was enhanced erosion both by solifluction and by extensive river systems flowing to the much lower base levels. Three such glacial maxima affected southern England; the most severe was of Anglian age whose most southerly expression as outwash gravels and till approximates to the axis of the London Basin marking the northern boundary of the area described here.

During the intervening warm stages, marine transgressions caused drowning of the lower courses of the river systems, principally the Thames and Medway rivers and their tributaries, and the breaching of the Straits of Dover.

The deposit descriptions below are grouped on the basis of their origin. Mass movement deposits are described first, followed by fluvial, aeolian and marine deposits. Their order does not imply relative age.

CLAY-WITH-FLINTS

Clay-with-flints is composed typically of orange-brown or reddish brown clays and sandy clays containing abundant flint nodules and rounded pebbles. At the

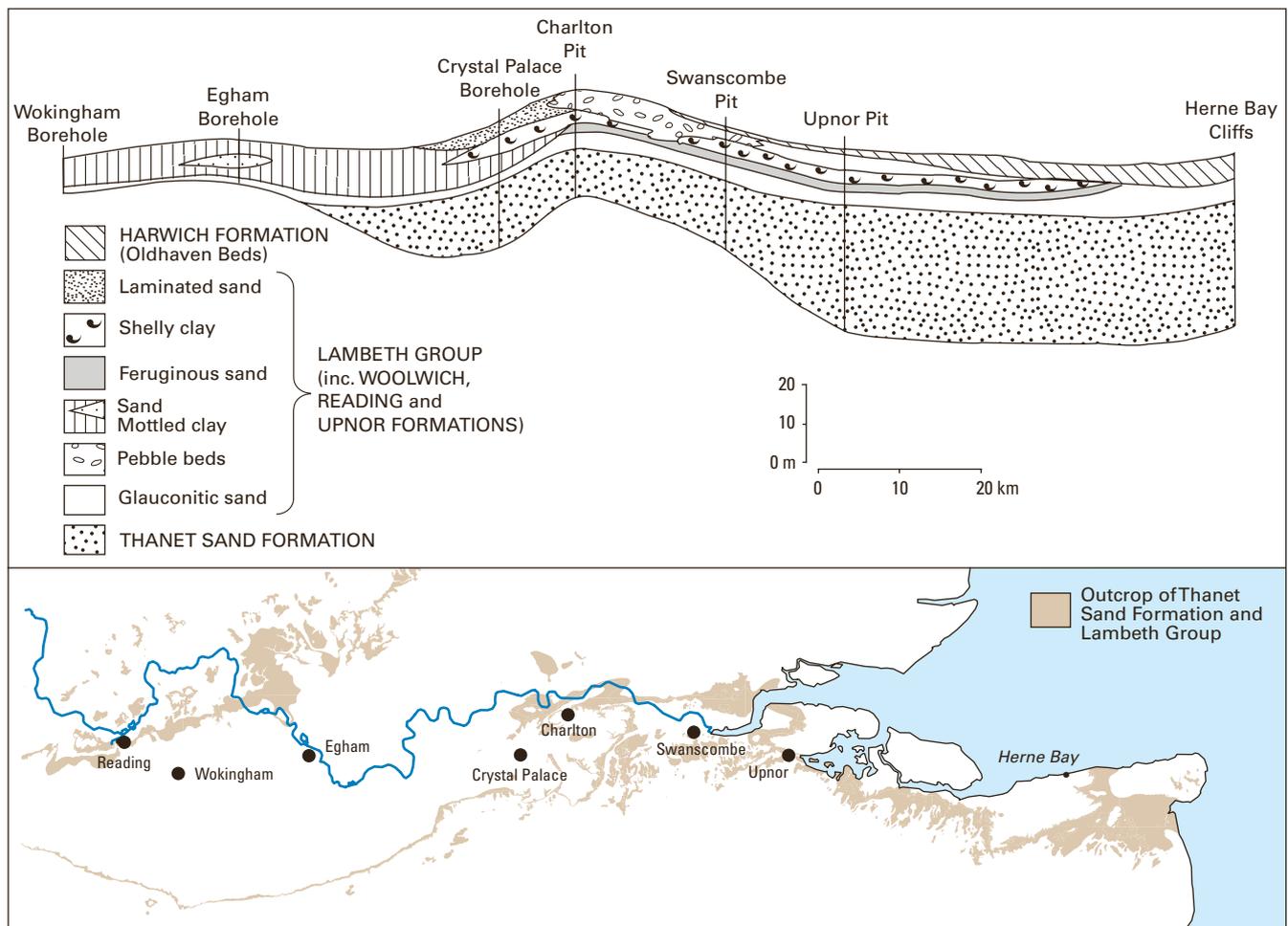


Figure 2.2 Lithofacies within the Thanet Sand Formation and Lambeth Group, (after Ellison, 1983).

Table 2.1 The Palaeogene sequence of the North Downs.

Group	Formation	Lithology and hydrogeology	Thickness
Bracklesham Group	Camberley Sand Formation	Yellow-brown, bioturbated, glauconitic, fine-grained sand with pale grey 'pipe' clays. As a whole the Bracklesham Group contains little potable groundwater but low volume springs are known from the Windlesham and Camberley Sand formations. That which does occur commonly contains much iron in solution.	70 m
	Windlesham Formation	Bioturbated sand and clay with coarse-grained glauconite overlain by organic-rich dark grey clay with sand lenticles.	12–30 m
	Bagshot Formation	Pale yellow fine-grained quartz sand with discontinuous basal pebble bed and thin lenses of pale grey clay.	40 m
Thames Group	London Clay Formation	Five sedimentary cycles of silty sandy clay with glauconite grains and well-rounded flints and clays which become more sandy and siltier up-sequence. The youngest part of this formation (the Claygate Member) supports a minor perched water table.	90–150 m
	Harwich Formation	Cross-bedded sand with well-rounded black flint pebble beds, pale cross-bedded shelly sands and variably glauconitic silty and clayey fine-grained sand with silty clays made up of volcanic ash.	c.12 m
Lambeth Group	Reading Formation	Predominantly clay but with cross-bedded medium-grained sand bodies, laminated and bioturbated silt and fine-grained sands. Groundwater resources are limited to low yields from the laterally impersistent river channel sand bodies.	Generally 10–15 m, maximum 22 m
	Woolwich Formation	Clays with ferruginous sands, thinly-bedded, fine-grained sands and lignites. Where saturated, small yields may be obtainable, and larger yields if the underlying Thanet Sand Formation also contributes.	10 m
	Upnor Formation	Well-rounded pebble bed overlain by medium-grained sand with coarse well-rounded glauconite grains.	5–6 m
	Thanet Sand Formation	Conglomerate with flints overlain by silty, fine-grained sand. The beds are generally permeable and are in hydraulic continuity with the underlying Chalk. Over much of the outcrop area they are part of the unsaturated zone above the Chalk water table. However, the Faversham to Gillingham area includes clays and silts confining groundwater in the underlying Chalk.	30–35 m beneath Thames estuary

base of the deposit the matrix is stiff, waxy and fissured (slickensided), and of a dark brown colour with relatively fresh nodular flints stained black and/or dark green by manganese compounds and possibly glauconite. The deposit gives rise to a stiff, red-brown, silty clay soils strewn with flints. This is primarily a deposit resulting from the modification of the original Palaeogene cover and dissolution of the underlying chalk. The clay-with-flints includes sarsen stones derived from the Palaeogene and fragments of shelly ferruginous sandstone thought to be derived from the Neogene. The thickness of the clay-with-flints is about 5 to 6 m as a general maximum but, in limited areas, usually where dissolution of chalk is most pronounced, this may rise to over 10 m. The distribution of solution features (dolines) is closely associated with the outcrop of the clay-with-flints and related deposits. These depressions are centred over solution pipes in the Chalk, which occur most frequently where major joint sets intersect. The features are commonly circular in plan, between 20 and 50 m across and from 2 to 4 m deep although examples which are larger, deeper and of a more complex plan are known. These depressions act as sumps collecting surface run-off and are still active. Figure 2.3 shows schematic cross-sections which demonstrate the relationship between the Palaeogene, Neogene and clay-with-flints in east and west Kent.

HEAD AND ASSOCIATED DEPOSITS

The superficial sequences mapped across the North Downs include a large number of deposits that can be attributed to deposition under periglacial conditions. They can all be considered as variants of cryoturbation and

solifluction processes, formed at different times and from the weathering of different source 'rocks'. They have been differentiated in the past on the basis of their lithology and geomorphological position and comprise thin but complex interlayered sequences of sandy silty clay, silt and rock debris with varying proportions of granular material (generally chalk, flint, and less commonly chert, sarsen and ferruginous sandstone). Those deposits derived from the Palaeogene, and the argillaceous and arenaceous Lower Cretaceous deposits of the Weald, are generally non-calcareous. The terms head, head gravel, head brickearth (younger and older), coombe deposits, taele gravel and downwash gravel are used to classify these deposits. Whilst generally thin (3 to 5 m) and of limited lateral extent, more extensive spreads of head and head brickearth are differentiated in north-east Kent. Although lithologically similar to deposits elsewhere, these spreads are thought to incorporate appreciable amounts of fine aeolian material.

FLUVIATILE DEPOSITS

There are two divisions within the fluvial deposits of the North Downs. To the west, and at high topographical levels, is a suite of degraded terrace deposits related to the drainage system of the pre-diversionary Thames. At a lower level and closely associated with all the present-day rivers is a second suite of relatively fresh-featured terraces all deposited in response to changes in the base-level of the post-diversionary Thames. Prior to the Anglian glaciation (about 500 000 years ago) the precursor to the Thames took a course through the Vale of St Albans and then north-eastward across Hertfordshire, Essex and

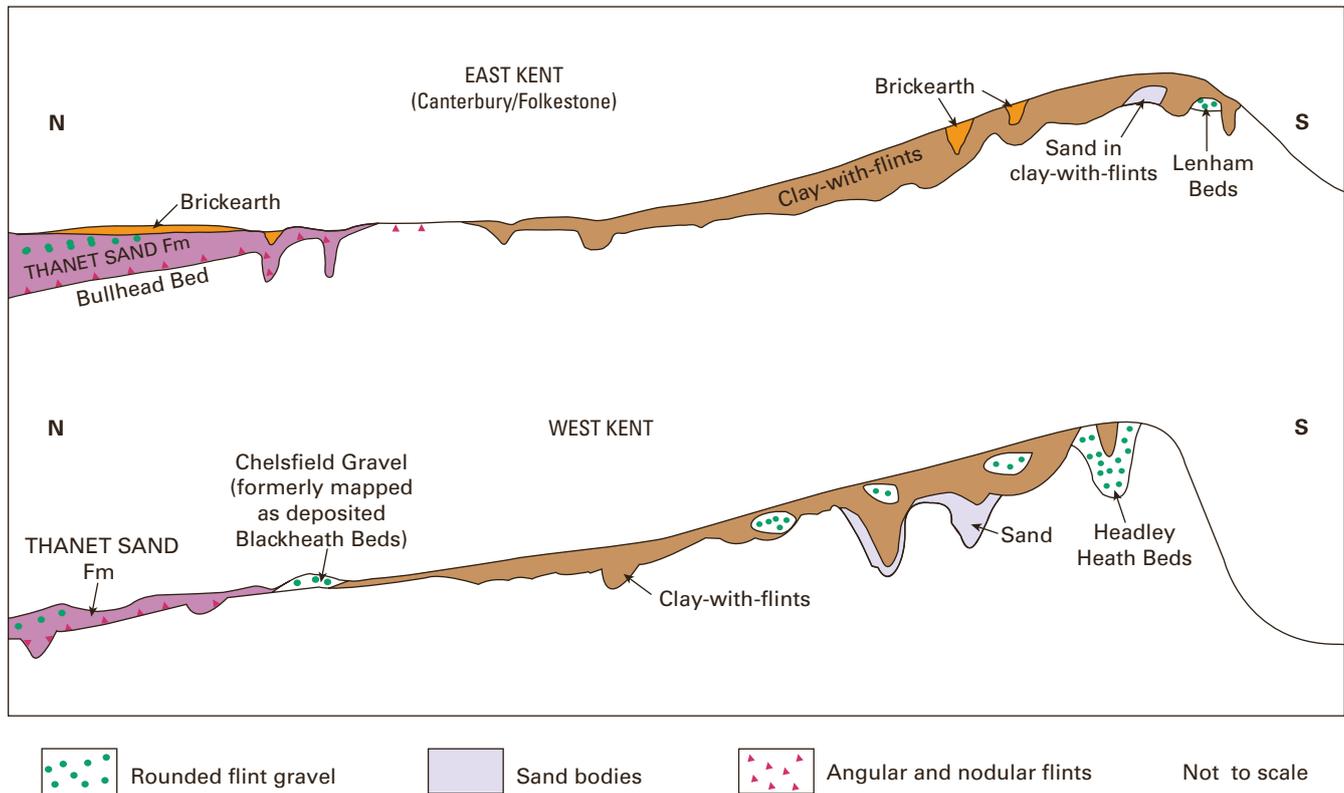


Figure 2.3 Schematic cross-sections showing the relationship between the Palaeogene, Neogene and clay-with-flints in east and west Kent.

Suffolk into the North Sea (proto-Rhine system). South bank streams of the proto-Thames had significantly longer northward profiles. Following the Anglian glaciation this north-eastward course was unavailable and the Thames migrated southward into its present course which runs generally south of the London Basin axis.

Post-diversionary terrace sequences of the Thames and its tributaries (Terrace 1 to 5) of the Thames, Wey, Mole, Darent, Medway and Great Stour systems are well-preserved as a 'staircase' caused by the progressive down-cutting and lateral migration of the rivers and are usually found within the recognisable valley of the present-day river. The Thames has the best preserved of these staircases as the river progressively migrated southward at each successive down-cutting and aggradation cycle.

AEOLIAN DEPOSITS

Fine-grained aeolian material is incorporated into many of the Quaternary deposits overlying the North Downs. The various 'brick earths' may well be substantially wind-blown in origin but later cryoturbated and soliflucted during which processes quantities of coarse material were incorporated. Small areas of blown sand are associated with the low-lying areas of Pegwell Bay, south of Ramsgate, and off Shell Ness on the Isle of Sheppey.

ESTUARINE AND MARINE DEPOSITS

In low-lying coastal areas and marginal to the drowned tidally influenced lower reaches of the major river valleys, deposits of fine grained marine and estuarine alluvium, salt marsh and tidal flats are mapped. They are a mixture of fine-grained marine estuarine alluvium, salt marsh and tidal flat deposits, with coarser beach, storm beach and shingle lithologies.

2.3 STRUCTURAL SETTING

2.3.1 Basin formation, tectonic history and structural setting

The southern limb of the London Basin Syncline forms the North Downs with generally shallow north or north-west dips. However in the area of the Hog's Back, in the south-west of this area, much steeper dips to the north are the result of reactivation of deep faults (the Variscan Front for example, see Chadwick, 1986) which define the southern margin of the London Platform, a relatively stable structural high throughout the Mesozoic. This front is known at depth, approximating to the position of the North Downs escarpment, and is imaged on seismic profiles as a series of step like faults, downthrowing to the south, which progressively limit the thickness of Jurassic and Lower Cretaceous strata to the north. Thus the Chalk Group sits on progressively attenuated Lower Cretaceous strata northwards onto the London Platform.

Smaller scale structures are known within the Chalk and overlying Palaeogene of the North Downs. Figure 2.4 gives an interpretation based on Wooldridge and Linton (1955) and Lake (1975) published in Jones (1981). A more detailed discussion of the structure of the Chalk of east Kent is provided by Aldiss et al. (2004).

2.3.2 Faulting and fracturing

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. Lithology has a significant control on the nature and extent of fracturing as discussed in Box 2.3.

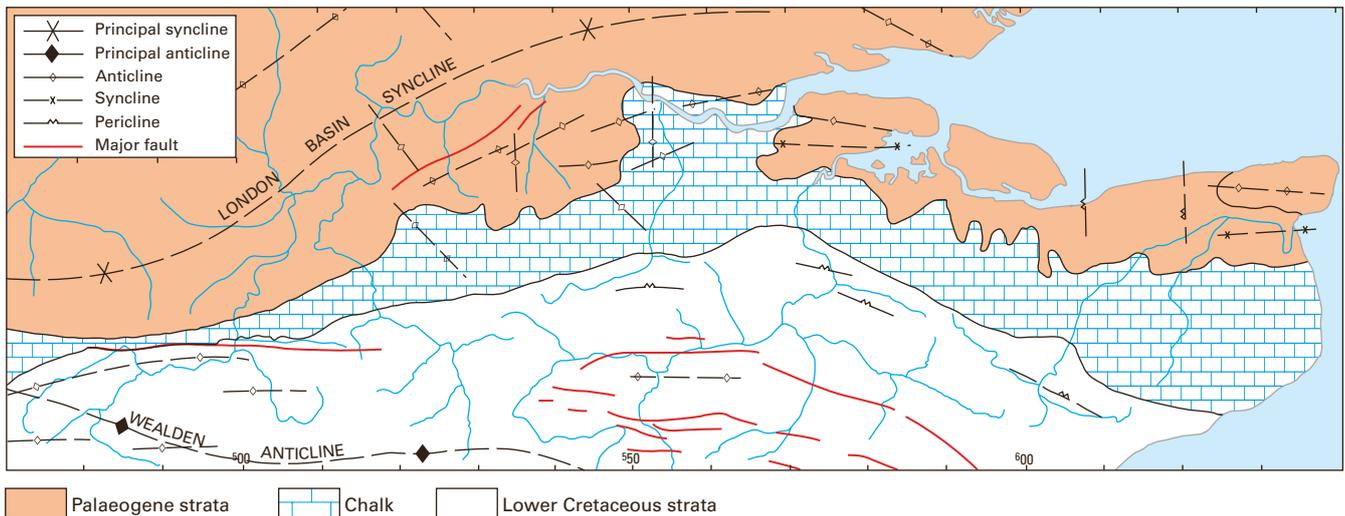


Figure 2.4 Small-scale structures within the Chalk and Palaeogene (after Wooldridge and Linton, 1955; and Lake, 1975).

BOX 2.3 LITHOLOGICAL CONTROLS ON FRACTURING IN THE CHALK

There is a significant difference in fracture style between chalks with marls (e.g. New Pit Chalk Formation) and pure white chalks without marl seams (e.g. Seaford Chalk Formation) (Mortimore, 1993). Chalk lithology also influences the predominance of horizontal or vertical fracture sets. Usually horizontal 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 North Downs and exert very different controls on the rate and direction of water infiltrating into the Chalk.

Many hardground and well-developed nodular chalk seams are interbedded with extremely soft to very soft chalks. Because of this variation in competency between layers the more brittle hardgrounds tend to be more densely fractured, presumably as the result of differential compaction. This style of fracturing is also associated with stylolitic contacts between nodules. The Melbourn Rock is an obvious example where fractured limestones and nodular chalks overlie the Plenus Marls and hence demonstrates

the way in which marls dissipate stresses subhorizontally and fractures open in the overlying hardground because of lateral 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. The intensity of fracturing within the different Chalk units significantly influences water storage capacity and yield potential. 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 Grey Chalk Subgroup (the Chalk Marl) with increased 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 (a chalk-rich head deposit) resting on a deeply weathered, and extensively fractured, profile. In contrast the Chalk beneath many of the interflues is little affected by destructive weathering and the chalk fracturing is tight.

The stress pattern affecting the Chalk during deposition and later during the Palaeogene, was the outcome of the north-westerly movement of the African plate against Europe and the south-easterly pressure of the North Atlantic spreading ridge. Non-parallel shear in the local stress field was influenced by long-standing basement fractures. Stress was either tensional or compressional, depending on geographic location such that each part of the Chalk aquifer had an individual stress regime, which also changed with time depending on the relative movement on the underlying fractures. The main Neogene (Miocene) uplift in south-east England produced the Weald Anticline but with numerous subsidiary folds developing in response to major deep-seated structures.

Much of the fracture pattern was imposed on the Chalk during the Palaeogene and Neogene. Two systems of meso-fractures are related to the folds and flexures of early

Oligocene to early Miocene times. The oldest of these strike east-west in response to north-south compression. The youngest strike mainly north-south or east-west but includes some that strike obliquely to those 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 mesofractures of Neogene age. The principal form of these fractures is a single set of vertical extension joints, but other types including conjugate sets of shear joints and normal mesofaults. 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 was formed during a phase of stress relaxation.

In common with other Chalk terrains in southern England, very few mapable faults have been recognised within the North Downs. Farrant and Aldiss (2002) note that those which have been identified previously are mostly of no great extent, and occur either along the scarp face or in the Medway valley. In this same study it is stated that few faults can be confidently located by desk interpretation alone, but construction of structure contour maps for the base of the Palaeogene, the base of the Seaford Chalk and the base of the Lewes Chalk suggested the presence of several previously unrecognised faults. These strike between north-north-east and east-north-east, being downthrown either to the east or to the west by between about 3 and 15 m. The occurrence and orientation of these faults was not tested by fieldwork, although Dines et al. (1971) note that faults of up to five metres throw seen at exposures in the Chatham area typically lie perpendicular to strike. The estimated amount of downthrow is particularly dependent on the details of the interpreted structure contours.

Linear inflections noted by Farrant and Aldiss (2002) in the basal Palaeogene surface were thought to mark fault displacement at depth, and many, if not all, could be associated with near-surface concentrations of subvertical fractures. Some of these lineaments appear to be aligned with faults inferred from other evidence, or with offsets in the North Downs escarpment. Additionally they assumed that drainage lines tend to follow major fractures within the Chalk, although the regional dip presumably also exerts a strong influence on valley orientation. Two strong preferred orientations are apparent in linear elements of the local drainage: one trending north-east to south-west, most clearly developed in the valleys south of Sittingbourne and Faversham, including that of the River Great Stour, and a second trending north-south. Two minor sets also occur: east to west and approximately north-west to south-east. These fracture zones may have a significant influence on water movement within the aquifer, even though faulting within them may be minor in terms of vertical displacement.

3 Hydrogeology

3.1 THE CHALK AQUIFER OF THE NORTH DOWNS

The aerial extent of the Chalk aquifer of the North Downs has been described in Chapter 1 and its outcrop area is shown in Figure 1.2. Figure 3.1 shows two cross-sections which run from the Gault outcrop in the south in a direction following the Chalk dip towards the north Kent coastline. The Chalk aquifer is unconfined at outcrop with the direction of groundwater flow being generally down dip (with minor local variations) with the exception of the Scarp Slope. The Gault Formation exerts a major influence on flow as it forms the lower, relatively impermeable boundary to the Chalk. In the Faversham area clays in the overlying Palaeogene Thanet Sand Formation locally confine the groundwater within the Chalk. Confined conditions also occur down-dip of the point at which the Chalk and the overlying Palaeogene deposits dip below the London Clay — as noted in Chapter 4, this has important implications for groundwater quality. Thus, the geological structure has a marked impact on both the regional and local hydrogeology and hydrochemistry.

Recharge occurs over the Chalk outcrop and is controlled by local meteorological (rainfall and evapotranspiration) processes, land use and geological (nature of the Chalk and/or its cover) and topographical conditions.

Springs and surface flows occur where the water table intersects the land surface. As the water table drops from

spring through to autumn, streams may dry up as the point of discharge of groundwater moves downstream — this is the typical bourne behaviour of Chalk streams. Along parts of the coast/estuary margins, springs are an important element of a marshland environment, much of which is protected by international conventions and/or European legislation. For all rivers of the North Downs, Chalk groundwater provides an important baseflow component. Some of these rivers also provide recharge to the aquifer and in some places (e.g. in the Mole and Dour valleys) the existence of swallow holes enhances this recharge effect.

Thus Chalk groundwater plays a significant part in maintaining the particular ecosystems of the rivers and coastline of the North Downs. However, there is significant pressure on this resource for the provision of water to public, agricultural and industrial supply. Thus, it is evident that a detailed understanding of the hydrogeology of the Chalk aquifer of the North Downs is essential for the achievement of sustainable development of the Chalk groundwater resource.

The Chalk has been regarded as several interlinked aquifers (Downing et al., 1993). Whilst the upper 50 m of the saturated zone generally has a much greater permeability than the deeper aquifer, those parts under areas with no ready outlet to surface water, e.g. interflaves, also generally exhibit lower permeability. Thus, a highly permeable zone coinciding with the alignment of the

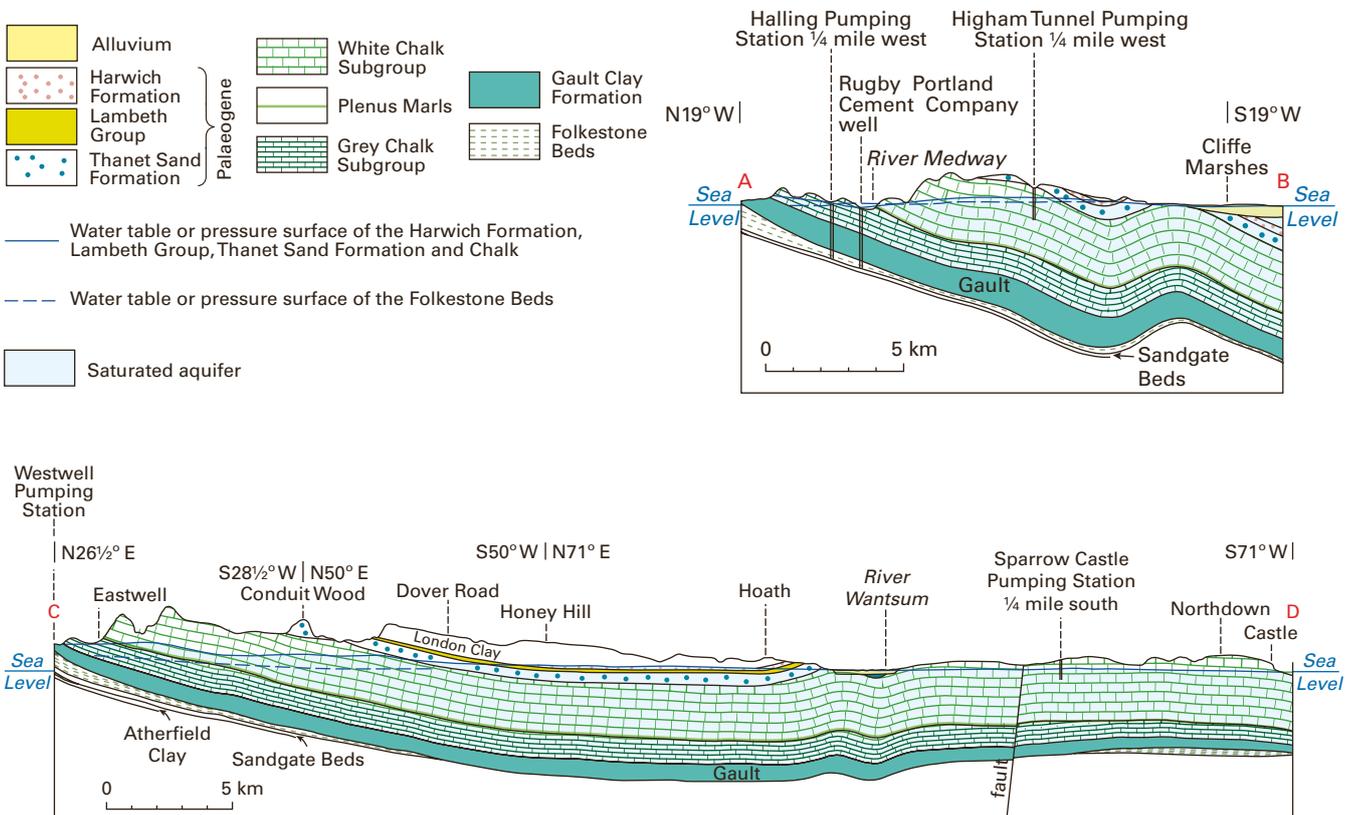


Figure 3.1 Hydrogeological sections across the North Downs. For lines of sections see Figure 1.2. (after Day et al., 1970).

valley system is flanked by an aquifer of significantly lower permeability below the interflaves. The upper 25 m or so of the saturated zone generally have a much greater permeability than the aquifer below that depth. However, where there are lithological differences in the sequence and differences in fracture density and style, groundwater may exploit opportunities to develop flow routes to discharge outlets.

Thus the Chalk is an important aquifer characterised by a generally high, and spatially variable, transmissivity but a relatively low storage capacity. Bloomfield (1999) recognised that, in general, the Chalk exhibits multiporosity rather than the conventionally stated dual porosity; the formation having a range of fracture apertures and matrix pore sizes. He identified five components of Chalk porosity as follows:

- matrix porosity
- fracture porosity
- enlarged fracture porosity
- fracture fill porosity
- modified matrix porosity associated with transmissive fractures.

It is the preferentially enlarged component of the fracture porosity that provides the principal permeability within the saturated zone. The unenlarged fracture porosity and smaller fractures on the other hand contribute to the specific yield. However, earlier studies indicated that these components alone were not sufficient to account for the total specific yield of Chalk aquifers.

In a study on the amount of water in storage in the Chalk aquifer in England, Lewis et al. (1993) compared volumes of water leaving two Chalk catchments as baseflow during long recessions with the estimated changes in groundwater storage. In all cases there appeared to be more water leaving the catchments than could be accounted for by the measured fall in water table. Lewis et al. concluded that this was due to continuous slow drainage from the unsaturated zone, which they termed delayed recharge. A subsequent study by Low et al. (1997) concluded that this drainage occurs at least partly from irregularities on the fracture walls and not, as had been proposed, from sets of micro fractures for which they found no evidence. Simple modelling confirmed that small irregularities present even on apparently smooth surfaces would hold sufficient water to explain the observed drainage. They concluded that this extra component of storage explains why the Chalk aquifer has generally proved more resilient to drought than expected.

The Chalk aquifer is also described as having dual permeability (Downing et al., 1993). Most of the flow tends to be concentrated in a few large fractures, often occurring at or within a few tens of metres of the water table. The form of fractures is closely linked to lithology and structural history. Dissolution-enhancement of original fractures is partly controlled by lithology and partly influenced by factors such as groundwater flux and the geochemical nature of the water. Periglacial periods will have resulted in changes of discharge elevation which also results in enhanced permeability at different horizons. At deeper levels the frequency and aperture of fractures decline, due to the increasing pressure of the overburden and the reduction in circulating groundwater and, therefore, dissolution. Flow velocities through larger fractures are of the order of tens to hundreds of metres per day.

A detailed discussion of the hydrochemistry of the North Downs Chalk aquifer is given in Chapter 4. However, with regards to contamination, transport of immiscible and miscible constituents takes place through domains having different properties. Dispersion and diffusion between the matrix and fractures control the distribution and rate of movement; in the Chalk, preferred flow rates along a few discontinuities is the rule rather than the exception.

3.2 EVOLUTION OF THE CHALK AQUIFER OF THE NORTH DOWNS

The close of the Cretaceous Period and the ending of chalk deposition was marked by great changes in geography. Tectonic uplift of Britain and north-west Europe was accompanied by the withdrawal of the Cretaceous seas and a stress regime which produced north-west to south-east and north-east to south-west joint sets and fault orientations. There then followed a period of erosion (about 5 my) before the deposition of the earliest Palaeogene deposits — the Thanet Beds. The uplift and regional tilting established at this time resulted in a regional east-west drainage system. The instability of the crust during the Palaeogene was due to movements which were precursors to the Alpine orogeny of the early Miocene which resulted in a series of east-west flexures and fractures in southern England; a major example of which is the Wealden anticline of Kent and Sussex. This is a simple structure with low regional dips, the outcropping Chalk on the northern limb of which forms the North Downs.

During the Quaternary, the course of the Thames was probably diverted southwards to its current location due to the impact of the Anglian ice sheet which reached as far south as London and the Cotswolds some 0.5 million years ago (Figure 3.2). The most recent glacial episode occurred during the Devensian (80 000–10 000 years ago)



Figure 3.2 The limits of the Anglian and Devensian ice sheets in southern Britain (after Boulton, 1992).

and sea levels fell to between 120 and 150 m below present sea level forming a significant base level for groundwater drainage from the Chalk (see Section 3.5.2)

Although no ice sheets reached as far south as the North Downs, the Chalk of this area would have been significantly affected by ground ice, i.e. periglaciation. Close to the surface an active zone underwent cycles of freezing and thawing which produced a weathered mantle some 1 to 2.5 m thick consisting of broken, rubbly chalk (Williams, 1987). In the top 5 to 6 m of chalk there is an observed increase in fracturing due to weathering. Periglacial activity was also responsible for the distribution of head deposits on the Chalk; these consist of soliflucted chalk and flints Palaeogene cover which occur mainly at the foot of scarp slopes and to a lesser extent on Chalk dip slopes.

The origin of the dry valley network of the Chalk is subject to much debate (see Goudie, 1990 for a review of hypotheses). The most commonly adopted theory involves periglacial activity when the cold climatic conditions reduced evapotranspiration and the permafrost layer reduced infiltration. Rapid melting of winter precipitation released a large volume of run-off, which easily eroded chalk that had been weakened by frost action.

Chalk intergranular permeability is very low and the porosity, although high, does not drain under gravity due to the small diameter of the pore throats. It is the presence of fractures that gives the Chalk the properties and characteristics of an aquifer. The development of these fractures was discussed above. Significant permeability is generally only developed towards the top of the aquifer. Allen et al. (1997) list the following observations:

- Permeability measured throughout the depth of a borehole is generally at least an order of magnitude greater than the matrix permeability, illustrating the importance of small fractures throughout the Chalk.
- Even so, most of the saturated thickness of the Chalk has very low permeability — only a few fractures providing the bulk of the transmissivity.
- Zones that have very high permeability correspond to fracture locations.
- Flow horizons tend to be concentrated near the top of the Chalk within the top 50 m of the saturated zone and the greatest flow is generally within the top 25 m below water level.
- The presence of hardgrounds at depths of less than 100 m below ground level can significantly increase the permeability of the Chalk.

The greatest permeability in the Chalk is observed in the zone of water table fluctuation where the movement of groundwater can enhance the aperture of fractures by dissolution. Recognition of this effect proved critical to the success of the development of a digital model of the east Kent Chalk aquifer (see Section 5.3.5).

Man's exploitation of the Chalk at depth and below Palaeogene deposits commenced in the early nineteenth century from excavated shafts. By the beginning of the twentieth century the practice of driving adits from the wells, usually constructed parallel to the coastline to intersect groundwater flow over a wider front, had been used to supplement yields in some areas. Prior to such activity, exploitation of groundwater had consisted of local abstractions from springs and shallow dug wells which had minimal impact on the natural steady state condition

that would have been established before abstraction commenced.

Thus, it is surmised that the steady-state groundwater conditions that existed prior to the onset of significant abstraction had been maintained for some 7000 years (Edmunds and Milne, 1999). This corresponds to the rise of sea level to near present levels and the establishment of the recognisable present-day English coastline. Prior to this, the related effects of glaciation and sea-level change would have led to significant changes in the hydrodynamics with longer flow paths towards the lower sea levels (see Section 3.5.2), lowering of water levels inland and increase in the volume of the unsaturated zone. These lowered sea levels existed for the order of 100 000 years, back to the last warm period (Eemian/Ipswichian). Before this, other periods of glaciation and climatic oscillations during the middle and late Pleistocene would have imposed an earlier cycle of disturbance on the groundwater systems. Thus, over the last 120 000 years, significantly lower groundwater levels than present have existed for more than 90% of that time — present-day groundwater levels may, therefore, be seen as exceptional. This well-established lower drainage level is an important feature of the hydrogeology of the North Downs.

3.3 THE UNSATURATED ZONE, RECHARGE AND INFLUENCE OF OVERLYING DEPOSITS

3.3.1 The unsaturated zone

The thickness of the natural unsaturated zone beneath the North Downs varies considerably, as the water table generally forms a subdued reflection of surface topography (Worssam, 1963; Dines et al., 1969). Beneath valleys the water table usually lies close to the ground surface, creating a thin (sometimes locally absent) unsaturated zone, while beneath interfluvial areas the water table tends to be much deeper.

Groundwater flow in the unsaturated zone of the Chalk is primarily controlled by the nature of Chalk porosity. Field experiments on unsaturated zone flow have been carried out at several sites on the Chalk outcrop in south-east England (see Box 3.1), although little work has been done in the North Downs itself. Measurements of moisture content and matric potential at various Chalk sites in Hampshire, Sussex, Oxfordshire and Cambridgeshire indicate that at depths of greater than 1 m there is virtually no change in water content as potentials decrease from -3 to -70 kPa (Gardner et al., 1990). Laboratory experiments (Price, 1987) indicate that approximately 80% of the total porosity of the Chalk is accounted for by pores with a narrow size range, connected by pore throats of between 0.05 and 1 μm .

If rainfall is sufficiently intense, rapid 'karst-like' flow through the unsaturated zone to the aquifer can also occur in any season via large solution features termed swallow holes. Karstic features have been identified in a number of areas, including the Mole valley in the western part of the North Downs, and the Dour catchment in the east. In the Mole valley a series of 25 active swallow holes have been recognised. Although the River Mole rarely dries up sufficiently to allow examination of the swallow holes, one dry period from 1948 to 1950 allowed the holes to be surveyed and identified. In addition, many inactive swallow holes are recognised both in the river bed and river terraces. New holes can develop rapidly and existing

BOX 3.1 GROUNDWATER MOVEMENT IN THE UNSATURATED ZONE

In situ measurements of hydraulic conductivity have been made at several sites in south-east England (Gardner et al., 1990). At matric potentials below about -5 kPa hydraulic conductivity was found to be almost constant, ranging between 1 and 6 mm d^{-1} , depending on the site. As potentials rose above -5 kPa (with decreasing pore water suction) hydraulic conductivity increased rapidly, with values in the range 100 to 1000 mm d^{-1} . This increase in hydraulic conductivity was caused by the increasing contribution of the fracture network to groundwater flow, as it becomes saturated. Thus, fractures only start to become saturated at potentials greater than approximately -5 kPa. Below this the conductivity is that of the Chalk matrix; above it, water can move through both the matrix and the fracture system, and the conductivity increases accordingly.

The frequency with which matric potentials exceed -5 kPa is therefore an important variable in determining whether rapid groundwater movement and recharge take place within the unsaturated zone. Estimates of the relative proportion of recharge via fracture (bypass) flow compared to matrix flow vary from 10 to 30% (Gardner et al., 1990; Jones, 1992).

Lysimeter studies from differing locations within the Chalk have identified 'piston flow' within the unsaturated zone (Jones and Cooper, 1998). This is where slow

movement of water through both the matrix and small fractures results from infiltrating water displacing water beneath. Due to high matric potentials, water that starts flowing through fractures is absorbed into the matrix, and it is only when matric potentials are low (i.e. the matrix is approaching saturation), that fracture flow occurs. Field evidence indicates that bypass flow through fractures in the unsaturated zone occurs when matric potentials exceed -5 kPa. The proportion of water that recharges by this mechanism appears to vary from about 30% (Fleam Dyke, Cambridgeshire) to almost zero (Bridget's Farm, Hampshire) (Jones and Cooper, 1998). It is probably highly dependant on factors such as weathering and cementation which affect matrix permeability. Conversely, in the saturated zone, both the matrix and the fractures are saturated and so the fractures will consistently provide the preferred flow paths due to their higher intrinsic permeability.

Groundwater movement in the unsaturated zone of the Chalk is, therefore, generally characterised by slow piston flow through the matrix and more rapid, although intermittent, bypass flow through fractures. In any season, unsaturated zone conditions also depend on antecedent moisture and current weather conditions. An additional control is the presence and nature of the soil and drift cover and weathered Chalk, which may play an important role in buffering the effects of rainfall, so leading to delayed recharge.

ones collapse as fast, even overnight (Fagg, 1958). It has been suggested that karstic features such as the ones distinguished here may be common in Chalk valleys, but are often obscured by recent deposits. Such features may provide a mechanism for rapid recharge to groundwater within dry valleys.

Direct point recharge into swallow holes has been observed in the Selling area between Faversham and Canterbury (Farrant and Aldiss, 2002). Streams draining the Palaeogene scarp in the area of Joan Beech Wood (approximately half way between Dunkirk and Chilham) and the outlier near Selling, sink underground upon reaching the Chalk. Recharge from the Thanet Sand Formation is likely to occur into the Chalk along the 'feather edge' of the Palaeogene outcrop, especially where dissolution has enhanced the permeability of the Chalk.

3.3.2 Recharge

Much of the North Downs is rural, covered with agricultural land (Figure 1.6), where direct rainfall recharge is the predominant source of aquifer replenishment. Further recharge may take place by downward leakage from minor aquifers within Palaeogene deposits where these overlie the Chalk.

Recharge to the North Downs Chalk aquifer has been estimated by a number of methods. The most detailed recharge estimate was made by the University of Birmingham and Acer Consultants Ltd for input to the east Kent model (Folkestone & District Water Company, 1991), see Section 5.3.5. A soil moisture balance technique was used with calculations depending on land elevation and the type of Chalk cover. For each kilometre square of the study area the relative proportions of head, alluvium, clay-with-flints and uncovered Chalk outcrop were determined. Where the Chalk is overlain by head or alluvial deposits the basic model was used. Where the cover is clay-with-flints a value of

0.1 mm d^{-1} was allowed to drain steadily from the base of the clay, with the remaining rainfall running off the clay cover. Where there is only a soil cover over the Chalk, 10% of rainfall was assumed to bypass the unsaturated zone through fractures, while the remainder was treated by the basic model.

The modelled area was also divided into three zones according to elevation: less than 70 m above OD, 70 to 130 m above OD, and over 130 m above OD. Because annual rainfall is greater over higher ground, estimated recharge is also greater on high ground than on lower ground with the same drift and vegetation cover.

Recharge calculations were done on a monthly basis, with a root constant varying from 45 to 135 mm depending on the month. Average annual recharge for the east Kent area for the years 1980 to 1990 was estimated at 297 mm. In a subsequent modelling study (Mott MacDonald, 2006), see Section 5.3.5, groundwater recharge in the unconfined Chalk was modelled as varying from 300 to 400 mm a^{-1} across the area. Taking an area where the recharge was 307 mm a^{-1} , the uncertainty in the calculation was reported as +10% or -8.8% . This figure reflects the potential recharge leaving the soil zone. The actual recharge arriving at the water table can differ from this if there are intermediate layers preventing or retarding flow. This effect is enhanced where the unsaturated zone is particularly thick, so that actual recharge at the water table may not only be diminished but also delayed from the time at which rainfall reaches the ground surface.

Recharge estimates carried out as part of other modelling studies have also been limited to particular regions of the North Downs area. Average annual recharge in the north Kent area is of the order of 210 to 220 mm (Southern Water and Mid Kent Water Company, 1989). Shirley (1997) calculated recharge for the four MORECS 40 km grid squares 162 to 163 and 173 to 174, using MORECS data for the years 1993 to 1996. Average

annual values from these calculations range from 80 to 347 mm. Values under 100 mm a⁻¹ were found for the north coast of Kent and values over 280 mm a⁻¹ to central and southern Kent. A subsequent modelling study (Water Management Consultants, 2006) used the Meteorological Office's MOSES data (which supersedes MORECS) and refined crop parameter data values to calculate recharge. This approach gave an average estimated recharge of 189 mm a⁻¹. The introduction of a daily rainfall threshold value, below which no bypass recharge would occur, gave an average reduction in recharge of around 5%.

The presence of low permeability drift cover may act to enhance total recharge to the aquifer, rather than restricting it (Folkestone and District Water Company, 1991). Where low permeability deposits cover the Chalk, such as clay-with-flints on interfluvial areas, a significant proportion of rainfall is deflected towards the edges of the deposits where they become more permeable or disappear altogether, and recharge at these points is enhanced. As noted earlier, recharge from the Thanet Sand Formation is likely to occur into the Chalk along the 'feather edge' of the Palaeogene outcrop, especially where dissolution has enhanced the permeability of the Chalk. In a recharge model of east Kent (Cross et al., 1995) a figure of 0.1 mm d⁻¹ for vertical recharge through the clay-with-flints was used, resulting in a decrease in infiltration from 175 to 35 mm a⁻¹ where the cover was present. The Environment Agency, Southern Region, estimate that all drainage from the clay-with-flints goes into the Chalk in the west of their area but less in Kent. The presence of clay-with-flints cover can have important implications for Chalk vulnerability to pollution (Box 3.2).

In most years recharge is concentrated in the autumn and winter months, when effective precipitation is highest. Estimates of the recharge season vary, e.g. between November and April (Southern Water and Mid Kent Water Authority, 1989), or between October and January (Shirley, 1997). Groundwater levels typically begin to recover in late November or early December, and peak sometime between late April and mid June, depending on location and the depth of the water table (Southern Water and Mid Kent Water Authority, 1989).

3.3.3 The influence of overlying deposits

EFFECTS OF PALAEOGENE HISTORY AND COVER

Following uplift and erosion of the Chalk in response to early 'Alpine' basin compression, the early Palaeogene deposits (Thanet Sand Formation) were laid down in a shallow southward extension of the expanding North Sea Basin. A short period of regression, represented in south-east England by the fluvial and estuarine deposits of the Lambeth Group, was followed by a major transgressive event (with smaller transgressive/regressive fluctuations) represented by the Thames and Bracklesham groups.

One of the main effects of Palaeogene cover on the hydrogeology of the Chalk aquifer is an increase in dissolution of the underlying Chalk close to the cover (Allen et al., 1997). Soil water associated with Palaeogene deposits tends to be acidic, and recharging water which drains through these deposits is geochemically aggressive (MacDonald et al., 1998). Soils associated with Palaeogene cover also tend to be clay-rich, and can act to deflect run-off onto the Chalk outcrop at specific points, increasing recharge in these areas (MacDonald et al., 1998).

Solution pipes and swallow holes in the Chalk can allow acidic recharge to penetrate deep into the unsaturated zone, and in particularly well-developed areas even to below the water table. The acidic recharge enhances the dissolution of fracture systems within the aquifer. If the cover is removed by erosion, the deeper enhanced fracture systems remain, allowing rapid groundwater flow (MacDonald et al., 1998).

Sands and gravels from unconsolidated Palaeogene deposits may be washed down through solution features and act to clog the fracture network. Problems have been experienced during pumping when induced rapid groundwater flow has disturbed sands in Chalk fractures, and running sand has been observed to enter boreholes down to 70 m below the ground surface (Southern Science, 1992).

EFFECTS OF PLEISTOCENE HISTORY AND COVER

The Pleistocene saw alternating glacial and interglacial periods with resultant fluctuations in sea levels which had a significant effect on both surface drainage and groundwater flow in the North Downs. Present-day dry valleys, as discussed above, are possibly remnants of active stream valleys formed during periods of higher sea levels. As sea levels varied, the water table was maintained at different levels. Dissolution was enhanced in the zone in which the water table fluctuated, allowing the development of numerous horizons of enhanced permeability (MacDonald et al., 1998).

BOX 3.2 RECHARGE AT THE MARGINS OF THE CLAY-WITH-FLINTS COVER AND ITS IMPLICATIONS FOR CHALK VULNERABILITY TO POLLUTION

It is commonly assumed that the clay-with-flints constitutes a homogeneous, relatively impermeable cover to the Chalk and that most precipitation runs off and enters the aquifer around the margins of the clay-with-flints. However, the lithological variation found within the clay-with-flints means that water can in fact move through voids of various sizes and form. Indeed, an estimate made by Klink et al. (1998) from data at Rothamsted in the Chilterns demonstrated that clay-with-flint is capable of transmitting all of the effective rainfall as recharge under certain conditions.

Recognising that the development of karst-like features in the Chalk, around the edge of and beneath the clay-with-flints cover, indicated the occurrence of preferential flow paths, Klink et al. (1998) developed a conceptual model of the recharge mechanisms associated with this type of cover — see Klink et al., 1998, fig 3.8.

The implications for vulnerability of the Chalk aquifer below clay-with-flints cover are:

- At the clay-with-flints contact, the Chalk aquifer is more vulnerable to bacteria and protozoa in run-off due to the high incidence of solution features and enhanced permeability of the Chalk.
- The vulnerability of the Chalk underlying the clay-with-flints cover to such contaminants as those arising from sewage sludge application is reduced.
- Compounds which affect the structural integrity of smectite within the cover, such as chlorinated solvents, may affect the bulk permeability of the clay-with-flints and enhance flow pathways, thus increasing the Chalk vulnerability.

3.4 THE SATURATED ZONE

3.4.1 Aquifer properties

INTRODUCTION

The hydraulic properties of the Chalk aquifer are complex, and result from a combination of matrix and fracture properties. The Chalk matrix is characterised by high porosity and a high degree of interconnection, and by small pore diameters and pore throat sizes. Intergranular permeability is extremely low, and groundwater flow in the saturated zone occurs primarily through fractures (Downing et al., 1993). Because of the very small pore throats the high porosity is not easily drained, so that effective groundwater storage is dominantly within the fracture network. The relative contribution to the storage coefficient from the matrix and the fractures is difficult to establish. Pore size distribution curves for the upper part of the White Chalk Subgroup (formerly the Upper Chalk) suggest that a maximum of some 3% of the total intergranular porosity represents usable storage. Box 3.3 discusses the variation of physical properties with stratigraphy in the Chalk. The Grey Chalk Subgroup (formerly the Lower Chalk) generally has smaller pore diameters and therefore lower intergranular porosity, indicating that the matrix is less important for storage (Allen et al., 1997).

The importance of fractures in determining the bulk properties of the Chalk is illustrated by tests which show that permeability measured throughout the depth of a borehole is normally at least an order of magnitude higher than the matrix permeability (Price et al., 1982). The initial occurrence and subsequent solution enhancement of fractures by the concentration of groundwater flow along them have created most of the characteristic features of the Chalk aquifer. Preferential development has led to an uneven distribution of hydraulic properties in the Chalk aquifer both laterally across the North Downs and vertically within the aquifer.

AQUIFER PROPERTIES DATA

The most extensive set of data on the physical properties of the Chalk aquifer in the United Kingdom is presented by Allen et al., (1997). Within the North Downs there are 41 locations where aquifer properties data have been obtained. Fifty-seven pumping tests have been recorded, providing 35 values of storage coefficient and 57 estimates of transmissivity.

Overall, transmissivity estimates for the North Downs Chalk have an approximate log-normal distribution. Values range from 52 to 7400 m²d⁻¹, with a geometric mean of 720 m²d⁻¹ and a median of 670 m²d⁻¹. However, there is a lack of low transmissivity values, with 25% of the values less than 350 m²d⁻¹ and 75% less than 1600 m²d⁻¹ (Allen et al., 1997). Production boreholes tend to be sited in valleys, where permeability and, therefore, yields are high, and groundwater levels are close to the ground surface. Data will, therefore, be biased towards the most productive parts of the aquifer.

Estimates of storage coefficients in the North Downs Chalk vary from 0.00001 to 0.060, with a geometric mean of 0.0031 and a median of 0.0036. The 25 and 75 percentiles of the data are 0.001 and 0.015 respectively.

VERTICAL DISTRIBUTION OF AQUIFER PROPERTIES

A general feature of the Chalk is that the highest permeability is generally only developed near the top of the aquifer, in the zone of water-table fluctuation. Here, concentrated groundwater flow has enhanced the aperture of fractures by dissolution. Significant groundwater flow tends to occur in only a few well-developed fractures within this zone. Modelling of the aquifer (Cross et al., 1995) has shown that within this zone of water-table fluctuation, transmissivity increases non-linearly with increasing groundwater level, while below this zone transmissivity remains constant.

This model of a non-linear decrease in transmissivity with depth is illustrated during periods of extreme weather conditions. During recent drought periods, the yields of major boreholes were reduced dramatically after only a slight decline in groundwater level, as important fractures near the top of the saturated zone were de-

BOX 3.3 MATRIX POROSITY, INTACT DRY DENSITY AND STRATIGRAPHY (AFTER JONES AND ROBINS, 1999)

It is generally accepted that chalk porosity varies with stratigraphy (Price, 1987, table 1). For example, the Grey Chalk Subgroup (Lower Chalk) typically has a porosity of 20 to 40%, the lower part of the White Chalk Subgroup (Middle Chalk) 30 to 40% and the upper part of the White Chalk Subgroup (Upper Chalk) typically has a porosity of 28 to 48%. In the purer chalks, low porosity values are associated with nodular and hardground development. For example the Melbourn Rock is typically 16 to 18% and the cemented calcisphere rocks of the Grey Chalk Subgroup are between 14 and 18%. Lower porosity values of <15% are representative of the clay rich, marly chalks in the West Melbury Marly Chalk Formation and the lower part of the Zig Zag Chalk Formation (the traditional Chalk Marl in the North Downs area). 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. These categories in turn relate to pore throat diameter. However, the median pore throat diameter may not be the most useful parameter to illustrate variation with intact dry density. The data quoted by Jones and Robins (1999) also showed 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. However, the values for porosity and the range of pore sizes reported do not easily relate to the density scale or other data for the Chalk in southern England, and more information is required on the types of chalk and their textures throughout the succession.

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

watered. Conversely, extreme recharge in the Chichester area during January 1994 caused groundwater levels to rise within the aquifer until sufficient large fractures were activated to discharge the water to the river, resulting in surface flooding (Allen et al., 1997).

Geological variation between the different Chalk formations has a significant impact on the properties of the aquifer through different bedding thicknesses, hardness of layers, fracture styles, fracture density and discontinuities for groundwater flow to exploit. What was termed the Upper Chalk (now the upper part of the White Chalk Subgroup) tends to show the highest transmissivity values, with the remainder of the White Chalk Subgroup (essentially the former Middle Chalk) also being a good aquifer. The Grey Chalk Subgroup tends to be marlier and, therefore, generally shows significantly lower transmissivity. Hardgrounds and marl layers, within all Chalk formations may alter the vertical distribution of aquifer properties. Many inflow zones detected in boreholes by fluid flow and caliper logging are located immediately above such low permeability marl layers or higher density low porosity hard bands (Folkestone and District Water Company, 1991) which have focused the groundwater flow along the discontinuities. Because the marl layers impede the downward percolation of groundwater, they cause a build up of head, and flow develops down dip along the top of the marl. This subhorizontal flow results in the observed solution feature development above marl layers. Where marls lie close to the ground surface they tend to be more fractured than the surrounding rock, and can show higher transmissivity.

AREAL DISTRIBUTION OF AQUIFER PROPERTIES

The valley-interfluvial model of Chalk transmissivity (see Section 3.1) appears to be well developed within the North Downs. Along valley floors aquifer properties are generally favourable with generally high transmissivity and storage coefficients. This basic pattern is modified by effects such as local geological structure, solution features within stream beds or artificial features like tunnels and adits.

The network of valleys within the North Downs appears to be structurally controlled, with a large number of dry valleys developed parallel to the dominant fracture set (Reynolds, 1970; Southern Water Authority, 1989). Transmissivity and storage coefficient values within valleys, both dry and flowing, are generally high. As a result, most public supply boreholes are located in main valleys, and pumping test data are biased towards the valley locations with little investigation on interfluvial areas. This helps to explain the lack of low transmissivity values for the area. Dry valleys and intervening interfluvial areas are thought to have been formed initially along dominant fracture directions, while later perennial streams which existed during glacial conditions helped to develop the observed high transmissivities. The structural controls on dry valleys are especially well illustrated in the Dover/Deal area in the east of the North Downs (Figure 3.3). Locally strike control is also evident.

For convenience the following detailed discussion splits the North Downs region into an eastern and a western area.

EASTERN AREA

The aquifer in the Dour catchment in the eastern part of the North Downs comprises mainly Middle and Lower

Chalk. Regional transmissivity values are correspondingly relatively low. Typical values for transmissivity given in the BGS Aquifer Properties Database are around $1500 \text{ m}^2 \text{ d}^{-1}$. These values are likely to be boosted by large productive fractures and cavities which generally develop preferentially along bedding planes and fractures in valleys, and which allow rapid groundwater flow (Reynolds, 1970; Cross et al., 1995). Modelling by the University of Birmingham suggests that transmissivity values in interfluvial areas are around $30 \text{ m}^2 \text{ d}^{-1}$, increasing non-linearly as groundwater levels rise (Cross et al., 1995).

Reliable estimates of storage coefficient are more difficult to obtain, but modelling suggests specific yields of about 0.015 for the valleys and 0.01 for the interfluvial areas. Data from pumping tests tend to be lower, e.g. a value of 0.005 (Southern Water Authority, 1975), possibly due to incomplete drainage during testing (Allen et al., 1997).

In the northern part of the Dover/Deal area transmissivity tends not to vary much over time, due largely to relatively stable groundwater levels throughout the year.

The pattern of dry valleys, and possibly fracture sets, illustrated in Figure 3.3 is also reflected in regional transmissivity patterns, giving an anisotropic distribution of transmissivity.

No aquifer properties data exist for the Isle of Thanet. However, the aquifer is thought to be generally well developed across the outcrop of the Chalk (Allen et al., 1997). Relief is generally low and valley systems are not fully developed, so that there are fewer differences in aquifer properties between valleys and interfluvial areas. Tunnels and adits are common on the Isle of Thanet, constituting artificial conduits which will significantly modify natural aquifer properties.

WESTERN AREA

There are fewer data for this region of the North Downs, but the general patterns of aquifer properties distribution are similar to the eastern area. High transmissivity and storage values are associated with fracture sets in dry valleys, particularly within the outcrop of the White Chalk Subgroup. Away from valleys, solution enhanced fractures and bedding plane apertures within the zone of water table fluctuation result in favourable aquifer properties for water supply.

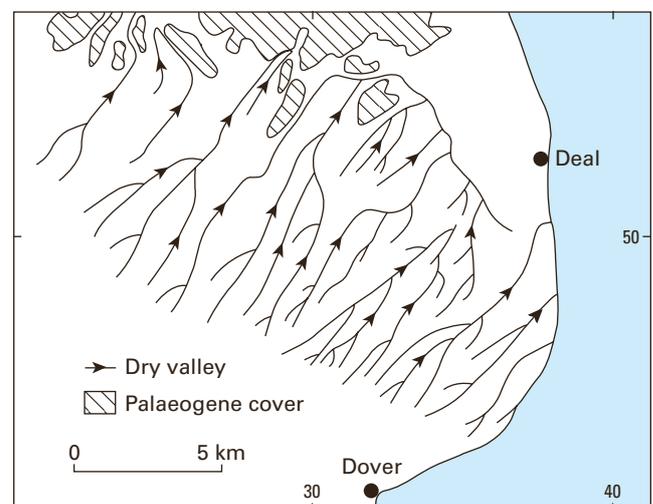


Figure 3.3 Dry valley occurrence in the Dover–Deal area.

As in the eastern area, public supply boreholes are located within principal river valleys, such as the rivers Stour, Darent and Cray, as well as within dry valleys. Although few pumping tests have been done on these boreholes, licensed abstractions are high, indicating good yields. Tests in the dry valleys between the Stour and the Medway gave transmissivity values of between 300 and 600 m² d⁻¹, and similar values are thought to occur in the dry valleys to the west between the Darent and the Medway and also near the Mole (Allen et al., 1997).

On the Hog's Back there has been significant folding of the Chalk, resulting in a narrow outcrop and steep, high relief, and corresponding poor development of aquifer properties.

As the Chalk dips north beneath Palaeogene strata and becomes confined, transmissivity and storage decrease markedly, although at the feather edge of these deposits pumping tests have proved high values for transmissivity. At Littlebourne and Faversham values of 3000 and 5000 m² d⁻¹ were obtained, thought to be due to enhanced dissolution and enlargement of fractures caused by increased chemically aggressive recharge due to surface run-off from the Palaeogene deposits (Allen et al., 1997).

3.4.2 Groundwater flow, storage and discharge

As noted earlier, the majority of groundwater flow occurs within about 50 m of the water table in dissolution-enhanced fractures. Smaller flows can be found at depths down to 140 m, especially close to the coast (Allen et al., 1997). These deep flow horizons are often associated with marl layers, flints or hardgrounds, and probably developed in the Pleistocene as a result of groundwater circulation, lowered sea level, or possibly sub-permafrost flow. Although they contribute little to the overall groundwater flow, they may be important in terms of the groundwater chemistry, especially where they are connected to the sea. Equally, flow horizons in the Chalk above current rest water levels will have developed when sea levels were higher than the present, and/or where land has risen (as in the South Downs).

Groundwater storage in the Chalk is difficult to characterise. Storage reflects the influence of seasonal changes in recharge, and, therefore, groundwater level, as well as any periodic changes in abstraction which may occur (Southern Water and Mid Kent Water Authority, 1989). As noted in Section 3.1, significant storage also occurs in the unsaturated zone.

Groundwater flows away from recharge areas to discharge to surface water through springs, as base flow in valleys, and directly to the sea. Flow is bounded by groundwater divides (groundwater catchment boundaries). Because water tables generally mirror topography, albeit in a subdued fashion, groundwater divides usually tend to coincide with major surface water boundaries. For example, there is a groundwater ridge between the Acrise-Denton Valley and the Dour catchment in the south-eastern part of the North Downs. The position of groundwater divides may migrate seasonally depending on the relative rates of recharge, pumping and losses from storage, and do not always coincide with surface water catchment divides.

There is a close relationship between groundwater and surface water drainage, with the seasonal stream flow pattern almost entirely dominated by changes in groundwater level, and base flow from the Chalk forming a significant component of river flow. Springs may occur either as free-draining water-table springs or at certain

horizons may be determined by lithology (Folkestone and District Water Company, 1991). In the eastern part of the region, groundwater flow in the Chalk emerges at springs at the northern foot of the Downs. The majority of the largest springs occur at the contact between the Seaford Chalk and the overlying Palaeogene deposits, although some also occur either within the Chalk or in the Palaeogene. In the west some of these springs are substantial, such as those at Fetcham on the River Mole. The presence of this spring-line can be attributed to sandy and silty clay in the lower part of the Thanet Formation (Aldiss and Farrant, 2002). Elsewhere the Thanet Formation is generally in hydraulic continuity with the underlying Chalk and upward leakage occurs when groundwater levels in the Chalk are high enough to allow upward flow through overlying strata (Folkestone and District Water Company, 1991).

The interaction between the aquifer and surface streams varies depending on the size and nature of the stream. Streams only penetrate a small proportion of the saturated depth of the aquifer. There are many times, especially with small streams, when the water table falls below the level of the stream bed (Folkestone and District Water Company, 1991). The relative positions of the stream level and the water table determine the interaction between the two, and the nature and amount of groundwater discharge to the stream.

Along most stretches of the coastline the water table is at or only slightly above sea level. However, in some areas, such as along the cliff line between Dover and Folkestone, the groundwater level is significantly above sea level, and there is groundwater flow towards the sea (Folkestone and District Water Company, 1991). Discharge is related to the amount of recharge during the previous months. If the water table is drawn down below sea level as a result of abstraction, saline intrusion of the aquifer is likely to occur with saline water advancing along solution-enhanced fractures.

3.4.3 The development of karst

Karstic features have been identified in the Mole Valley (Fagg, 1958). A series of 25 active swallow holes were identified which were classified into the following groups according to location:

- in the bottom of depressions in the river bed
- higher up the river bed near the river bank – i.e. can be bypassed at low flows
- on the vertical sides of river valleys
- in depressions on the flood plains.

New holes were seen to develop very quickly, one hole in the river bed collapsing overnight. It has been suggested by later workers that such features could be common in Chalk valleys but are obscured by glacial and periglacial deposits (Docherty, 1971). Allen et al. (1997) postulate that this might provide a mechanism by which rapid recharge could occur within dry valleys and explain why ephemeral streams often dry up in distinct stages.

MacDonald et al. (1998) note that the surface of Chalk, where overlain by cover, has undulations similar in appearance to the clints and grykes more commonly associated with limestone karst. These 'karst'-like features in the Chalk have often been exposed in quarries and excavations. Klink et al. (1998) suggest that the reason they are not seen at outcrop is that the Chalk is too soft to maintain them.

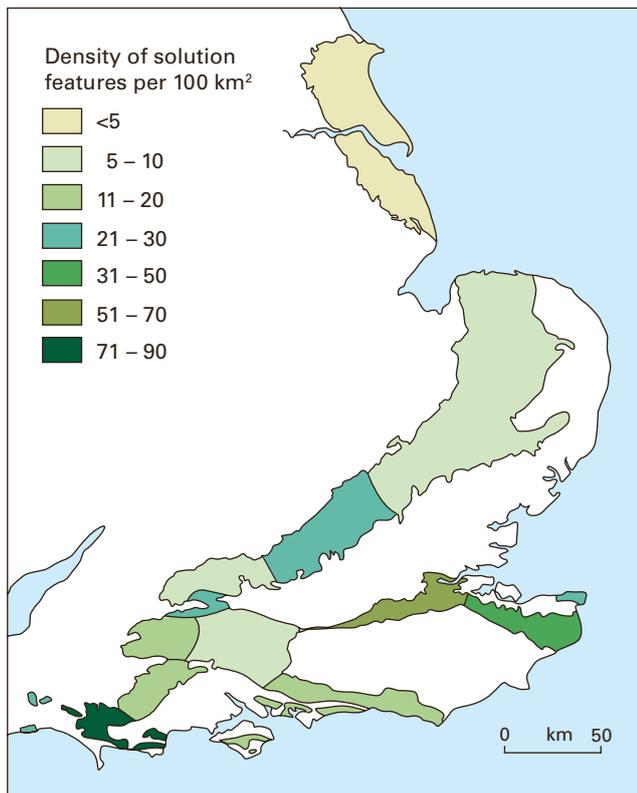


Figure 3.4 The density of solution features on the outcrop of the Chalk per 100 km² (after Edmonds, 1983).

The abundance of solution features in any particular region can be used as an indication of the degree of karstification. Figure 3.4 (after Edmonds, 1983) indicates a frequency of 31 to 50 solution features per 100 km² on the eastern half of the North Downs rising to a frequency of 51 to 70 solution features per km² in the west. However, as MacDonald et al. (1998) point out, the link between surface karstic features and rapid groundwater flow is uncertain.

The high degree of solution activity associated with cover is partially accounted for by the soils associated with Palaeogene deposits and clay-with-flints tending to be acidic (Edmonds et al., 1992), run-off remains undersaturated with respect to calcite until it reaches the Chalk. Additionally, the clay-rich soils are likely to concentrate run-off to discrete points.

In a vulnerability-mapping study of an area of some 97 km² of North Downs centred approximately 1 km south-east of Faversham (Hewitson, 1999), epikarst features were identified. However, there was no evidence found for the development of a karst network within the saturated zone.

A further indication of the development of karst (MacDonald et al., 1998) is a poorly developed surface drainage pattern on the Chalk outcrop. The dendritic patterns that are seen on most other geological formations are not observed; instead the valley patterns tend to be orthogonal, possibly defined by fracture directions (Figure 3.3). The lack of surface drainage indicates the higher permeability of chalk strata with most water flowing through the catchment as groundwater.

The existence of swallow holes in the Mole valley, the Dour catchment and the Selling area has already been noted in Section 3.3.1. Further evidence of karst development in the Chalk of the North Downs is provided by the caves

of anthropocentric (i.e. explorable) dimensions at St Margaret's Bay (Reeve, 1976); a cave system some 90 m long. There have also been indications of karstic cave development from the construction of wells. Reeve (1976) quotes Sills (1907) as describing a cave found in a well at Rochester Waterworks at Strood in 1887. He also quotes Sills as reporting two other caves in wells at Knockholt near Sevenoaks and Luton near Chatham.

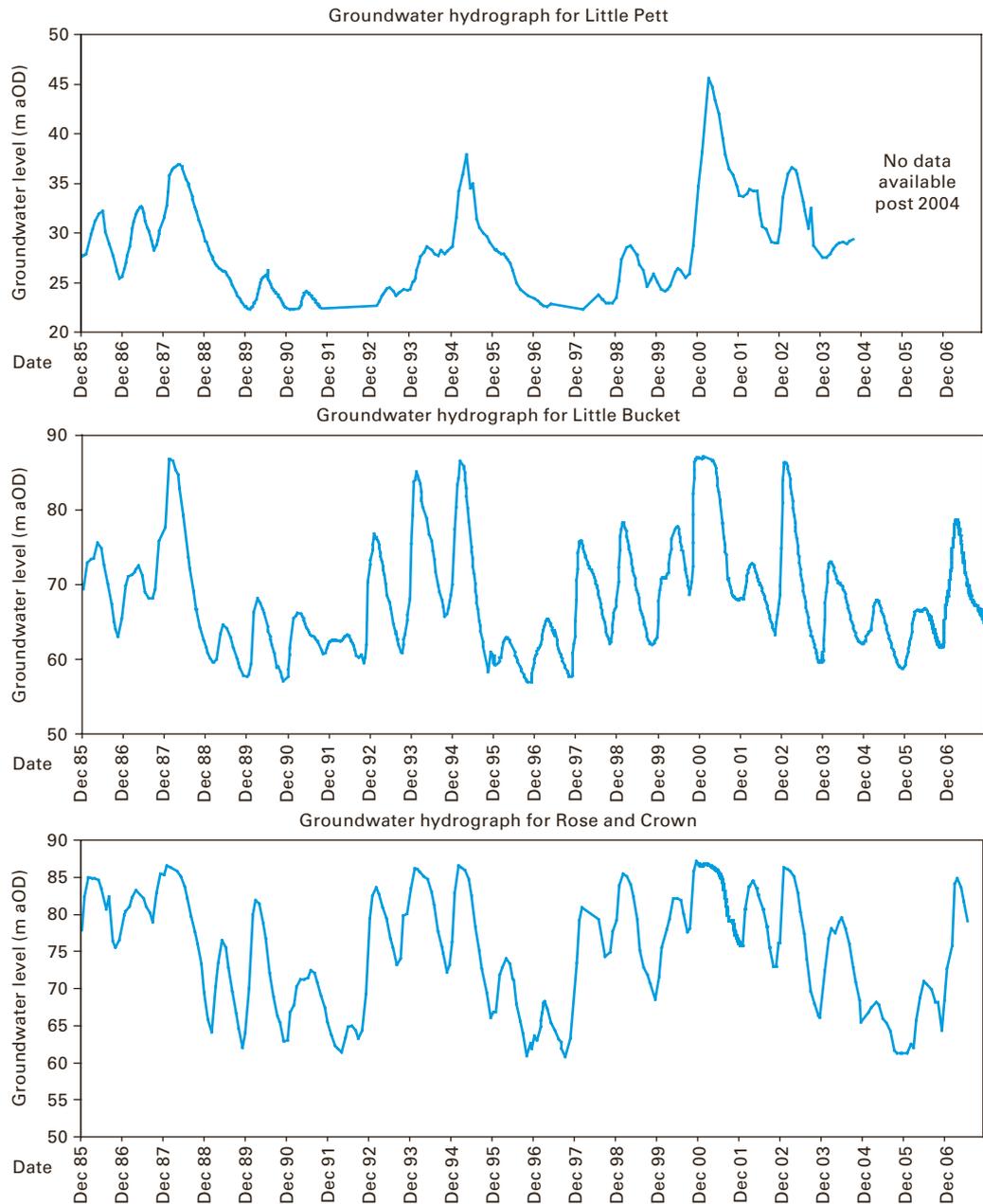
3.4.4 Groundwater level fluctuations

Groundwater levels are monitored in the North Downs by the Southern and Thames regions of the Environment Agency. A number of records for observation wells on the North Downs are available in the British Geological Survey groundwater archive. Most of these are historical records spanning periods ranging from less than 10 to over 30 years. Four are currently monitored as part of the National Hydrological Monitoring Programme, with the length of record ranging from 22 to 127 years. Groundwater levels since 1985 are illustrated by hydrographs for three of these wells: Little Bucket Farm [TR 1225 4690], Rose and Crown [TQ 3363 5924] and Little Pett Farm [TQ 8595 6095], in Figure 3.5. Little Bucket Farm is one of the BGS index wells, chosen because it is located in an area where there are believed to be few anthropogenic influences on groundwater level, so that groundwater levels reflect natural conditions as far as possible.

The hydrographs for Little Bucket Farm and Rose and Crown show similar patterns in the timing of groundwater highs and lows, although the magnitude of the fluctuations varies. There was a rapid groundwater recession in 1988 and the years from 1989 to 1992 saw generally lower than average water tables, with a similar rapid recovery of water levels in the 1992 to 93 recharge season. Another marked fall in groundwater levels occurred during the summer and autumn of 1995, with low water tables persisting throughout 1996 and 1997. Little Pett Farm displays a slightly different pattern, partly because the well is not deep enough for observation purposes; water levels fell beneath the base of the well twice in the last 15 years, in 1991 and 1992. However, this well also shows a marked groundwater recession in 1988 which continued throughout 1989, followed by a long period of low water tables. Groundwater levels did not recover to the high of 1988 until 1995.

All three wells show a very marked response to the recharge event of the winter of 2000 to 2001 and similar high levels are seen to have been reached in the 2002 to 2003 winter. The recharge event of the winter of 2000 to 2001 was exceptional, resulting in unprecedented rises in groundwater levels and prolonged groundwater flooding in many areas of southern England. In 2000, unsettled weather patterns in April and May ensured that soils did not begin to dry out until late spring. Although the summer rainfall was below average, the consequence of the wet spring was rapid elimination of soil moisture deficits (SMDs) and unusually high baseflow contributions to rivers in early autumn. Indeed, September saw the most rapid decline in SMDs seen in the 40-year Meteorological Office Rainfall and Evaporation Calculation System (MORECS) series. Subsequent exceptional rainfalls through to April 2001 established many new national and regional rainfall records; by the end of February, six-month rainfall totals exceeded the annual average across most of the English lowlands. At the catchment scale, maximum recorded rainfall totals

Figure 3.5
Groundwater level hydrographs for three observation wells in the North Downs Chalk.



across most of the country were eclipsed over a range of timescales, although it is recognised that this in part reflects the limited period over which flow and associated catchment rainfall records have been maintained.

The elimination of soil moisture deficits in October 2000 resulted in an extended recharge season which, combined with the sustained rainfall, resulted in record autumn recharge totals. In parts of the Chalk of southern England recharge in October and November alone exceeded the annual mean. The September to April hydrologically effective rainfall in Kent exceeded 450% of the long term average.

Whilst the hydrographs in Figure 3.5 shows that steep winter groundwater recoveries have not been uncommon in the recent past, they generally have commenced from a low base. However, in 2000 after three successive winters of above average rainfall, recovery commenced from around the seasonal mean. From mid October the water-table rise gathered momentum and by late autumn were remarkable. Water tables remained at the long-term high values until the following winter.

In the winter of 2000 to 2001, major urban flooding events were observed in the Whyteleaf area of the Warlingham/Caterham valley [TQ 339 583]. Groundwater flooding also occurred on the Chalk dip slope 'dry' valleys upstream of the River Ravensbourne at Addington and West Wickham [TQ 387 652]. Thames Water Utilities Ltd. was asked to maintain a higher than needed pumping rate from the Addington source to help lower levels. This excess pumping was maintained through to late summer (Robinson et al., 2001).

3.5 LITHOLOGICAL AND STRUCTURAL CONTROL ON GROUNDWATER FLOW

3.5.1 Introduction

So far in this report, the discussion on groundwater flow has essentially been in general terms and on a regional basis. However, it is important to note that lithology and structure

both influence the direction of groundwater flow, not only on a regional but also a local basis. In this section the influence of these factors is interpreted from borehole geophysical logs.

The relatively large amount of geophysical logging undertaken in the region stems from the work of the Geological Survey in the 1950s when it was recognised that electrical resistivity logs provided distinctive profiles in the Chalk which could be related to the stratigraphy (Gray, 1958). Particular resistivity peaks were found to be related to important hard bands e.g. Chalk Rock, Top Rock, Melbourn Rock, and resistivity lows could be related to certain marl seams e.g. Plenus Marls, Southerham Marl. Several relatively deep cored boreholes were drilled by the Geological Survey to examine the stratigraphy of the Chalk and relate it to the geophysical logging (e.g. Canvey Island, Warlingham, Fetcham Mill) (Gray, 1965). The resistivity log profiles in particular allowed a subdivision of the Chalk into Upper, Middle and Lower Chalk, based on the location of the Chalk Rock and Melbourn Rock/Plenus Marls marking the (then) base of the Upper and Middle Chalk respectively. This permitted the various Chalk units to be easily recognised and correlated in boreholes without actually having site of the material drilled through. (Murray, 1982; 1986). Much of the resistivity logging recorded prior to 1970 was not continuous profiling, but point measurements recorded at 5 feet (1.52 m) intervals, and also at a time when water levels were, in places, well below OD due to abstraction.

At the same time the Geological Survey also developed fluid logging techniques (fluid electrical conductivity, fluid temperature and borehole flowmeter) for use in water boreholes and employed CCTV examinations of the Chalk aquifer and its fractures (Tate, et al., 1970; Tate and Robertson, 1975) which allowed water inflows in the boreholes to be identified. The application of the logging techniques provided valuable new information on the flow of groundwater and the conceptualisation of the Chalk aquifer of the North Downs (Headworth, 1978; Headworth, et al.; 1982, Price et al., 1993).

Figure 3.6 shows typical resistivity log profiles for the Chalk from deep boreholes in the South Downs and the North Downs from south to north. It shows the subdivision into modern stratigraphic units and selected named horizons. Particular harder chalk horizons, such as the Melbourn Rock horizon can be recognised.

The change from high resistivity to low resistivity at the base of the Holywell Nodular Chalk, formerly the base of the Middle Chalk, identifies Melbourn Rock (higher resistivity) overlying the low resistivity Plenus Marls. Gamma ray logs usually resolve the Plenus Marls and the Glauconitic Marl at the base of the Chalk Group because they are thick, but they do not always clearly identify thin marl seams that can be recognised by the resistivity log (e.g. New Pit Marls). The gamma ray log also sometimes responds positively to some of the hardground horizons, where they contain gamma emitting elements such as glauconite and francolite.

In the 'Maidstone Block' strata dip north-westwards at 15 to 20 m km⁻¹ whilst the water table and potentiometric surface are relatively flat. To the south of the Block in the Stockbury Valley Borehole [TQ 830 602], the water table is situated in the Holywell Nodular Chalk, not far above the Plenus Marl horizon. Traced down catchment it steps upwards through the New Pit and Lewes Chalk formations and occupies the Seaford Chalk which is

eventually confined by the Palaeogene strata. Fluid log profiles indicate a base of active groundwater circulation at about -110 m OD.

3.5.2 Groundwater movement in the coastal zone along the Thames Estuary

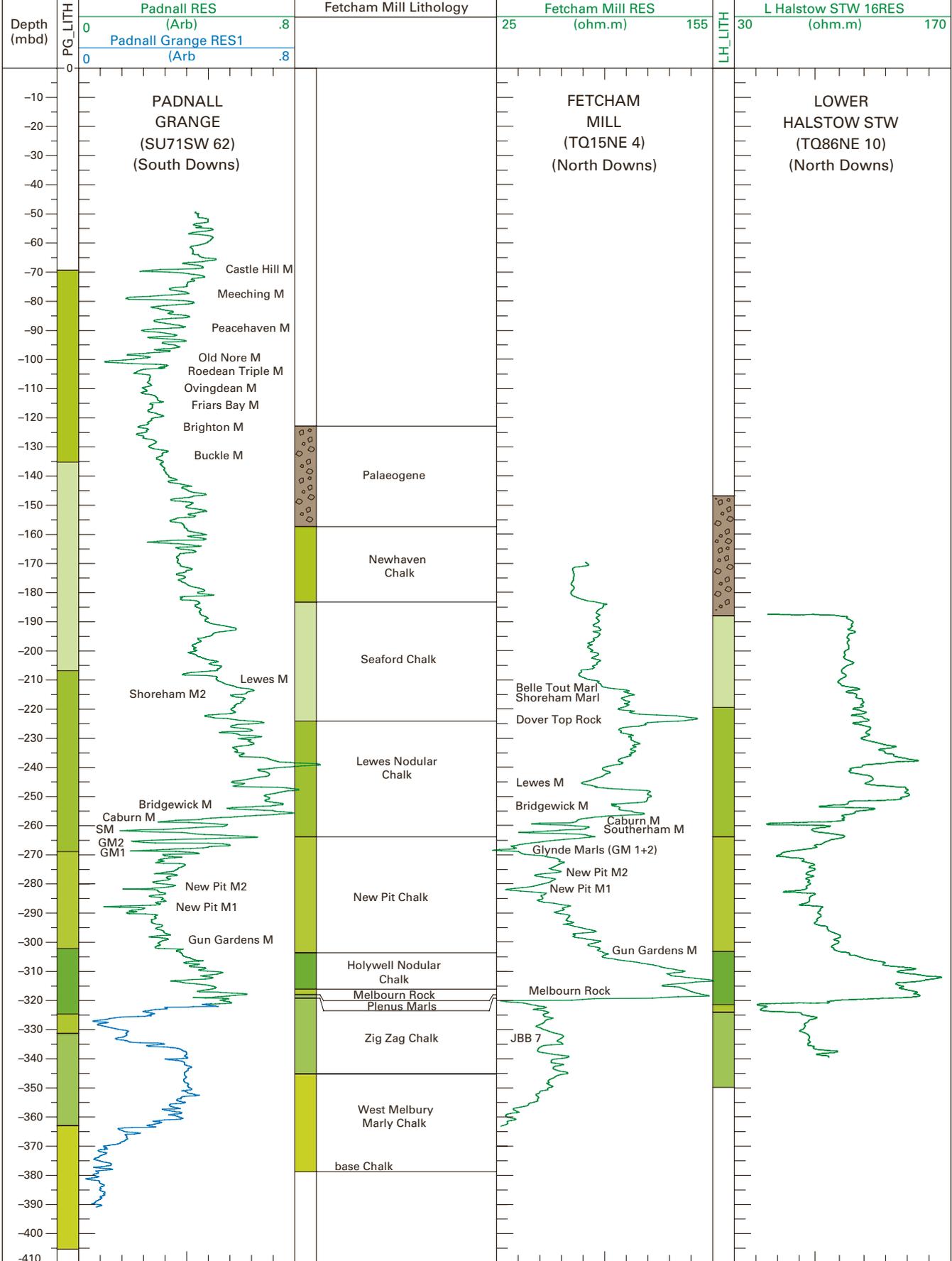
Close to the Thames Estuary and the coastline, where natural saline water occupies the rock matrix and fractures, the resistivity log profiles become subdued and the profiles are no longer distinctive or characteristic of the lithology. In these situations, sonics density logs and gamma-ray measurements, which are not affected by salinity, can still indicate the geological subdivision and hence structure of the Chalk. Saline water entered the Chalk aquifer either via permeable Palaeogene deposits or directly where Chalk is exposed in the bed of the River Thames, due to excessive groundwater abstraction prior to the 1960s. Areas affected north of the river included the Isle of Dogs, West Ham, Dagenham, Purfleet, and south of the river included Northfleet, Swanscombe, Bermondsey and Deptford.

The effect of elevated pore fluid salinity on resistivity profiles is evident in Figure 3.7 which shows a composite plot of geophysical logs from the Reculver Borehole 1 which was drilled just inside the seawall at Reculver [TR 2295 6938] on the edge of the Thames estuary. The resistivity log profiles showed a zone from -50 m to -125 m OD with lowered values. This coincides with elevated pore fluid chloride content centrifuged from core samples collected during drilling.

The geophysical logs of the confined Chalk at this location illustrate several hydrogeological features of the confined Chalk aquifer near the coast. The borehole allows observation at the end of the onshore groundwater flow system within the accessible part of the confined aquifer which continues under the estuary. The regional groundwater flow is from south to north and continues under the present Thames estuary where the Chalk aquifer dips under increasing thicknesses of Palaeogene sediments. It was drilled on the edge of the estuary in May 1991, to locate a suitable source of brackish groundwater close to the coast for a reverse osmosis plant. It was drilled down to the Melbourn Rock and Plenus Marls at 205 m depth, and penetrated 170 m of Chalk confined by about 35 m of Palaeogene sands and clays. The rest water level was about 1.5 m above mean sea level. The Chalk aquifer is unconfined about 2 km to the east on the Isle of Thanet and more than 10 km to the south in the main recharge area of the North Downs.

Like many Chalk boreholes it was acidised after drilling and testing and this improved the capacity by 400%. The pre- and post- acidisation caliper logs shown in Track 1 in Figure 3.7 are colour infilled (in yellow) to highlight the effect of the acid. The effect appeared to be concentrated above -90 m OD. Resistivity logs recorded after drilling and prior to the acidisation showed low resistivity and featureless profiles from -50 to -125 m OD (Track 2). This coincided with a zone of increased chloride content in pore fluids centrifuged from core samples (Track 5). The higher pore fluid salinity was due to saline intrusion and was confirmed by isotopes to be of probable Holocene age (Smedley et al., 2003); whilst lower salinity and higher resistivity above -55 m OD represents modern refreshing of the Holocene saline body where the fissuring and present day throughflow is most concentrated.

Comparison of resistivity log profiles from South Downs (Padnall Grange) and North Downs.
 Logs are aligned on base Lewes Nodular Chalk, and depths (metres) are correct only for Padnall Grange Borehole



GM1 and GM2 = Glynde Marls; SM = Southerham Marl

Figure 3.6 Typical resistivity log profiles for the Chalk from the South Downs and the North Downs, from south to north.

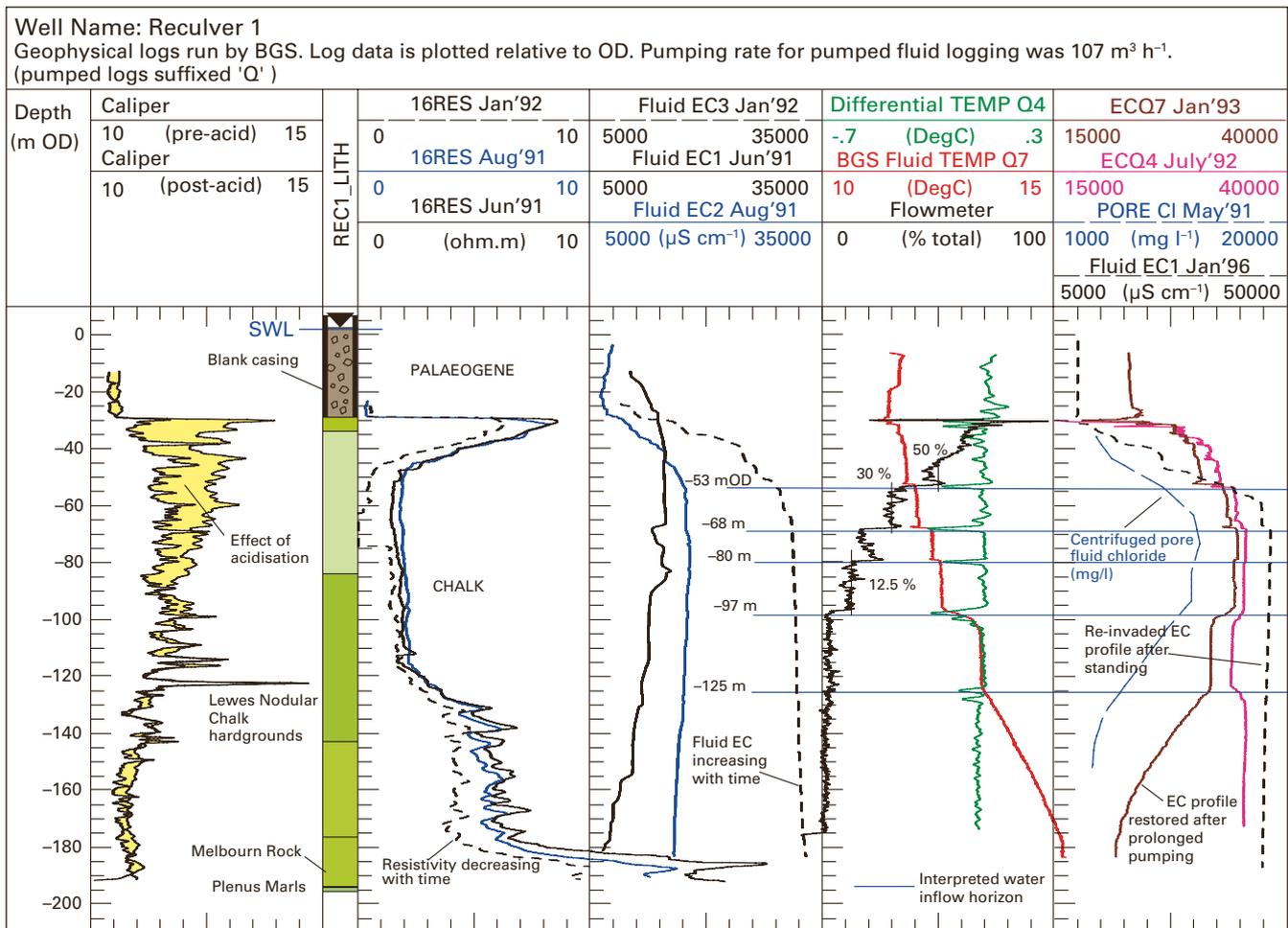


Figure 3.7 Composite plot of geophysical logs from the Reculver Borehole 1.

Resistivity logs (16RES) run on different occasions (Track 2) showed a reducing resistivity with time which was matched by an increasing borehole fluid EC (EC1-3, Track 3). This was believed to be due to the brackish water entry into the borehole and density-settling below -55 m OD. The borehole was later test pumped for six months during which fluid and flowmeter logging identified fluid entries by stepwise reduction in fluid temperature and fluid EC alongside the flow horizons. These water entries clearly cooled and freshened the borehole fluid as it moved up to the pump.

Flowmeter logs recorded that about 70% of the total pumped water was obtained from above -55 m OD. The fluid TEMP log profile suggested groundwater movement was taking place down to -125 m OD below which groundwater was either immobile or moving very slowly and not disturbing the geothermal gradient. Sampling and isotopic testing showed that this slowly moving water was of probable Pleistocene age. The younger groundwaters were generally moving above a prominent hardband, the Dover Top Rock horizon.

The fluid logging at intervals during the test pumping documented a progressive change in the fluid EC profile (Track 5) and the eventual restoration of the original tripartite zonation shown by pore-fluid chloride measurements, as the invaded water was recovered by the pumping. Logging again some three years after the test pumping (Fluid EC1-01/96 Track 5) demonstrated re-invasion and displayed relatively constant borehole fluid salinity below -55 m OD.

The local geological structure also influences the salinity distribution and the seaward flow of groundwater. Several boreholes drilled in the area early last century for coal exploration identify the base of the Chalk and the Plenus Marls horizon. Figure 3.8 shows a down-dip cross-section of the confined Chalk aquifer based on the existing borehole information and geophysical logging data which reveal plunging anticlinal and synclinal folding parallel to the coastline. The folding interrupts and diverts the seaward regional groundwater flow away from the area. As a consequence there has been restricted refreshing of the Holocene inundation north of the anticline. This is evident from the elevated fluid EC values seen in the boreholes north of the structure compared to the fresher waters found in boreholes located to the south of the structure (boxed values, Figure 3.8). Folding parallel to the coastline which influences the seaward or basinward flow of groundwater, is a feature affecting the Chalk of coastal regions of southern England. It influences the course and extent of saline intrusion in coastal areas of both the South Downs and the North Downs (Jones and Robins, 1999). High yielding boreholes can sometimes be located up gradient of these structures. The folding also represents a partial barrier preventing sea-water from advancing further inland, except where drainage has cut through the structures, and the river valleys become the focus for saline intrusion.

The water inflow horizons identified by studies in the Reculver boreholes are at similar elevations as water inflows observed in boreholes at Oare Creek, Sittingbourne

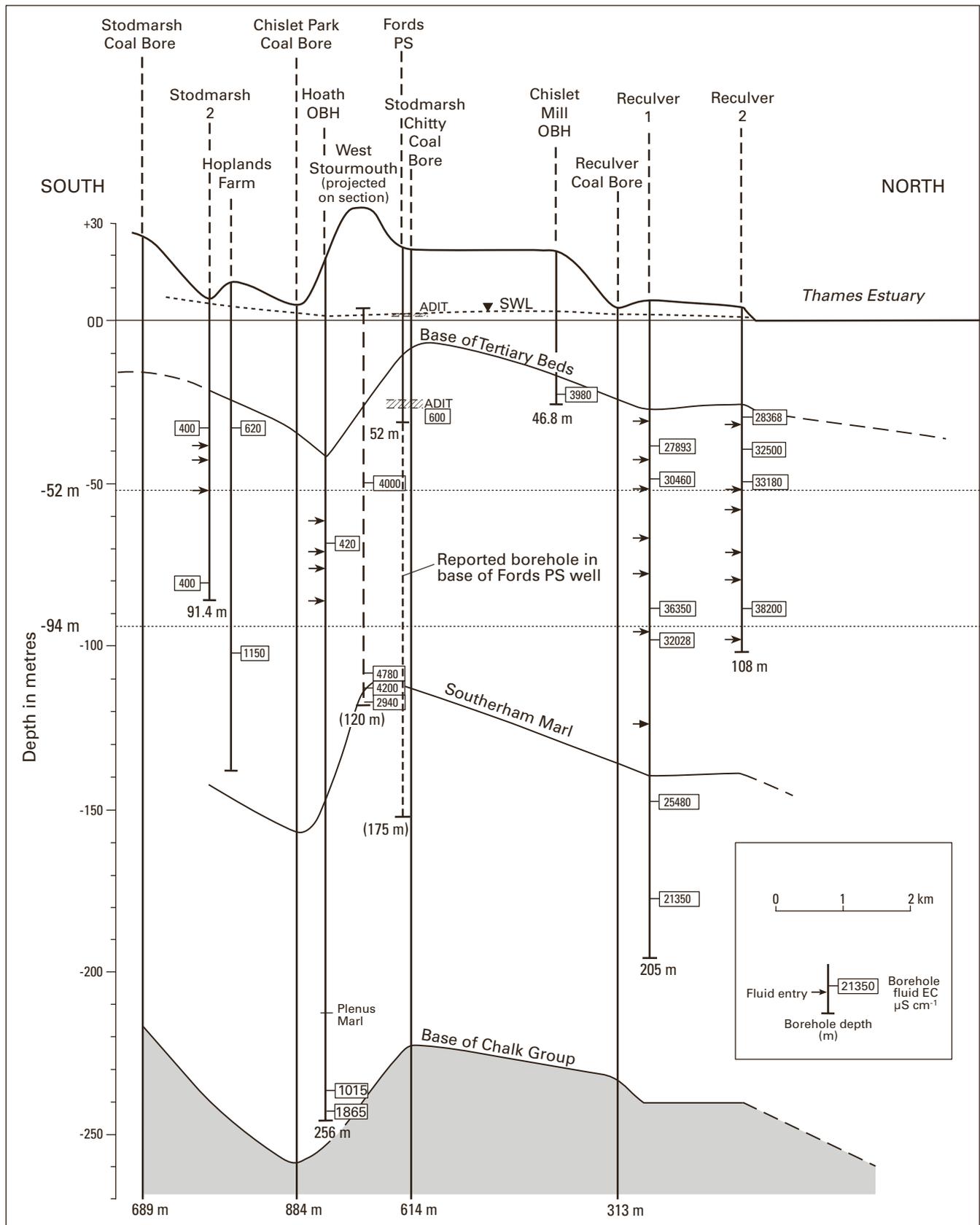


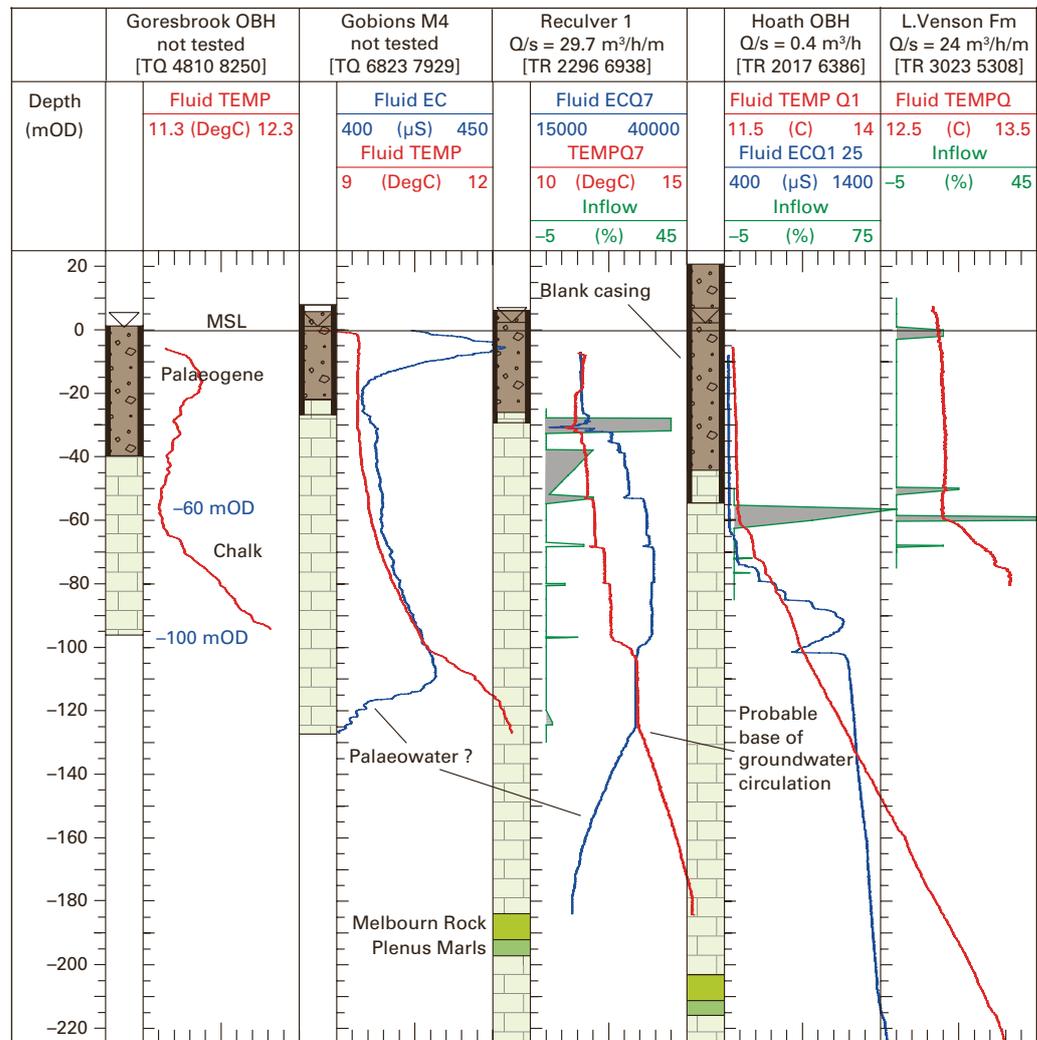
Figure 3.8 Geological structure and fluid entry levels identified from geophysical logs, north Kent.

and Lower Halstow which also penetrate confined Chalk adjacent to the Thames estuary. Figure 3.9 is a compilation of fluid logs from a selection of boreholes both north and south of the estuary drawn to illustrate this relationship. In each of these boreholes the coolest groundwater and lowest fluid EC is generally present above -60 m OD and

-100 m OD, whilst at greater depth temperature increases steadily, demonstrating little or reduced groundwater circulation taking place below.

Interpretation of seismic survey and drilling results enabled Bridgland and d'Olier (1995) to identify buried channels in the Thames estuary which indicate a former

Figure 3.9 Fluid logs of selected boreholes adjacent to the Thames estuary.



drainage pattern (Figure 3.10). It is believed that these deeper outlets were developed during the Pleistocene glaciations when sea level was as much as 130 m lower than at present. The morphology of the River Stour drainage suggests it formerly drained into the extended basin to the north-east, but was subsequently captured by east-west drainage. This may have been related to the breaching of the channel land bridge. The buried channel contours reveal that the local base level for this earlier river and groundwater circulation must have been approximately -60 m OD maximum. Further east, channel maximum depths in excess of 100 m are indicated some 10 km off the coast from Dover.

The coincidence of the fluid inflows in the coastal boreholes with the channel depths offshore strongly suggests that the fissure and permeability development seen in the confined Chalk aquifer has been a response to the outlet geometry and the groundwater circulation to outlets at former base levels of about -60 m OD, and further east, near Dover, of -100 m OD. These developed when sea levels were significantly lower during the Pleistocene. The relatively cooler groundwaters present in the Chalk aquifer down to these depths in the boreholes studied, suggest that the current groundwater flow system in the confined Chalk aquifer, is occupying and further developing these earlier flow horizons by circulation to the former base level outlets.

3.6 THE REGIONAL WATER BALANCES

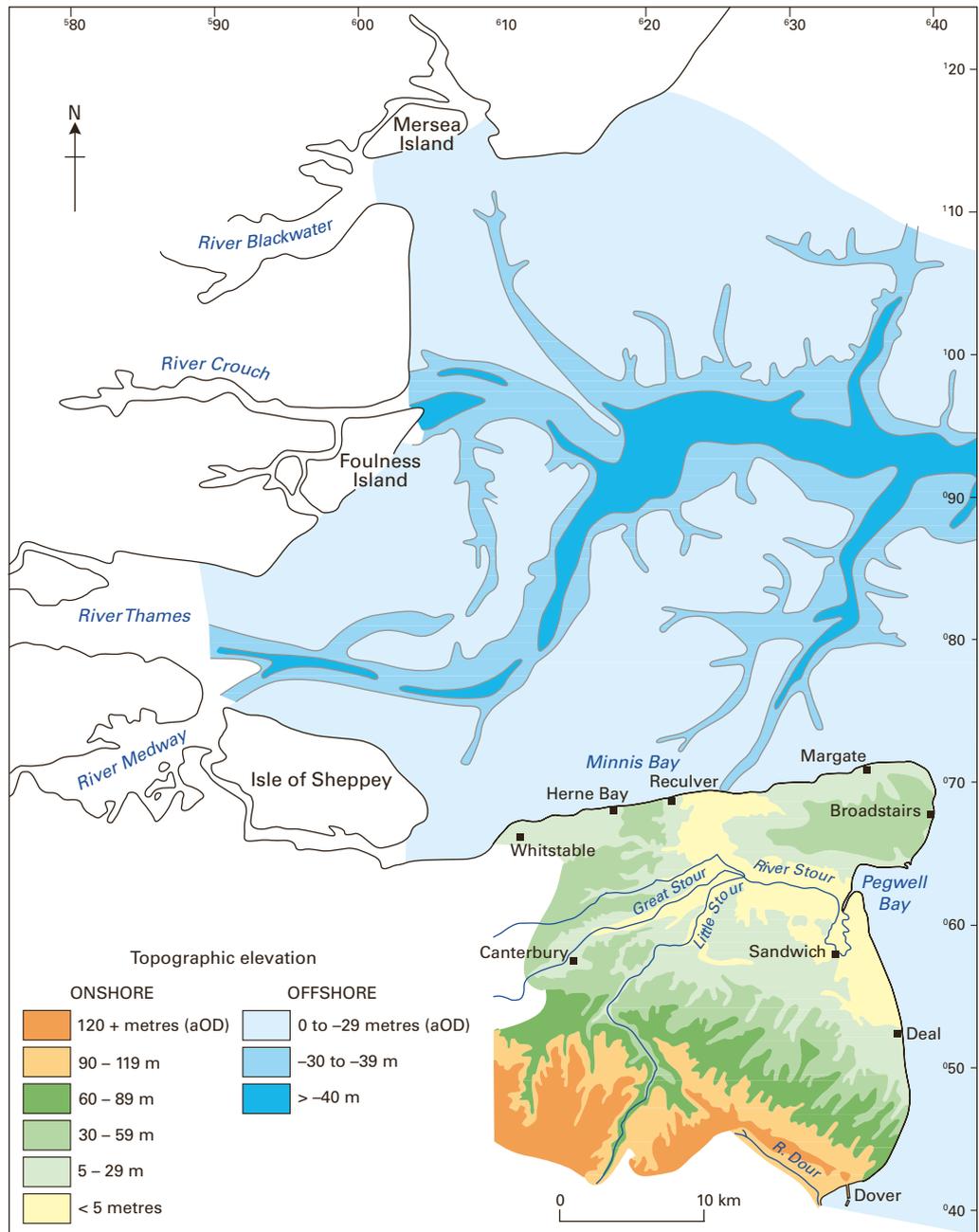
The North Downs comes under the jurisdiction of the Thames and Southern regions of the Environment Agency. The Thames Region of the Environment Agency is responsible for the management of water resources of the Chalk aquifer from the western end of the study area to the boundary of the Ravensbourne catchment with the River Cray (a tributary of the River Darent) in the east (Figure 1.3). The larger area of the North Downs further east is managed by the Southern Region of the Environment Agency.

3.6.1 Thames Region

The Chalk is the most important aquifer in Thames Region and in the North Downs area its importance is no exception. As is the case throughout southern England, the vast majority of Chalk groundwater abstraction is for public water supply. In the North Downs Chalk outcrop area, 29 water company groundwater sources are in operation between the Wey Valley at Guildford in the west to the Upper Ravensbourne Valley in the east. These are licensed for a total of $9.1 \times 10^4 \text{ Ml a}^{-1}$ which averages 250 Ml d^{-1} . In the confined Chalk of the south London basin there are seven public water supply sources licensed for $2.65 \times 10^4 \text{ Ml a}^{-1}$, or 73 Ml d^{-1} .

Other smaller abstractions, mainly in the confined strata, are used for hospitals, laundries, cooling and

Figure 3.10 Buried channels offshore of north Kent (after Bridgland and d'Olier, 1995).



bottling. Very little is used for industrial processes, and this has been the major change since before the 1970s. In the unconfined strata, the majority of recent new licences have been for golf course irrigation.

Water balances have been carried out for all unconfined units along the North Downs of the Thames Region of the Environment Agency (Ingles, 1991). This was a substantial study to estimate the complete water balance for an average year for the North Downs groundwater resources unit. The year chosen was the water year October 1 1985 to September 30 1986. The unconfined Chalk of the North Downs was divided into six sub units:

- River Wey
- Clandon Downs
- River Mole
- River Hogsmill
- River Wandle; and

Upper Ravensbourne.

Combining these six sub-catchments the water balance was calculated as follows:

Recharge	...	...	...	...	+301 Ml d ⁻¹
Mains leakage and inflow from other groundwater units	...	...	...	...	+25 Ml d ⁻¹
Groundwater flow to London basins	...	...	...	...	-111 Ml d ⁻¹
Groundwater flow to rivers	...	...	...	...	-42 Ml d ⁻¹
Actual groundwater abstractions	...	...	...	...	-173 Ml d ⁻¹

This water balance was used at the starting point for the North Downs part of the London Basin Model (see Section 5.3.4). A wide variation in the above figures is seen in other years of different weather and rainfall distribution. It was clear, however, that the resource utilisation had reached the point where dip slope springs had to be frequently artificially augmented and that, in this resource

unit there is now no additional groundwater available for consumptive use.

Catchment Abstraction Management Strategies (CAMS) is a process to look at determining sustainable use of the resources of an area (see Section 5.4). These will provide updates of the water balance for the North Downs.

3.6.2 Southern region

The water balance summary presented in Table 3.1 comprises estimates for Southern Region's three separate aquifer blocks subdivided, where appropriate, into their constituent 'resource areas' (see Section 5.2.2). Levels

of abstraction commitment under average-year rainfall conditions vary from 27% in the Little Stour area to 158% in the West Medway area; corresponding rates of actual abstraction run at 17% and 85% respectively. The picture for extreme drought conditions presented in Table 3.2 is based on the 1989 to 1992 rainfall record and this serves to illustrate the precarious state of resources in the north and north-west where actual abstraction during the three-year period averaged between 85 and 124% of effective rainfall.

The total quantity of water authorised for abstraction from the Chalk for all purposes currently stands at 814 Ml d⁻¹ or approximately 83% of the average annual

Table 3.1 North Downs Chalk aquifer water balance summary: average year conditions in the Southern Region.

Aquifer block	Resource area	Recharge area			Average annual rainfall mm	Potential evaporation mm	Actual evaporation mm	Effective rainfall mm Mm ³		Authorised abstraction			Actual abstraction		
		Un-confined M & U Chalk km ²	Thanet sands km ²	Total recharge area km ²						PWS Mm ³	All uses Mm ³	Balance % commitment	PWS Mm ³	All uses Mm ³	Balance % abstraction
North-west	Darent	216	31	231 ❶	680	575	420	260	60.0	74.2	93.4	156	54.7	60.0	100
	West Medway	113	27	127 ❶	626	540	421	205	26.0	22.0	41.0	158	12.6	22.0	85
North		352	0 ❷	352	650	540	420	230	81.0	50.0	67.0	83	40.0	54.0	67
East	Great Stour	172	0	172	720	525	473	247	42.4	21.6	24.6	58	19.0	20.0	47
	Little Stour	287	0	287	740	525	424	316	90.4	24.2	24.4	27	15.0	15.0	17
	Dour	131 ❸	0	131	810	510	485	325 ❹	42.6	30.1	35.6	83	16.0	16.5	38
	Thanet	86	0	86	580	570	418	162	13.9	10.0	10.6	76	3.4	3.6	26
Totals		1357	58	1386	691	540	434	257	356.3	232.1	296.6	83	160.7	191.1	54

❶ = Chalk + 50% Thanet ❷ = Thanet taken as impermeable ❸ = Including Deal coastal ❹ = From modelled estimates

Table 3.2 The 1989 to 1992 drought: estimated average annual resource commitment (Southern Region, Environment Agency).

Resource area	Average annual rainfall 1989 to 1992 (mm)	Effective rainfall 1989 to 1992 (mm)	Recharge (Mm ³)	Authorised		Actual	
				Abstraction (Mm ³)	% Commitment	Abstraction (Mm ³)	% Take
Darent	632	210	48.5	93.4	193	60.0	124
West Medway	583	155	19.7	41.0	208	22.0	112
North Kent	605	180	63.4	67.0	106	54.0	85
Great Stour	659	182	31.3	24.6	79	20.0	64
Little Stour	683	258	74.0	24.4	33	15.0	20
Dour	750	272	35.6	35.6	100	16.5	46
Thanet	515	90	7.7	10.6	138	3.6	47
North Down Totals	638	202	280.2	296.6	106	191.1	68

effective rainfall. Of this, public supply accounts for 636 Mld⁻¹; about 75%. Overall, actual abstraction in an average year would leave a balance of resources equivalent to 46% of the total natural baseflow yield of the North Downs and under severe drought conditions, such as those encountered in 1989 to 1992, this would fall to less than 30%. Exploitation of the groundwater resource has left a legacy of depleted water-table levels and a progressive deterioration in the flow and biodiversity of important spring-fed streams and wetlands. The Environment Agency is not yet in a position to answer the key question as to the minimum proportion of aquifer resources that needs to be reserved in each instance where there is a requirement to restore and sustain the essential characteristics of the region's Chalk streams. It is unrealistic to envisage a return to wholly natural conditions free of the influence of abstraction but it is accepted as a management objective that there should be a 'reasonable' balance established between water supply demands and environmental objectives. This principle underpins the Environment Agency's strategy for the future management of the aquifer.

Observation of aquifer response to extended drought conditions also prompts questions concerning the resilience and long-term yield of the resource. These aspects have special significance in view of the likely future impact of climate change.

3.7 A CONCEPTUAL MODEL OF GROUNDWATER CIRCULATION IN THE CHALK

Recharge to the Chalk of the North Downs' aquifer occurs across the majority of its outcrop area. It is dominated by winter rainfall when the reduced evapotranspiration allows the soils to reach field capacity and hence recharge to take place. The intensity of the resultant recharge and the pre-existing water content of the Chalk matrix

below the root zone determines the nature of the flow in the unsaturated zone (i.e. piston flow or rapid by-pass flow). Instead of restricting recharge, the presence of low permeability drift cover (such as clay-with-flints on interfluvial areas) can actually act to enhance total recharge to the aquifer. This occurs where a significant proportion of rainfall is deflected as run-off to the edges of the deposits. The soils associated with Palaeogene deposits and clay-with-flints tend to be acidic (Edmunds et al., 1992), therefore, run-off remains undersaturated with respect to calcium until it reaches the Chalk, resulting in a high degree of solution activity. Further recharge may occur by downward leakage from minor aquifers within Palaeogene deposits where these overlie the Chalk.

Figure 3.11 shows a groundwater level contour map of the North Downs. September 1976 groundwater levels have been used to indicate conditions following a significant drought. The map indicates regional groundwater flow directions but does not take account of local groundwater/surface water interaction. Groundwater movement is predominantly in a northerly or north-easterly direction with local variations to the regional flow direction adjacent to the main rivers. Groundwater head can be as much as 40 m different between a valley and the adjacent interfluvial with permeable Chalk extending to a much greater depth beneath valleys (Aldiss et al., 2004). Thus recharge can move rapidly from interfluvial to valley with the interfluvial generally acting as barriers to groundwater flow between adjacent valleys. In the Faversham area, clays in the overlying Thanet Sand Formation confine groundwater in the Chalk, while in the western half of the North Downs, the Thanet Sand Formation is in hydraulic continuity with the Chalk. Further north the groundwater is confined beneath the London Clay, see Figure 3.1. There is also a smaller southerly component of groundwater flow from just north of the North Downs interfluvial, which discharges as spring flow at, or near, the foot of the scarp slope onto the Gault.

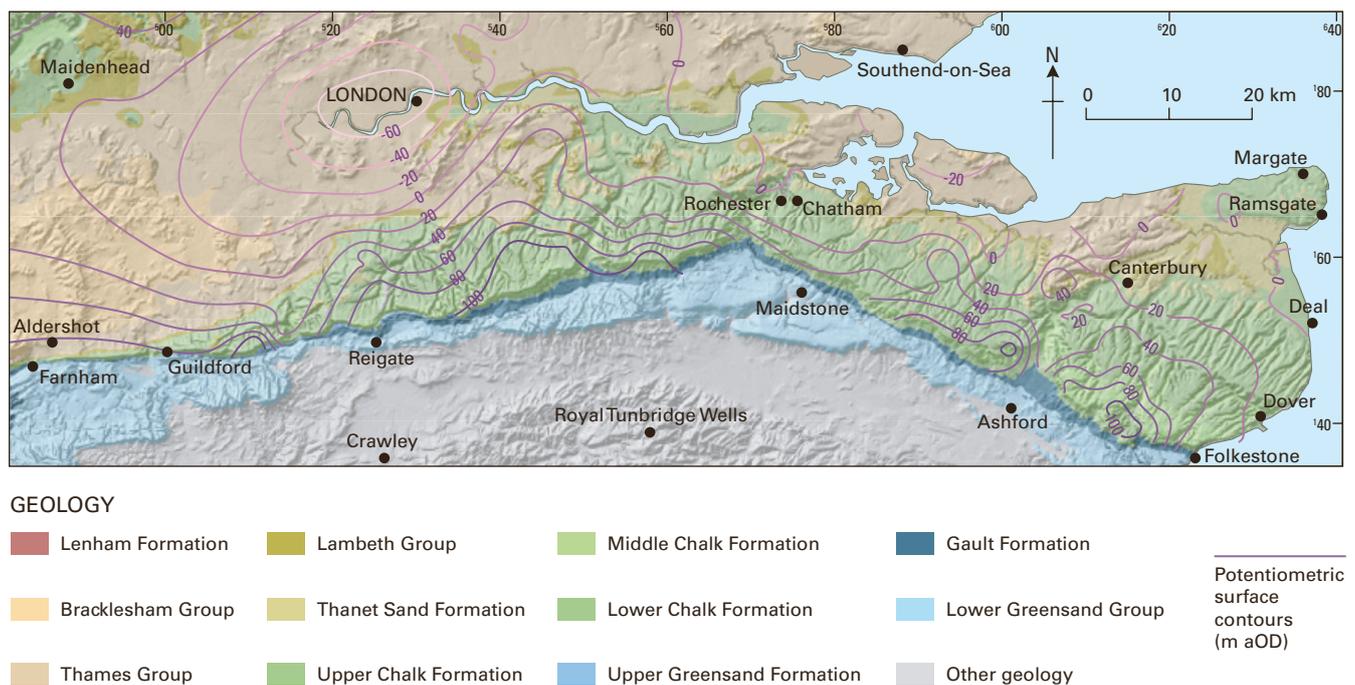


Figure 3.11 Generalised potentiometric surface based on September 1976 groundwater levels. This map indicates regional groundwater flow directions but does not take account of local groundwater/surface water interaction.

Springs and surface flows occur where the water table intersects the land surface. As the water table recedes during the summer months, streams may dry up as the point of discharge of groundwater moves downstream – this is the typical bourne behaviour of Chalk streams. Where the Chalk water table reaches the surface near to the coast, seasonal fluctuations in level are less pronounced and, in many places in North Kent, springs are an important element of the marshland environment, much of which is protected by international conventions and/or European legislation. For rivers that rise south of the North Downs and flow northwards, Chalk groundwater provides a significant baseflow component once the water table intersects the riverbed. Elsewhere, where the riverbed is permeable, river flow can recharge the Chalk aquifer. In some places (e.g. in the Mole and Dour valleys) the existence of swallow holes enhances this recharge effect.

Where there is a significant dip of the strata, it is expected that the groundwater may follow that horizon down-dip for a certain distance. Then it tends to step up, via fractures and faults, and develops permeability by circulation en route to the nearest lowest outlet where it can discharge to surface water. This effect is seen in Figure 3.12, where the zone of permeability development moves up-sequence from the Lewes Nodular Chalk in the Well House Observation Borehole to the Seaford Chalk in the Woodcote Borehole over a distance of approximately 6 km. The development of permeability, therefore, relates to both the lithology (layering) and local discharge elevations.

The tendency to develop permeability at shallow depth is also the reason why groundwater flowing down-dip in the Chalk tends to go around synclinal fold structures rather than develop permeability at greater depth under the structure containing lower permeability material, (e.g. London Clay). If the sediments overlying the Chalk contain permeable material then flow will preferentially take place within the Palaeogene sediments instead of in the Chalk. This is sometimes evident on temperature logs where a thick Palaeogene sequence above Chalk is cased out, and cooler fluid temperature can be observed in the casing opposite the sandier (lower gamma ray) layers denoting the groundwater circulation within them. Anticlinal folding parallel to the coastline south of Reculver acts as a barrier to groundwater flow from the south.

Downhole logging, video inspection and imaging of borehole walls show that openings at depth where groundwater movement takes place in the Chalk are few, and are generally at the surfaces of discontinuities. These can be at the surface of flint bands, at marl seam contacts and particularly associated with the surfaces of hardbands and nodular chinks. Videoscans and CCTV surveys of Chalk boreholes reveal that there are very few open fractures below water table, and the water inflows identified are solution openings associated with proximity to hardband surfaces and flint bands or intersecting fractures, and are usually less than 5 mm wide. Although the solution openings are small, flow logging shows they are the features responsible for the overwhelming bulk of fluid inflow when boreholes are pumped.

Because the Chalk is soluble, groundwater flow tends to develop permeability by solution. As a consequence the permeable horizons tend to be concentrated at shallow levels and develop from the top downwards. It would seem from observation that current recharge could probably be dissipated by groundwater flow within a relatively thin interval of Chalk, close to the water table. Hence the permeable horizons sometimes encountered in sandstone/mudstone sequences at great depth, even in tilted and folded strata, are not normally found in the Chalk. Instead the deepest inflows are permeable horizons which have developed in a narrow zone associated with shallow groundwater flow to the rivers and streams. The maximum depth of the inflows would appear to be controlled by the outlet elevations when the static water levels were deeper (down to about –130 m OD) during the Pleistocene cold periods. The development of permeable horizons in the Chalk is, therefore, closely linked to the groundwater flow system history, and particularly the influence of the Pleistocene climate and the accompanying changes in local and regional base levels, see Figure 3.10.

This conceptualisation of groundwater flow in the North Downs is also supported by study of the hydrochemistry of the area which is discussed in detail in Chapter 4 and in Smedley et al. (2003). Groundwaters evolve from compositions consistent with modern recharge in the unconfined aquifer of the North Downs area towards older groundwaters in the confined near-coastal aquifer.

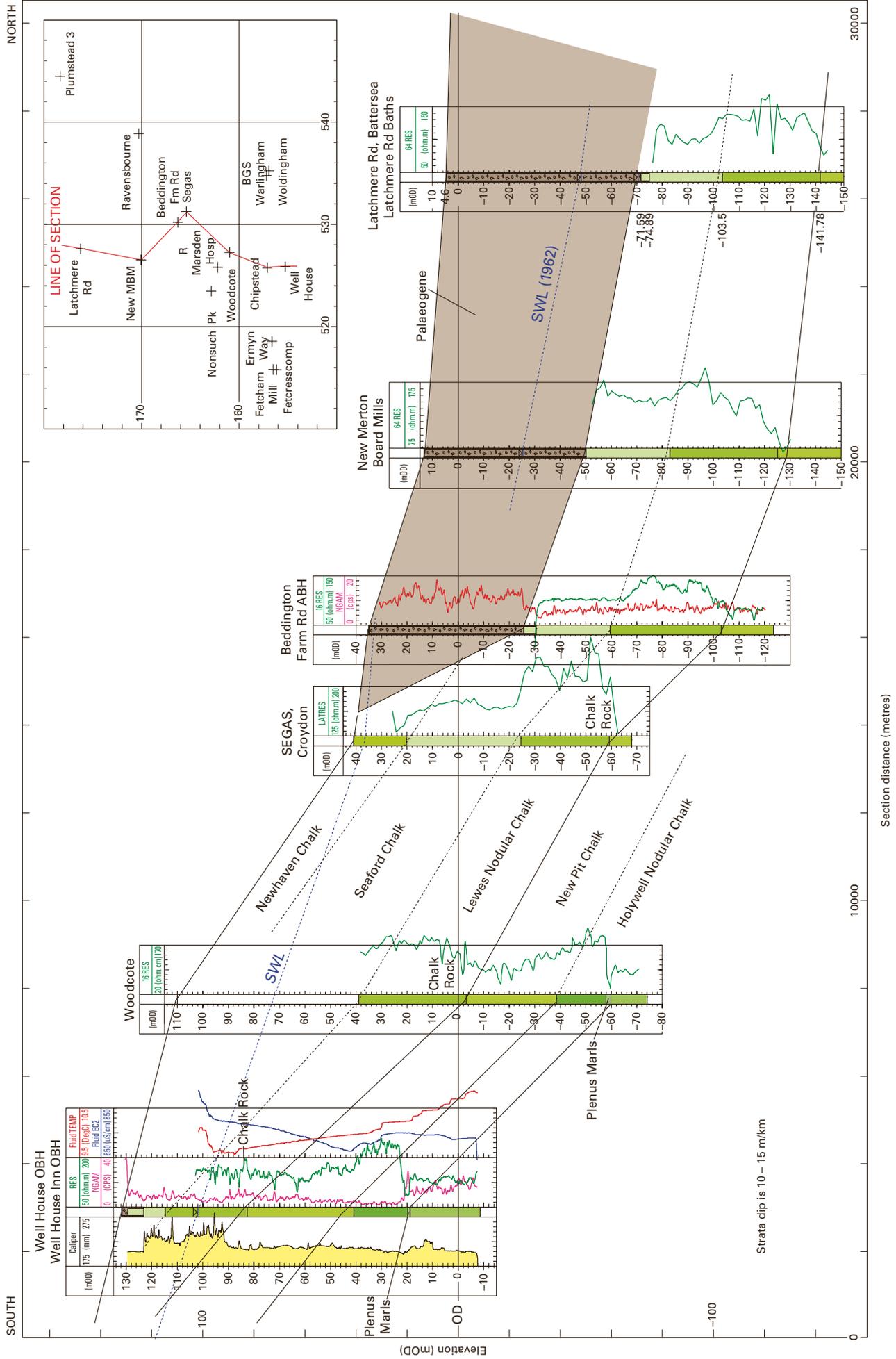


Figure 3.12 Cross-section from Well House Borehole down dip to Latchmere Road Borehole.

4 Groundwater chemistry

4.1 INTRODUCTION

The geochemistry of groundwaters from the Chalk of the North Downs is described using compiled data from archived BGS, water company and Environment Agency databases. Most available chemical analyses are of pumped groundwaters representing compositions integrated over a range of depths. However, a limited number of bailed samples and extracted porewaters from discrete depths are also available and have been described where appropriate. BGS data are compiled from distinct studies in the Sheppey–Sittingbourne and Reculver areas, aspects of which have been discussed by Edmunds and Milne (1999) and Edmunds et al. (2001). Data used from the water companies (Southern Water, Thames Water, Folkestone & Dover Water Company) and the Environment Agency are for raw groundwater sources from a number of pumping stations in the region. Data provided by these organisations were usually multiple analyses of given sources ranging over the period 1990 to 2000, with varying numbers of both samples and analytes. Where multiple analyses were available, average values have been produced and much of the following discussion considers these averaged values for such sites. For a more detailed discussion of the chemistry of the groundwater of the North Downs, reference should be made to Smedley et al. (2003).

The chemical compositions of the groundwaters are controlled by a number of factors, the principal one being carbonate reaction, which is rapid and leads to strongly buffered groundwater compositions. As the northern section of the North Downs aquifer along the estuarine and coastal margin is confined respectively by Palaeogene sediments of the Thanet Sand Formation and the London Clay Formation, groundwaters in this section become confined and redox processes thus become an important control on the water chemistry. The effects of saline intrusion are also observed in some estuarine and coastal sites. As most abstraction for public supply and industrial use is from the unconfined chalk aquifer, groundwater pollution from agricultural and industrial sources is also an important issue in some areas. Nitrate, pesticides and organic solvents have been detected in some abstraction sources and are monitored closely by the Environment Agency and the water companies. Although coal mining operations ceased in the region in 1988, minewater discharge from the Tilmanstone and Snowdon collieries has left a local residue of contaminated saline water in the Chalk aquifer which has still not fully dissipated (Box 4.1 and Section 5.3.1). In addition, as with other parts of the Chalk of southern Britain, geological structure and weathering patterns have been influential in controlling groundwater flow and flow rates. These have resulted in chemical variations, both laterally and with depth, particularly in the confined near-coastal parts of the aquifer.

4.2 REGIONAL HYDROGEOCHEMISTRY

4.2.1 Major-element variations

Recharge to the Chalk aquifer of Kent occurs over the North Downs outcrop area and infiltrating groundwaters

reach rapid equilibrium with the chalk matrix. These therefore take on the chemical characteristics of carbonate-dominated groundwaters. Most are saturated or near-saturated with respect to calcite and the pH values are buffered at near-neutral compositions. The groundwaters have typically high total hardness and high Ca concentrations. The range of Ca in the outcrop groundwaters is 90 to 160 mg l⁻¹, with a more variable

BOX 4.1 TILMANSTONE AND SNOWDON COLLIERY DISCHARGE

Discharge of mine water from Tilmanstone and Snowdon collieries in the Kent coalfield via lagoon seepage to the unconfined Chalk has resulted in more than 30 km² of the aquifer becoming contaminated with saline water (Bibby, 1981; Headworth et al., 1980; Carneiro, 1996). The discharge to the Chalk began in 1907 and has been most serious from the Tilmanstone Colliery where discharge to lagoons continued until 1974, at which point a pipeline was constructed to transport the mine effluent directly to sea. An estimated 358 000 tonnes of chloride (Cl) had infiltrated the aquifer (Carneiro, 1996), with only a limited amount (around 15%, Headworth et al., 1980) having been subsequently discharged from the aquifer. During the 1970s, test pumping of a borehole at Eastry and two other borehole sites close to the points of mine discharge revealed concentrations of Cl at shallow levels in the aquifer up to 3000 mg l⁻¹. Concentrations diminished slightly with greater distance from the plume source and with depth. The quality of water at Wingham Pumping Station was also affected by contamination from Snowdon, with observed Cl concentrations reaching in excess of 300 mg l⁻¹ during the 1930s (Bibby, 1981). By 1996, the maximum concentration of Cl in the groundwater plume was around 1000 mg l⁻¹ (SO₄ up to 200 mg l⁻¹) and the plume was estimated to be 100 m thick (Carneiro, 1996).

Surface water quality has also been severely impaired in both the north and south streams, some 6 km north-east of Tilmanstone. These each receive a significant proportion of baseflow from the contaminated part of the aquifer. Water from the north and south streams has been monitored regularly since 1973 (Carneiro, 1996). A range of parameters was also measured in the three observation boreholes at Thornton Farm, Venson Farm and Eastry by the NRA in 1995. Complete analyses for major cations and anions have been made by Buchan (1962), Oteri (1980), Peedell (1994) and Hazell (1998). The impaired quality of groundwater in the Chalk of east Kent has persisted, particularly in the area affected by discharge from Tilmanstone colliery. However, conditions have been gradually improving since the 1970s (see Section 5.3.1). At Wingham Pumping Station, Cl concentrations were around 45 mg l⁻¹ in 1998 and by 2006, the concentration was close to an estimated baseline (pre-contamination) value.

range in the groundwaters affected by saline intrusion. Alkalinity values are variable but are also relatively high with a range around 160 to 343 mg l⁻¹ at outcrop, increasing to in excess of 400 mg l⁻¹ in the confined groundwaters.

Magnesium values typically range between 2 and 7 mg l⁻¹ in the outcrop zone. Representative analyses of groundwaters from the Sittingbourne–Canterbury areas are given in Table 4.1 and Table 4.2.

Table 4.1 Representative analyses of Chalk groundwater from the Sittingbourne–Canterbury areas, north Kent (BGS data). Groundwaters are pumped except where indicated as bailed depth samples.

Sample	Easting	Northing	Well depth* m	Temp °C	pH µS cm ⁻¹	SEC mg l ⁻¹	DO mV	Eh mg l ⁻¹	Ca mg l ⁻¹	Mg mg l ⁻¹	Na mg l ⁻¹	K mg l ⁻¹	HCO ₃ mg l ⁻¹	SO ₄ mg l ⁻¹	Cl mg l ⁻¹	NO ₃ -N mg l ⁻¹	NO ₂ -N µg l ⁻¹	NH ₄ -N mg l ⁻¹	
Unconfined aquifer																			
971410	58472	16772		12.1	7.18	524	9.8	345	111	4.91	11.8	1.98	297	17.17	20.3	1.64	<5	<0.01	
971412	57776	16940		12.7	6.97	2030	0.9	347	161	27.1	245	14.15	322	115	392	13.2	5	<0.01	
971417	58216	16750		17.0	6.87	811	3.9	352	146	5.67	29.4	5.16	337	84.6	40.9	6.6	<5	<0.01	
971419	57798	16554		11.5	7.12	657	7.0	269	124	2.54	13.4	1.92	343	7.37	22.4	6.2	<5	<0.01	
971420	58397	16543		12.0	6.98	635	6.4	291	123	3.67	15.3	2.76	329	15.7	26.5	7.3	<5	<0.01	
971422	56630	16618		11.4	7.04	480	7.1	244	111	2.03	8.9	1.56	312	4.74	15.2	4.1	<5	<0.01	
971423	57768	16625		12.0	7.03	691	7.0	331	130	3.00	22.8	2.80	322	24.4	34.5	11.0	8	<0.01	
961270	62090	16139	5	11.9	7.31	590	7.1	364	96.8	4.89	15	1.87	293	9.22	24.3	3.0	<2	<0.01	
971425	60173	16360	110	11.7	7.17	511	7.8	255	113	2.62	10.5	1.44	321	5.71	18.6	3.6	<5	<0.01	
971426	60129	16471		12.7	7.06	547	0.3	221	110	4.85	10.6	1.63	329	14.8	16.7	0.33	<5	<0.01	
Confined aquifer																			
971413	59085	17204	64	15.6	7.05	921	<0.1	153	102	37.8	37.4	16.93	394	91.3	50.7	<0.01	<5	0.56	
971414	58760	16780		13.5	7.03	654	<0.1	174	98.6	17.3	14.6	3.79	336	36.4	23.8	<0.01	<5	0.02	
971415	59118	17469	170	15.8	7.83	1100	<0.1	73	299	17.8	176	16.24	354	127	87.0	<0.01	5	0.78	
971416	59113	17528		16.1	8.05	1010	<0.1	396	15.7	7.72	188	11.33	287	148	73.5	0.03	<5	0.85	
971424	58299	16845		16.9	7.11	1850	0.1	226	127	25.7	231	5.01	271	101	393	0.18	<5	<0.01	
961263	62015	16387	80*		7.57	812			40.1	18.2	96.8	9.22	361	37.7	48.5		<2	0.24	
961265	62015	16387	90*		7.59	824			40.5	18.8	96.3	9.49	361	38.3	49.9		<2	0.31	
961268	62015	16387	105*		7.98	1860			16.8	14.4	384	9.56	382	112	370		<2	0.55	
961267	62015	16387	115*		8.10	2120			13.9	12.4	443	9.50	393	126	440		<2	0.27	
961264	62015	16387	150*		8.12	2120			13.3	12.2	467	9.55	377	130	450		<2	0.28	
961266	62015	16387	240*		8.16	2320			12.0	11.2	495	9.09	384	135	510		<2	0.34	
961269	62055	16170		12.8	7.17	623	<0.1	334	91.8	12.1	22.8	4.52	306	24.2	26.3	0.42	<2	<0.01	
961273	62033	16545	51.8	12.1	7.21	1510	<0.1	306	97.8	30.20	173	10.8	332	84.5	270		<2	0.08	
930379	62287	16936	205	12.9	6.80	26200	0.1	50	337	599	4980	163	467	1059	9040	<0.2		3.35	
960123	62350	16940	100	12.2	6.90	26800	<0.1	112	399	689	5820	175	493	1140	10700	<0.3	<3	4.40	

* Indicates depth of bailed sample. DO: dissolved oxygen; SEC: specific electrical conductance (25°C).

Table 4.2 Representative analyses of selected trace elements in Chalk groundwaters from the Sittingbourne–Canterbury areas (BGS data). Groundwaters are pumped except where indicated as bailed depth samples (see Table 4.1 for depths).

Sample	Si mg l ⁻¹	Ba µg l ⁻¹	Sr µg l ⁻¹	Fe _T µg l ⁻¹	Mn µg l ⁻¹	B µg l ⁻¹	I µg l ⁻¹	Br mg l ⁻¹	F mg l ⁻¹	Cr µg l ⁻¹	Co µg l ⁻¹	Ni µg l ⁻¹	CU µg l ⁻¹	Zn µg l ⁻¹	Mo µg l ⁻¹	Cd µg l ⁻¹	Pb µg l ⁻¹	U µg l ⁻¹
Unconfined aquifer																		
971410	6.2	73	460	93	4.2	44	1.4	0.07	0.24	0.14	0.13	2.87	1.10	6.3	0.26	<0.05	0.13	0.38
971412	6.2	69	509	160	13	186	60	1.40	0.18	<0.11	1.64	6.61	0.50	7.7	<0.3	<0.09	0.38	1.17
971417	4.5	45	308	<6	<1.2	92	15.1	0.15	0.14	<0.06	0.20	2.40	2.88	354	0.18	0.08	0.94	0.80
971419	5.4	39	250	<6	<1.2	17	4.3	0.08	0.08	0.22	0.42	15.03	3.56	296	<0.2	0.17	0.82	0.28
971420	5.5	47	279	<6	<1.2	19	3.8	0.08	0.10	0.28	0.51	9.35	13.75	6.7	<0.2	<0.06	0.36	0.50
971422	5.2	30	219	<6	<1.2	<12	2.9	0.06	0.10	0.26	0.47	8.68	4.00	<2	<0.2	<0.06	0.26	0.30
971423	5.6	41	266	<6	<1.2	46	5.1	0.10	0.07	0.20	0.15	2.01	4.64	7.0	<0.1	<0.05	0.39	0.35
961270	6.3	31	590	<6	<1.2	33	4.9	0.10		0.18	0.22	4.59	0.98	7.9	0.18	0.07	0.07	0.35
971425	4.2	57	298	<6	<1.2	<12	2.3	0.04	0.15	<0.21	0.44	9.25	0.48	47.6	0.22	<0.06	0.17	0.46
971426	4.6	129	1000	<6	1.5	12	2.9	0.56	0.40	<0.21	0.47	10.64	0.51	6.5	0.61	<0.06	0.09	1.26
Confined aquifer																		
971413	6.3	45	3310	2470	74	74	8.1	0.17	0.16	<0.06	0.18	1.05	0.18	8.1	<0.1	<0.05	0.05	0.07
971414	5.7	68	2640	490	6.8	35	16.5	0.08	0.54	<0.06	0.08	1.72	<0.04	39.2	0.22	<0.05	0.04	<0.05
971415	4.8	28	1700	260	18	153	20.4	0.24	0.35	<0.06	0.03	0.38	0.14	<2	0.43	<0.05	0.13	<0.05
971416	4.5	25	846	87	21	146	9.4	0.26	0.89	<0.06	<0.02	0.14	0.55	<2	<0.1	<0.05	0.10	<0.05
971424	5.6	66	834	120	26	88	9.6	1.50	0.21	<0.11	0.21	2.71	1.25	32.9	<0.3	<0.09	0.23	0.66
961263	11.3	55	3640	330	11	309	29.7	0.21		0.12	0.15	1.55	1.41	19.2	0.41	<0.04	0.11	0.01
961265	11.6	54	3870	230	10	322	33.1	0.20		0.08	0.09	1.08	0.60	14.6	0.44	<0.04	0.05	<0.01
961268	6.7	39	2950	46	3.2	1348	196	1.38		0.47	0.06	0.83	1.12	2.7	0.43	<0.04	0.04	<0.01
961267	6.1	37	2550	41	2.3	1562	227	1.52		0.49	0.05	0.63	0.97	3.9	0.30	<0.04	0.06	0.02
961264	5.7	38	2510	25	1.8	1604	237	1.53		0.57	0.04	0.42	0.72	4.3	0.32	<0.04	0.05	<0.01
961266	5.1	29	2340	10	<1.2	1712	268	2.17		0.56	0.06	0.50	1.11	5.0	0.38	0.07	0.05	0.01
961269	9.7	72	2330	<6	<1.2	73	5.7	0.10		1.34	1.32	12.9	0.71	5.5	2.28	<0.04	<0.03	0.61
961273	9.1	41	3950	22	12	283	27.8	1.06		0.22	1.51	9.20	2.60	12.7	1.51	0.05	0.38	0.41
930379	8.3	33	15500	1430	32	2239			2.20									
960123	8.8	25	15700	1350	38	2480	280	36.50	1.17	9.08	1.62	17.45	4.16	34.4	1.34	<0.06	0.43	0.01

Most of the groundwaters have low Na and Cl concentrations but these increase appreciably in the estuarine/coastal areas where saline intrusion has occurred (e.g. Figure 4.1). Baseline concentrations of Na are typically 10 mg l⁻¹ or less and Cl typically less than 20 mg l⁻¹. However, in the near-coastal groundwaters of Reculver, near Herne Bay [TR 235 694], they each reach in excess of 5000 mg l⁻¹ (Figure 4.1; Table 4.1). Sodium and chloride also increase as a result of pollution in some outcrop areas, and concentrations of each element in excess of 50 mg l⁻¹ are not uncommon. Saline intrusion also has an impact on several other major elements, with increased concentrations of Mg, K and SO₄ in the more saline groundwaters (e.g. Figure 4.2).

Some increases in K and SO₄ above regional background levels (1.5 mg l⁻¹ and 18 mg l⁻¹ or less respectively) are also observed in fresh groundwaters from the outcrop, particularly in the north-west. These may be related to

pollution. A number of landfills in the area in particular may have contributed towards the increased concentrations of these elements.

Groundwaters from the unconfined aquifer are generally aerobic with observed concentrations of dissolved oxygen up to saturated values (around 10 mg l⁻¹) and redox potentials (Eh values) often in excess of 300 mV (Table 4.1). Under such conditions, nitrate, derived naturally from the soil zone but enhanced by pollution from agricultural and other sources, persists and often reaches values close to or in excess of the EC MAC of 11.3 mg l⁻¹. The regional distribution of NO₃-N concentrations (averaged values) is shown in Figure 4.3. In the outcropping area, values of NO₃-N in excess of 6 mg l⁻¹ are typical, but are lowest (often less than 4 mg l⁻¹) in the central North Downs (Throwley to Nashenden), perhaps reflecting smaller applications

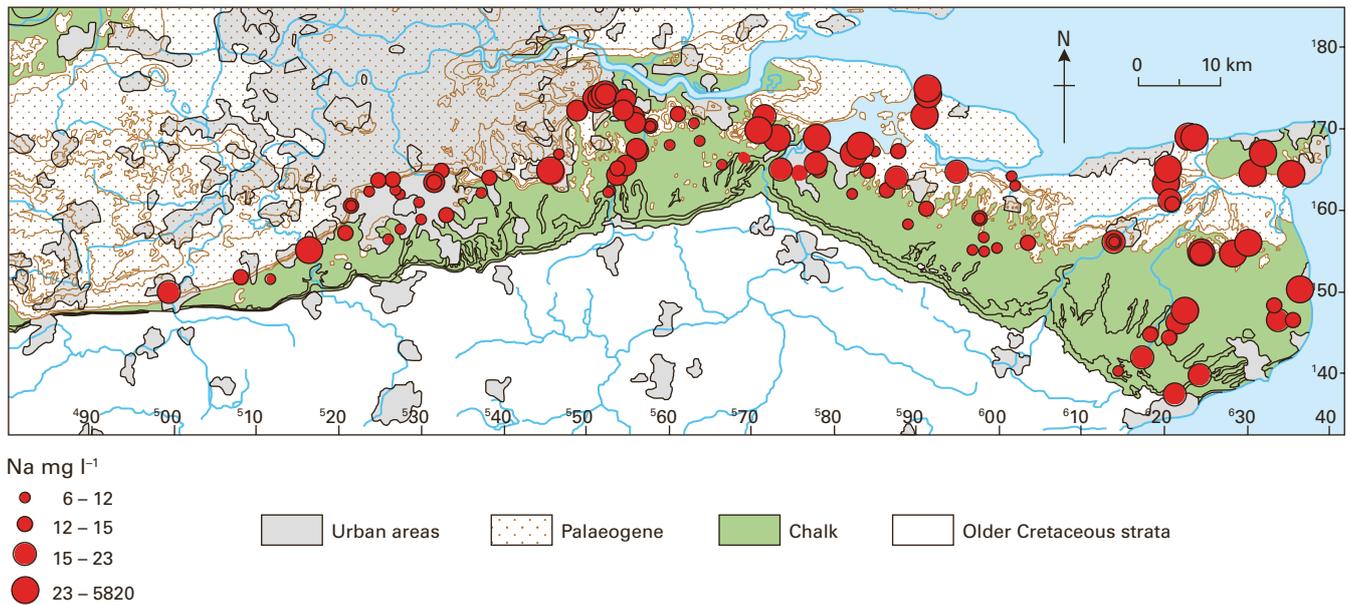


Figure 4.1 Regional distribution of Na in the North Downs Chalk groundwaters (values averaged where more than one analysis was available and concentration classes represent rounded quartiles).

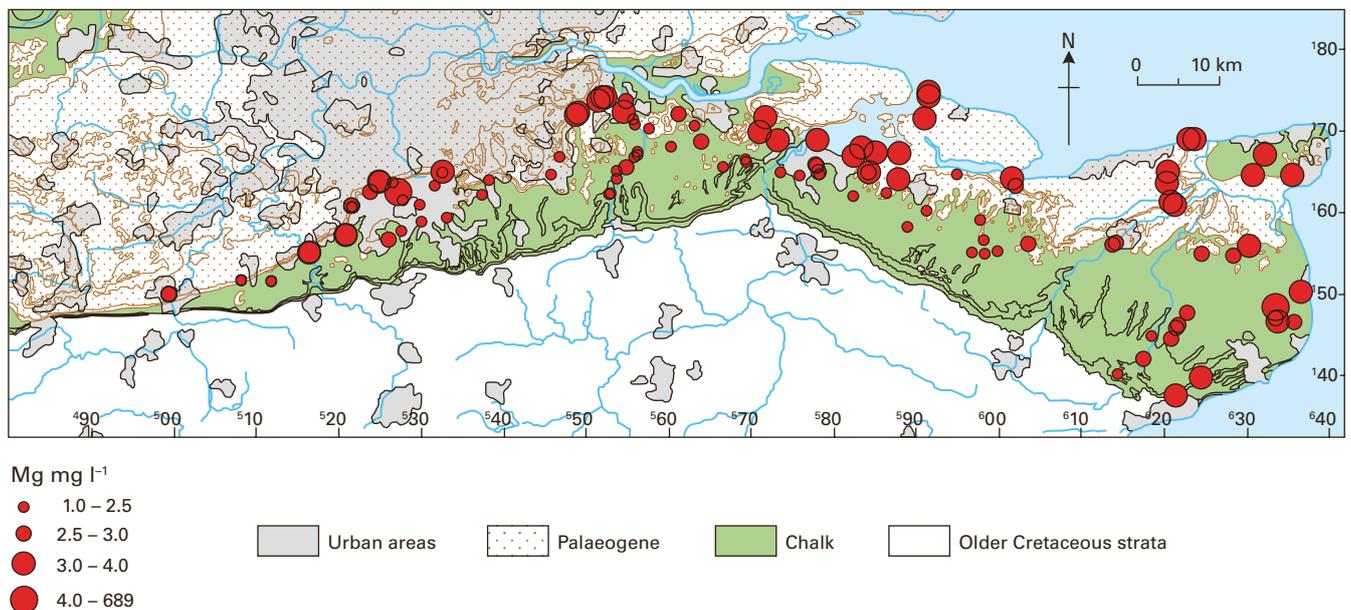


Figure 4.2 Regional distribution of Mg in the North Downs Chalk groundwaters (values averaged where more than one analysis was available).

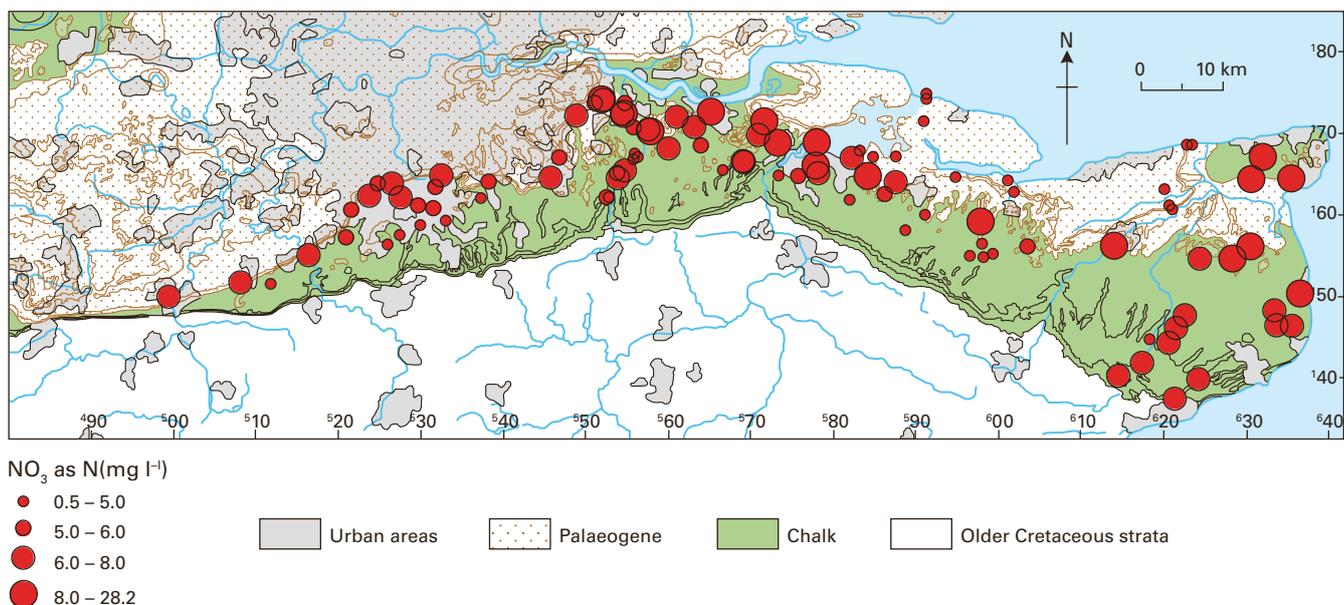


Figure 4.3 Regional distribution of $\text{NO}_3\text{-N}$ in the North Downs Chalk groundwaters (values averaged where more than one analysis was available and concentration classes represent rounded quartiles).

of agricultural nitrate and lower inputs of urban pollutants.

In the unconfined groundwaters, concentrations of nitrite ($\text{NO}_2\text{-N}$) and ammonium ($\text{NH}_4\text{-N}$) are low and most frequently below analytical detection limits. These are typically less than $2 \mu\text{g l}^{-1}$ and less than $20 \mu\text{g l}^{-1}$ respectively.

Relatively few data are available from the confined aquifer of north Kent, but from available sources, groundwaters below the Palaeogene cover become progressively more reducing with low or no detectable dissolved oxygen and redox potentials of typically less than 200 mV. Under these conditions, nitrate concentrations diminish significantly (either due to denitrification or pre-modern recharge). Nitrite concentrations remain low in the confined aquifer, but concentrations of ammonium increase and in some cases, the increase is considerable. A value of $4.4 \text{ mg l}^{-1} \text{ NH}_4\text{-N}$ was detected in Reculver No. 2 Borehole (Table 4.1). This is considered to be naturally-derived, rather than as a result of local pollution.

4.2.2 Trace-element variations

Analysed trace elements also demonstrate the prominent effects of carbonate reaction, redox processes and saline intrusion. Pollution is also likely to have affected the concentrations of many trace elements, though the significance and the sources are difficult to quantify and to distinguish from other processes.

One of the main trace elements controlled by carbonate reaction is Sr. This varies between 200 and $300 \mu\text{g l}^{-1}$ in the groundwaters at outcrop but reaches up to 16 mg l^{-1} in the confined near-coastal aquifer (Reculver; Table 4.2). Increases in Sr concentration can also be related to saline intrusion, but since Sr in sea-water has a concentration of around 6 mg l^{-1} , not all the observed dissolved Sr can be sea-water derived. The extreme concentrations in the brackish groundwaters indicate significant mineral reaction (calcite and possibly aragonite and celestite) as a result of chalk diagenesis and imply a prolonged groundwater residence time. Similar enrichments in

Sr have been recorded in pore waters from deep Chalk boreholes elsewhere in Britain (Edmunds et al., 1992) and have been attributed to prolonged water–rock reaction. Observed Sr concentrations up to around 30 mg l^{-1} in pore waters from Chalk to a depth of 500 m at Trunch in Norfolk have even been taken to represent connate waters dating back to the time of chalk deposition (Bath and Edmunds, 1981).

Some of the key trace-element indicators of saline intrusion are B and Br, and to some extent I and F. Variations in Br concentration in the groundwaters suggest that increases are specifically related to saline intrusion in the coastal areas. Observed concentrations in groundwaters from the Isle of Sheppey and Reculver areas have Br compositions which lie on a simple mixing line between rainfall and sea-water (Figure 4.4). Groundwaters from the unconfined aquifer have low Br concentrations ($<0.1 \text{ mg l}^{-1}$), while concentrations reach up to 36 mg l^{-1} in brackish groundwaters from the coastal parts of the aquifer.

Dissolved iodine also shows a salinity-related increase in the groundwaters (Figure 4.4), with outcrop groundwaters generally $<10 \mu\text{g l}^{-1}$ and brackish groundwaters in excess of $100 \mu\text{g l}^{-1}$. However, the trend shows a significant increase above sea-water values which, like Sr, suggests that values are enhanced by water–rock reaction. Potential sources of I include organic matter in the chalk and the carbonate matrix itself. Development of high I concentrations also implies that the brackish groundwaters have had a prolonged residence time, though more precise dating is not possible with trace elements alone.

The regional variations in dissolved fluoride also show a relationship with salinity. Values are typically low in the outcrop groundwaters (less than $100 \mu\text{g l}^{-1}$; Figure 4.5) as Ca concentrations are high and the solubility of fluorite (CaF_2) in such conditions is low. Dissolved concentrations increase in the reducing, more saline groundwaters as ion-exchange reactions and mixing produce groundwaters with high Na and lower Ca concentrations such that saturation with fluorite is not achieved. The dominant sources of fluoride are likely to be fluorapatite in the Chalk. Fluoride concentrations in the saline groundwaters from the north

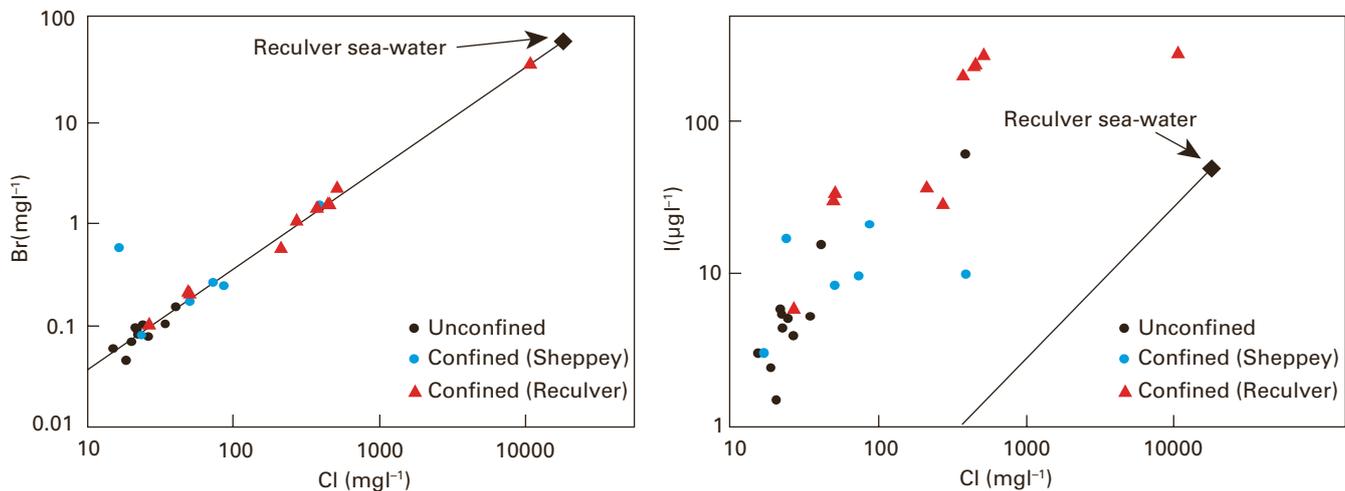


Figure 4.4 Relationship between Br, I and Cl in groundwaters from the Isle of Sheppey–Sittingbourne and Reculver areas of north Kent. Sea-water dilution lines are also indicated.

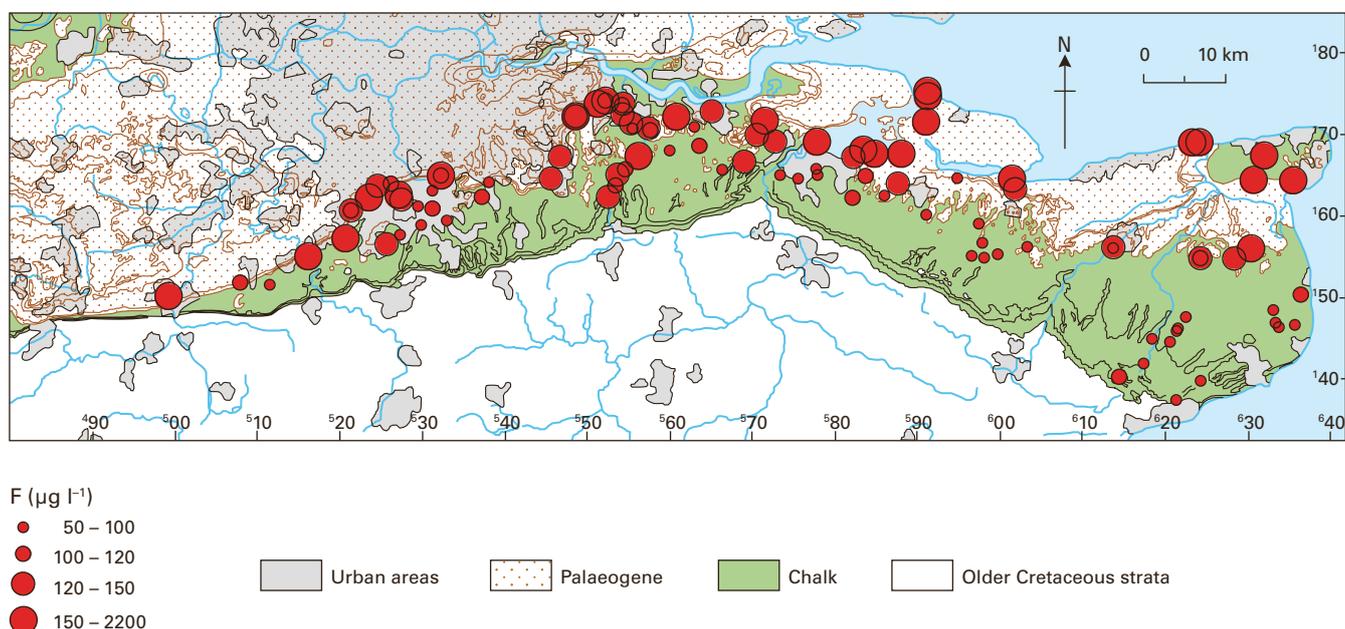


Figure 4.5 Regional distribution of F in the North Downs Chalk groundwaters (values averaged where more than one analysis was available and concentration classes represent rounded quartiles).

Kent coast reach up to 2.2 mg l^{-1} (Reculver; Table 4.2; Figure 4.5). Concentrations of dissolved P are also higher in the confined groundwaters than those at outcrop, values reaching up to $300 \text{ } \mu\text{g l}^{-1}$, also as a result of natural mineral reaction, principally of apatite and fluorapatite.

Diagnostic trace elements indicative of changing redox conditions across the aquifer include Fe and Mn in particular. In the unconfined aquifer, concentrations of dissolved Fe and Mn are low as a result of the oxidising conditions. However, concentrations increase where groundwaters become anaerobic under confined conditions. Greatest increases are seen with Fe, which is found occasionally in excess of 1 mg l^{-1} . Increases in Mn are less extreme, but nonetheless reach up to $74 \text{ } \mu\text{g l}^{-1}$ in the confined groundwaters. Both are derived by natural dissolution (principally of iron and manganese oxides) in the reducing conditions.

Measured concentrations of many trace metals are low in the Chalk groundwaters under the near-neutral conditions. Concentrations of Cd are typically $<0.5 \text{ } \mu\text{g l}^{-1}$, Pb mostly

$<3 \text{ } \mu\text{g l}^{-1}$, Ni mostly $<5 \text{ } \mu\text{g l}^{-1}$ but with values up to around $15 \text{ } \mu\text{g l}^{-1}$, Cu mainly $<20 \text{ } \mu\text{g l}^{-1}$ with a few values in excess of $100 \text{ } \mu\text{g l}^{-1}$, Zn usually $<20 \text{ } \mu\text{g l}^{-1}$ and Al mostly $<10 \text{ } \mu\text{g l}^{-1}$. Concentrations of dissolved As are also low ($<2 \text{ } \mu\text{g l}^{-1}$) throughout the aquifer, including in the confined zone. Selenium concentrations are $<3 \text{ } \mu\text{g l}^{-1}$ in most analysed samples, although no data are available for the reducing groundwaters.

4.2.3 Potability of the Chalk groundwaters

A summary of the occurrence of various trace elements (and some major elements) in the Chalk groundwaters of north Kent is given in Table 4.3 in relation to potability. It should be noted that the summary statistics given relate to raw groundwaters and hence should not be used as indicators of the quality of public water supplies which have, in most cases, undergone treatment before distribution. Nonetheless, the summary gives an outline of the main inorganic water quality and problems that

Table 4.3 Summary of the occurrence of measured inorganic constituents in raw Chalk groundwaters from north Kent in relation to European Commission drinking-water limits.

Constituent	Symbol	European Commission drinking water limits ($\mu\text{g l}^{-1}$ unless indicated)	Number of sites investigated	% exceedance (above European Commission drinking water limit)	Comment
Aluminium	Al	200	69	0	Typically $<10 \mu\text{g l}^{-1}$.
Ammonium	$\text{NH}_4\text{-N}$	390	99	6	High values in confined aquifer as a result of reducing conditions
Antimony	Sb	5	63	0	Values around or less than $1 \mu\text{g l}^{-1}$; often much less
Arsenic	As	10	63	0	Values $<2 \mu\text{g l}^{-1}$
Boron	B	1000	90	3.3	All high values occur in the confined aquifer, affected by sea-water
Cadmium	Cd	5	45	0	Values $<1 \mu\text{g l}^{-1}$, mostly $<0.5 \mu\text{g l}^{-1}$
Chromium	Cr	50	74	0	Values $<10 \mu\text{g l}^{-1}$
Copper	Cu	2000	89	0	Typically $<5 \mu\text{g l}^{-1}$
Fluoride	F	1500	97	1.0	High values in confined aquifer; usually $<200 \mu\text{g l}^{-1}$ in unconfined groundwaters
Iron	Fe	200	98	6	Up to 2.5 mg l^{-1} in confined aquifer (reducing conditions)
Lead	Pb	10	70	1.4	Mostly $<3 \mu\text{g l}^{-1}$; highest value 2.5 mg l^{-1}
Manganese	Mn	50	96	1	High values in the confined aquifer (reducing conditions). Highest value $73 \mu\text{g l}^{-1}$
Nickel	Ni	20	63	0	Mostly $<5 \mu\text{g l}^{-1}$
Nitrate	$\text{NO}_3\text{-N}$	11.3 mg l^{-1}	92	9	Exceedances typically in the range $12 - 16 \text{ mg l}^{-1}$, all in the unconfined aquifer
Nitrite	$\text{NO}_2\text{-N}$	152	88	0	Mostly $<10 \mu\text{g l}^{-1}$
Selenium	Se	10	44	0	$<3 \mu\text{g l}^{-1}$ where measured
Sulphate	SO_4	250 mg l^{-1}	98	2	High values in confined saline groundwaters; unconfined groundwaters usually $<50 \text{ mg l}^{-1}$

exist in the natural Chalk groundwaters of the region. The summary highlights the fact that nitrate is the main inorganic problem constituent in the unconfined groundwaters. In the reducing confined groundwaters, increases in salinity and in concentrations of Fe, $\text{NH}_4\text{-N}$ and to some extent, K, B and F become important.

4.2.4 Organic compounds

As most abstracted groundwater from the North Downs Chalk is from the unconfined section of the aquifer, the groundwaters are vulnerable to pollution from agricultural and industrial sources. This is manifested, not only by increased concentrations of inorganic constituents such as nitrate and chloride, but also occasionally by the presence of some organic compounds. Of the compounds analysed, those found most frequently in the groundwaters include the persistent pesticides atrazine and simazine, as well as diuron and carbophenothion (data from various water

companies). Concentrations of atrazine and simazine have been detected, albeit rarely, at up to $0.228 \mu\text{g l}^{-1}$ and $0.13 \mu\text{g l}^{-1}$ respectively, though they are each more typically present at less than $0.03 \mu\text{g l}^{-1}$. In the unconfined aquifer, lowest concentrations (typically less than $0.01 \mu\text{g l}^{-1}$) are found in groundwaters from the central North Downs area (Cuxton to Throwley), with some higher values in groundwaters from the western section (Crayford–Orpington area), the Isle of Thanet and the south-east.

Concentrations of the herbicide diuron have also been detected at up to $1.2 \mu\text{g l}^{-1}$ although they are usually less than $0.02 \mu\text{g l}^{-1}$. Carbophenothion has been detected rarely at up to $12.9 \mu\text{g l}^{-1}$ with values more typically up to $0.08 \mu\text{g l}^{-1}$.

Other organic compounds detected occasionally include the pesticides 2,4D (up to $0.515 \mu\text{g l}^{-1}$), and chlorotoluron (up to $0.098 \mu\text{g l}^{-1}$ but typically less than $0.02 \mu\text{g l}^{-1}$). Carbon tetrachloride (used as a pesticide and for other

industrial purposes) has occasionally been detected at concentrations up to $1.5 \mu\text{g l}^{-1}$, although they are typically less than $0.1 \mu\text{g l}^{-1}$.

Other components include trichloromethane (chloroform; up to $12 \mu\text{g l}^{-1}$, usually less than $1 \mu\text{g l}^{-1}$), tetrachloroethene (up to $66 \mu\text{g l}^{-1}$ but usually less than $10 \mu\text{g l}^{-1}$, the EC maximum permissible value for this compound) and hexachlorobutadiene (up to $0.33 \mu\text{g l}^{-1}$ but usually less than $0.001 \mu\text{g l}^{-1}$). The polycyclic aromatic hydrocarbon (PAH) compound indeno (1,2,3 cd) pyrene has been detected at up to $27 \mu\text{g l}^{-1}$, but is usually present at concentrations less than $10 \mu\text{g l}^{-1}$. This may be a contaminant from fossil fuels or used motor oils. Dichlorobromomethane has also been detected: concentrations are typically less than $0.1 \mu\text{g l}^{-1}$ but have been observed at up to $1.5 \mu\text{g l}^{-1}$.

Despite these occurrences, concentrations of measured total organic carbon (TOC) are usually low in the groundwaters from the unconfined aquifer, being typically less than 2mg l^{-1} and frequently less than 1mg l^{-1} . Lowest TOC concentrations are found in the central parts of the North Downs. Slightly higher values are found in the western section (Crayford to Snodhurst) and in the south-east (e.g. Denton Valley). The patterns have some relationship with those found for $\text{NO}_3\text{-N}$, atrazine and simazine distribution. No data are available for TOC in the confined aquifer.

Groundwaters from the confined aquifer are not generally monitored for organic compounds as they are not used for public supply. However, concentrations of organic compounds in the confined aquifer are likely to be generally low.

4.3 TEMPORAL CHEMICAL VARIATIONS

Water-quality monitoring data collected by the water companies and the Environment Agency over the last 10–15 years for the Chalk groundwaters suggest that major-element compositions are broadly stable, although variations occur in some elements. Constituents of pollutant origin show some apparent variations, although there are no discernible long-term trends over the monitored interval.

Concentrations of SO_4 for example show some temporal variations, particularly in the groundwaters with higher concentrations. Variations up to 30% are seen in some groundwaters with average concentrations of around 60mg l^{-1} (Figure 4.6). These higher values may be pollution-derived and the variations are likely to reflect variations in pollutant loads with time.

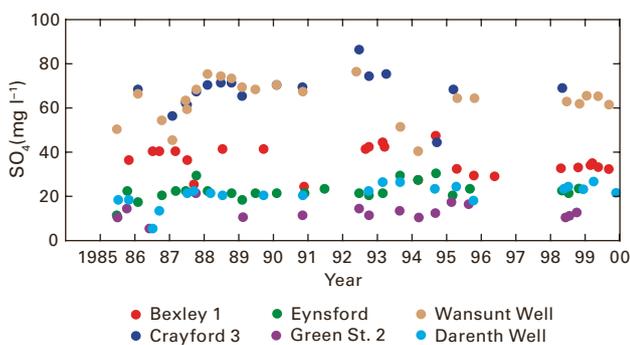


Figure 4.6 Temporal variation in SO_4 concentrations in groundwaters from the north Kent Chalk over the interval 1985 to 2000.

Nitrate is one of the most frequently measured of the inorganic compounds as it is the most likely inorganic constituent in the unconfined groundwaters to exceed the drinking-water regulations. Some variations in nitrate concentrations have been apparent in individual boreholes over the last decade, but there appear to have been no distinctive long-term changes. Significantly, concentrations do not appear to have increased over the interval for which data are available (Figure 4.7).

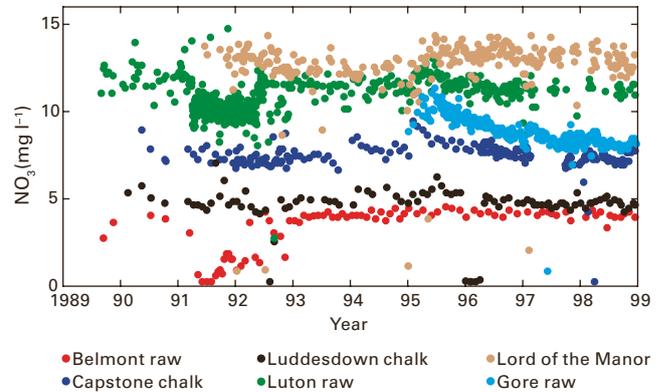


Figure 4.7 Temporal variation in $\text{NO}_3\text{-N}$ concentrations in groundwater from seven boreholes in the Chalk aquifer of north Kent over the interval 1989 to 1999.

As noted above, among the most prevalent pesticides in the unconfined Chalk groundwaters are atrazine and simazine. Where detectable, concentrations of these appear to have decreased with time over the last decade in many of the groundwaters, as observed for some sites in Figure 4.8. Values of both atrazine and simazine

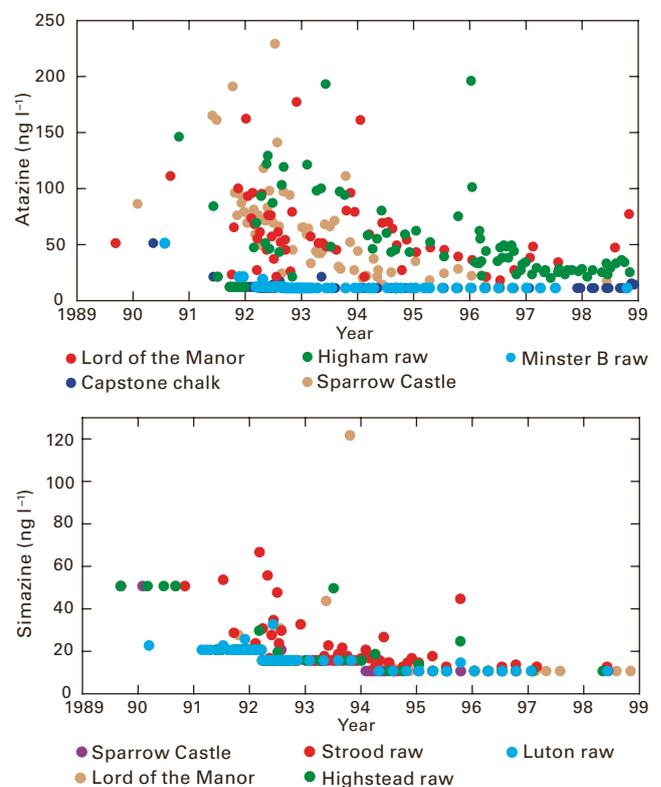


Figure 4.8 Temporal variations in atrazine and simazine concentrations in groundwater from selected sites in the unconfined Chalk aquifer of north Kent over the interval 1989 to 1999. (Data from Southern Water).

appear to have diminished markedly over the interval 1992 to 1994 and are substantially lower in more recent groundwater samples, although the compounds are still often detectable. These decreases with time are likely to be a reflection of the ban on atrazine and simazine applications in the UK during the early 1990s.

4.4 GROUNDWATER RESIDENCE TIME

The inorganic chemical data discussed above give some indications of residence times of groundwater in the Chalk aquifer of the North Downs. The evidence from the unconfined aquifer, with often high concentrations of $\text{NO}_3\text{-N}$ and occasional presence of organic compounds (pesticides and chlorinated solvents) point towards these groundwaters being derived from younger recharge, probably dominantly of a few years to decades in age. Combined chemical and isotopic evidence indicates that residence time increases significantly in the confined aquifer, particularly in the coastal areas investigated. As noted above, increased concentrations of Sr and I in the coastal groundwaters of the Reculver and Sheppey areas indicate reaction with the Chalk and require time in the aquifer for reaction to proceed. Evidence from stable carbon isotopic compositions also indicates prolonged reaction in the near-coastal waters. Groundwaters from the unconfined aquifer have $\delta^{13}\text{C}$ compositions of dissolved inorganic carbon (DIC) typically around -15‰ (Figure 4.9), consistent with compositions of modern recharge

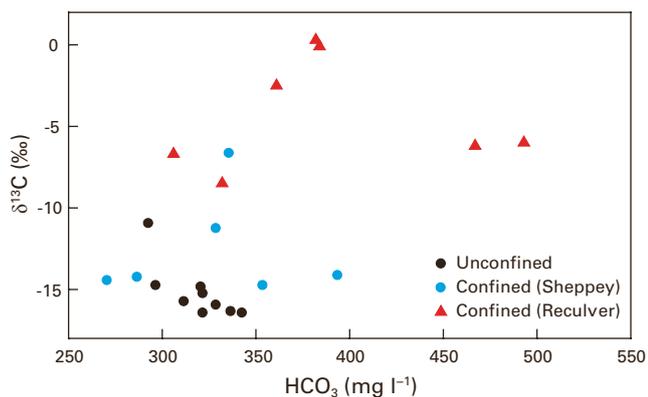


Figure 4.9 Relationship between $\delta^{13}\text{C}$ and HCO_3^- in the north Kent Chalk groundwaters.

(e.g. Clark and Fritz, 1997). Those from the confined aquifer with higher HCO_3^- concentrations (more than 350 mg l^{-1}) contain DIC with generally more enriched $\delta^{13}\text{C}$ compositions, in the most extreme cases close to 0‰ , a value typical of marine calcite (e.g. Faure, 1986; Clark and Fritz, 1997). This trend towards more enriched $\delta^{13}\text{C}$ compositions therefore indicates progressive reaction of groundwater with marine chalk down the groundwater flow gradient.

Stable isotopes of oxygen and hydrogen also demonstrate a variation in groundwater residence time along the flow line. Unconfined groundwaters from the Sittingbourne and Canterbury areas have a range of $\delta^{18}\text{O}$ compositions around -6.8 to -7.8‰ and $\delta^2\text{H}$ around -42 to -50‰ (Figure 4.10) and, as with other chemical and isotopic evidence, are believed to be indicative of modern recharge compositions. Fresh groundwaters from the confined aquifer of the Sheppey and Reculver–Canterbury areas have more depleted compositions (e.g. $\delta^{18}\text{O}$ in some

samples less than -8‰ ; Figure 4.10). This suggests that recharge of these groundwaters occurred during a colder climatic period than that of the present day, as has been observed for other confined groundwaters in the UK (e.g. Darling et al., 1997; Edmunds et al., 2001). More enriched compositions of saline groundwaters from the Reculver coastal area ($\delta^{18}\text{O}$ greater than -5‰ ; Figure 4.10) are related to mixing of sea-water with an $\delta^{18}\text{O}$ and $\delta^2\text{H}$ composition by definition of 0‰ .

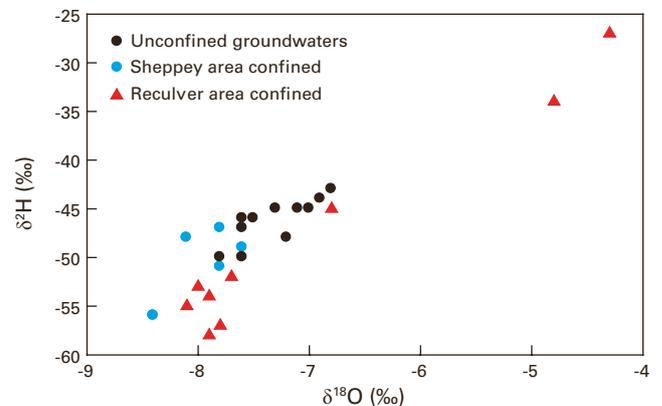


Figure 4.10 Variation of ^{18}O with ^2H in groundwaters from north Kent.

Variations in stable-isotopic compositions of groundwaters from the Reculver–Canterbury area are shown in more detail in Figure 4.11. The plot summarises data collected for an investigation of groundwater salinity and age relationships in the area (Buckley et al., 1996; Edmunds and Milne, 1999). Two boreholes drilled at the coast at Reculver during the mid 1990s were cored and logged and porewaters were extracted. The two boreholes, Reculver 1 and Reculver 2, were drilled into the Chalk to 205 m and 110 m depth respectively. Results for pumped groundwaters from each borehole, saturated-zone chalk porewaters from each borehole and pumped

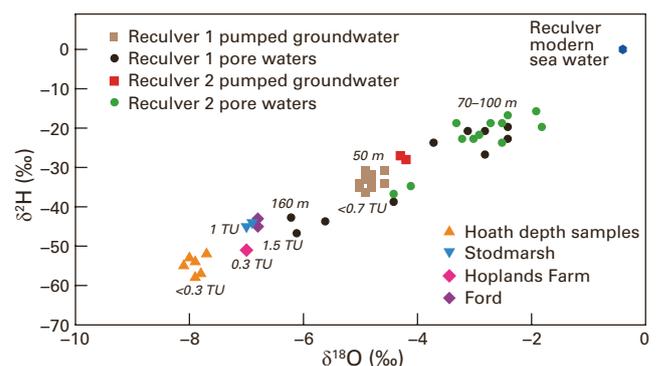


Figure 4.11 Variation of ^{18}O with ^2H in pumped groundwaters and saturated-zone porewaters from the Reculver–Canterbury area of north Kent. Tritium values for selected pumped groundwater samples are also given.

groundwaters from other boreholes in the local area indicate a large range of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ compositions (Figure 4.11). The samples are aligned in an approximate flow line from the southern part of the aquifer (Stodmarsh), through Chalk confined by increasing thicknesses of Thanet Beds sediments to Reculver on the Kent coast.

Groundwaters from Stodmarsh, Ford and Hoplands Farm have modern stable-isotopic compositions ($\delta^{18}\text{O}$ around

-7 ‰) and contain small though detectable amounts of tritium (1.0 TU, 1.5 TU and 0.3 TU respectively). These sources are taken to include an important component of modern recharge, though the overall low tritium concentrations suggest that a proportion of the groundwaters are of pre-1950s origin. Presence of nitrate in the groundwater from Stodmarsh (3 mg l⁻¹; Table 4.1) supports the suggestion that this source is largely modern water and is consistent with its location close to the edge of the Palaeogene covering sediments in unconfined conditions.

By contrast, depth samples collected from a 100 m deep borehole at Hoath, just 5 km inland from the coast, indicate the presence of a much older water, with no detectable tritium (<0.3 TU) and a more depleted stable-isotopic composition ($\delta^{18}\text{O}$ around -8 ‰). This highlights the heterogeneity of groundwater chemistry and flow rates in the Chalk of the area.

Pore waters and pumped groundwaters from Reculver show the greatest range of stable-isotopic compositions (Figure 4.11). Pumped groundwaters from the boreholes have a salinity equivalent to around 50% sea-water (Cl concentration 9000 mg l⁻¹) with $\delta^{18}\text{O}$ compositions in the range -4 to -5 ‰ and no detectable tritium (<0.3 TU; Figure 4.11). Measured radiocarbon activities of pumped groundwaters are around 11 pmc. These data indicate that the Reculver groundwaters do not represent modern recharge but have estimated residence times of the order of several hundreds to 2000 years (Edmunds and Milne, 1999; Edmunds et al., 2001).

Results from both bailed depth samples and pore waters extracted from the saturated chalk in the Reculver boreholes indicate a significant salinity stratification (Figure 4.12). The results show an upper zone of brackish groundwater at around 30 to 50 m depth (e.g. Cl concentrations in the range 5000 to 10000 mg l⁻¹), a zone of highest salinity at 50 to 100 m depth (Cl up to 15000 mg l⁻¹) and a lower zone of slightly fresher composition (Cl 4000 to 10000 mg l⁻¹) at more than 100 m depth (Figure 4.12). The salinity trends appear slightly offset in the different boreholes, most likely because of slight variations in surface elevation and thickness of overlying Palaeogene sediments. Despite the similar salinities of the pore waters in the upper and lower zones, the stable-isotopic compositions are distinctive, with those from the deeper than 100 m zone being significantly more depleted ($\delta^{18}\text{O}$ around -6 ‰; Figure 4.11). This suggests that the deeper matrix waters in the Chalk may be significantly older than those from the upper saturated zone of the north Kent coastal area.

Flow-meter logging has highlighted seven major flow horizons in the Chalk in the Reculver boreholes, with inflow from the upper, middle and lower zones respectively in the proportions 4:2:1 (Section 3.5.2 and Edmunds and Milne, 1999). As fracturing in the Chalk of the Reculver area is best developed in the upper 50 m or so of the Chalk and the flow logging results indicate more substantial flow from the upper horizons, the brackish water at the shallowest depths is taken to be the youngest groundwater

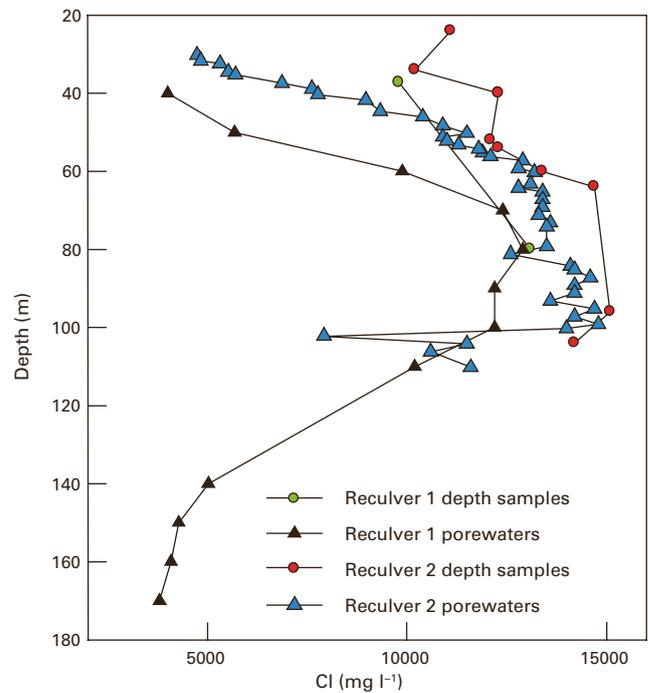


Figure 4.12 Variation in Cl concentration with depth in depth samples and pore waters from the Chalk in two boreholes at Reculver (after Edmunds and Milne, 1999). The base of the Thanet Beds in these boreholes occurs at approximately 30 m below ground surface with static water level some 2 to 3 m below ground surface.

in the profile. The data for this shallow zone are consistent with throughflow refreshing of a body of pre-existing saline Holocene groundwater in the Chalk.

Groundwater from the middle saline zone at Reculver is believed to represent an older generation of water, possibly infiltrated during a period of Holocene sea-level rise (around 7000 years BP). The brackish groundwaters in the deepest horizons (greater than 100 m) are in chalk with poor fracture development and little fracture flow (Section 3.5.2). These are considered to be the oldest recorded in the Reculver profile and may predate the period of Holocene sea-level rise and sea-water infiltration of the middle saline zone. The variable salinity profiles reflect the dominance of fracture flow in the aquifer.

The presence of old and variably saline groundwater in the boreholes at Hoath, Reculver and nearby boreholes at Pluck's Gutter [6272 1638] and [6276 1618] (Shaw, 1981) indicate that groundwater flow patterns and salinity trends in the area are highly complex. These are likely to be areas of slow groundwater flow and appear to be controlled by local structural features in the Chalk. Both Hoath and Pluck's Gutter boreholes are downgradient of a local east-west anticlinal structure within the Chalk. This, as described in Section 3.5.2, is likely to have severely impeded groundwater movement locally in the confined aquifer and hence led to substantial heterogeneity in groundwater chemistry and age relationships.

5 Groundwater management

5.1 INTRODUCTION

In terms of the proportion of the resource committed for all water supply purposes, the Chalk of the North Downs must rank as one of the most intensively developed aquifers in the British Isles. The introduction to the Geological Survey memoir *The Water Supply of Kent* (1908) records that the county ‘...contains the largest supply in the world that is got solely from wells’. The region is also one of the driest in the UK, with annual rainfall in the eastern extremity averaging less than 580 mm, and the aquifer has to support levels of pumped abstraction from boreholes approaching, and in some instances exceeding, the average rate of natural replenishment. The Chalk of the North Downs provides a resource for six water companies with total abstraction (public water supplies, industry and agriculture) averaging some $254 \text{ Mm}^3 \text{ a}^{-1}$. This represents 70–80% of the total water supply although there are parts of east and south east Kent which are entirely dependent on supplies drawn from boreholes in the Chalk.

The difficulties which have faced water companies in recent years have often been attributed to this heavy dependence on groundwater, a resource which is almost wholly reliant on winter rainfall for its annual replenishment. The region is, therefore, particularly vulnerable at times of below-average winter rainfall and the experiences of the long drought of 1989 to 1992 prompted the National Rivers Authority to adopt a presumption against granting licences for abstraction from the Chalk for all consumptive uses, including public supply.

More than 50% of an average years’ effective rainfall (the proportion of total rainfall accruing to groundwater storage) is abstracted for public supply and other uses. The disposition of the main urban centres (many of them along the coast or close to major rivers) is such that very little of the treated effluent finds its way back into the aquifer. Much of the drainage of the area is either wholly or largely supported by groundwater discharge in the form of spring flows or seepages and the consequent depletion of natural storage has produced a corresponding decrease in the baseflow component of streams draining the outcrops of the Chalk and other major aquifers. In the most extreme cases, the result has been a total loss of flow over substantial lengths of the watercourse and in many other instances, groundwater abstraction has had a profound and detrimental effect on the seasonal pattern of surface flow.

There is now evidence to indicate a progressive depletion of storage throughout large areas of the Chalk of north and east Kent. The condition has its origins in the steep post-war increase in demand coupled with what appears to be a fairly consistent decrease in average annual rainfall taking place since the early years of this century. Conditions have of course been exacerbated by recent droughts but, even allowing for this, the trend in groundwater levels for some parts of the area suggests that there is now a danger of ‘mining’ groundwater resources. Rates of abstraction exceed the average annual winter recharge for the more severe and protracted droughts and it can require two or

three years of above-average recharge to bring about full recovery of storage. It would seem that in order to achieve sustainable management of the aquifer’s resources it will be necessary to make changes in the geographical and seasonal distribution of groundwater abstraction. This in turn requires some revision of the criteria for assessing the long term balance of resources so that the Environment Agency will need to work toward a general reduction in the level of dependence on groundwater and to suspend the granting of new consumptive-use licences until annual abstraction totals can be brought back to rates that can be sustained.

Control over abstraction falls to the Environment Agency under special provisions of the 1963 and 1991 Water Resources Acts and the 2003 Water Act. No one for example, may abstract from an aquifer or, for that matter, from any other controlled water, unless they hold a licence from the Environment Agency specifying the authorised purpose and quantities or have explicit exemption (examples here being fire fighting and dewatering to protect works). The first licences were granted in mid 1965 but the conditions of issue allowed very little scope for the authority at that time to exercise effective control. This was because the legislation entitled anyone who could demonstrate proper existing use of a borehole or other recognised source of supply, to a licence ‘as of right’ for the appropriate quantities — and in perpetuity. With few exceptions, this provision, almost by definition, had to be applied automatically to all public water supply undertakings (the largest abstractors) not to mention some fairly large industrial users. Effectively, this put much of the Chalk into deficit from the outset. The subsequent 40 years of water resource management has been largely dedicated to attempts to redress this imbalance in the face of rising demand and increasing pressure on the water environment. As part of their remit, the Environment Agency has also developed a long-term strategy for water resources that looks 25 years ahead and considers the needs of both the environment and society. Allied to this are various items of European legislation such as the Habitats Directive and more importantly Water Framework Directive (see Section 5.4).

5.2 GROUNDWATER ABSTRACTION

As noted previously, the North Downs come under the jurisdiction of the Thames and the Southern regions of the Environment Agency. It is therefore convenient to consider each of these management regions separately.

5.2.1 Thames Region

In Thames Region, the confined Chalk aquifer north of the North Downs into the London Basin to the River Thames receives recharge from the North Downs outcrop area. As the London Basin is a syncline it also receives water from the Chilterns to the north. As groundwater here is confined, it does not follow that the River Thames is the limit of influence of water from the North Downs.

Because of the varied geography and hydrogeological nature of the North Downs the Thames Region's area of responsibility has been split up into a number of subunits from west to east.

THE HOG'S BACK WEST OF GUILDFORD

Because of the very narrow outcrop of this area of Chalk strata, steeply dipping northwards under the west London Basin, very little recharge is received by the aquifer. As a consequence very little groundwater flux is available northwards into the deeply confined strata to the north of this area. These factors combine to ensure that almost no secondary storage and permeability is developed, resulting in a large area of 'dead aquifer' with very low groundwater yield. No abstractions currently exist in the area and boreholes drilled in the past, usually ignoring professional advice, have been abortive.

RIVER WEY VALLEY TO RIVER MOLE VALLEY

The section of North Downs which includes the valleys of the Wey in the west at Guildford and the larger River Mole in the east between Dorking and Leatherhead forms a distinct hydrogeological unit. Three major Chalk groundwater abstractions for public water supply are situated at Guildford in the Wey valley, two being a short distance from the confined Chalk to the north and intercepting water which would have moved north-eastwards into the London Basin.

In the Mole valley there is a major concentration of public water supply abstractions at Leatherhead at two closely linked sites with a total of eight boreholes. A smaller source at Fetcham Springs lies just to the south-east of Leatherhead. This complex is licensed for a total of $2.04 \times 10^4 \text{ Ml a}^{-1}$ and is partly supported by the adjacent River Mole. This river has a complex hydrogeological behaviour as it flows over the 6 km of Chalk outcrop in the Mole Gap. At low flows, much of the river flow is lost into swallow holes between Dorking and West Humble (see Sections 3.3.1 and 3.4.3). Occasionally it dries completely in this 3 km stretch. The flow reappears at large springs in the river bed south of Leatherhead in the area of Thorncroft. The flow accretes very rapidly from here until the river flows onto the confining Palaeogene strata of the London Basin. This natural phenomenon is well known and has been recorded over many centuries and is not caused by groundwater abstraction at Leatherhead. Once the river has been re-established through Leatherhead, there appears to be some depletion of the flow by the northern group of Leatherhead boreholes. This is not an environmental issue as the flows are always adequate at this point but the Environment Agency has stated that no further increase in abstraction would be permitted through the Mole Gap.

The North Downs outcrop begins to widen between Guildford and Leatherhead due to the reducing angle of dip of the strata but the indications are that very little groundwater flows northward beyond the dip slope spring line into the confined London Basin. As there is some uncertainty about this, measures are in hand to investigate the situation. Moderately sized dip slope springs occur at Clandon with flow ranging between dry and around 2 Ml d^{-1} . These, plus the two small public water supply abstractions at Clandon and West Horsley, account for most of the north flowing groundwater balance. A single, major spring source occurs at the base of the scarp slope to the south. This is the Silent Pool Spring which is perennial. Its flow varies from between 1 and 10 Ml d^{-1} . In extremely dry weather, the top lake, the Silent Pool, dries completely. This is

formed by a dam which artificially creates the lake in which the water exhibits the blue 'opalescence' typical of deep water chalk spring pools. A second pond, again dammed, exists just down stream and never dries. Outflow from this is continuous and joins the River Tillingbourne locally. Why there should be only one large scarp slope spring source along the 17 km stretch of scarp is unknown. Because of the environmental sensitivity of all these dip and scarp slope springs and the area of complex river behaviour in the Mole valley, there is no scope for further groundwater abstraction in this unit. Groundwater yield in the confined strata to the north is very small and there are no licensed abstractions in this area. The Environment Agency is implementing sophisticated measures to investigate these field observations as there is a need to understand the hydrologic processes involved.

EPSOM TO THE RIVER WANDLE CATCHMENT

This area starts immediately east of the Mole Gap and comprises the River Hogsmill, Beverley Brook and River Wandle sub-catchments. Of these, the Hogsmill and Wandle start as substantial dip slope spring sources formed at the Chalk-Palaeogene contact; the Hogsmill at the Bourne Hall spring and ponds at Ewell and the Wandle at two groups of sources. The western area of the Wandle starts at a large group of springs at Carshalton from St Philomenas School, Carshalton Ponds and the Grotto in Carshalton Park. The eastern area starts at a very large spring at Waddon Ponds just south-west of Croydon. From Waddon, the river Wandle flows east along the strike of the Chalk accreting flow until it is joined by the Carshalton tributary at Hackbridge where it flows north across the London Basin to the Thames.

The Sutton and East Surrey Water Company are the main abstractors in this unit of the North Downs and the unconfined aquifer is very heavily used. A total of 16 sources abstract groundwater with very large groups of shafts and boreholes at Sutton and Cheam. A number of sources have adit systems and, at Sutton, four levels of adits are present. Thames Water Utilities operates two public water supply sources at Epsom and three sources in the Croydon area in the confined Chalk. As a result of this high utilisation, the spring sources at Ewell and Carshalton have required augmentation schemes to compensate for the effects of depletion due to groundwater abstraction for public water supply. At Ewell Springs, the Bourne Hall Ponds have been artificially lined to retain water and groundwater is pumped from a borehole downstream, just on the confined Chalk, and piped upstream to the ponds to maintain a prescribed flow out of the ponds into the upper reach of the River Hogsmill. At Carshalton, the large ponds have been completely lined but allow Chalk spring water to flow in round the edges. This flow can be very substantial in winter. In summer, River Wandle water is pumped back from below the confluence of the west and east tributaries and piped directly into the ponds to maintain a prescribed flow of 4.5 Ml d^{-1} .

These augmentation requirements are built into a number of Water Company groundwater licences across the area. The system works well and allows groundwater use to a very high level. Long-term monitoring of groundwater levels indicates that this part of the North Downs is at equilibrium with no long-term downward trends visible. However, no further increase on the annual licensed quantity for the whole of this zone will be permitted as the practical limit of augmentation of the dip slope spring line has been reached. A feature of this abstraction

is that it has no effect on the amount of groundwater passing northwards in the London Basin confined Chalk aquifer. Abstraction from the unconfined area simply reduces the amount of water issuing along the dip slope spring line, i.e. at Ewell, Carshalton and Waddon, which acts as a hinge line on the groundwater contour map of the North Downs. There is always a groundwater gradient northwards, the constant flux in this direction limited mainly by the lower permeabilities in the confined Chalk. There is, however, a zone of highly productive confined Chalk which is a relatively narrow corridor running north from Carshalton, approximately below the course of the river Wandle, towards Merton. With the prospect of no further development on the unconfined strata, the Sutton and East Surrey Water Company have developed a large source at New Road, Hackbridge 2.5 km into the confined strata. This source is very productive and comprises three boreholes spread north to south over 600 m. An exploration borehole 1.5 km further east at Beddington produced very low yields. Given that no extra licences will be granted, other measures are now being developed including the injection of excess winter water into the aquifer for abstraction during the summer. This approach is known as Aquifer Storage and Recovery (ASR).

The Hackbridge source is licensed for an average of 5 Mld⁻¹ but a peak daily rate of 12 Mld⁻¹. This has a large affect to the north where Thames Water Utilities has two sources at Merton and Streatham which are also very productive. Historically the Merton source has caused substantial long-term drawdown since its construction in the early part of the 20th century. It was not used between the mid 1960s and 1998. During this period the Chalk groundwater under London was rising due to the dramatic reduction of commercial and industrial abstraction which started to diminish in the mid 1960s. In Central London groundwater levels rose from a low of -88 m OD to around -45 m OD by the mid 1990s. At Merton, the groundwater level recovered to its historic natural level of 15 m OD (almost artesian overflow at ground level) in 1995. Since then, the sources at Merton and Streatham have been refurbished and a moderate amount of intermittent abstraction has taken place. This, combined with substantial operation of the new Hackbridge source by the Sutton and East Surrey Water Company caused groundwater levels to fall significantly, but have now reached equilibrium.

Further north, Thames Water drilled and test pumped two sites designed to control and use London's rising groundwater. At these sites in Battersea and Brixton, short term yields over a few days were extremely large by any standard for the confined Chalk, and these sites now have operational licences and are putting water into supply. A strategy is in place for maximising and licensing future abstraction in south London. This strategy must be flexible to respond to field observations as understanding of the system improves. The amount of groundwater derived from the North Downs through the narrow Hackbridge - Merton corridor is considerably less than the total proven short term yield of the various sources currently available. The London Basin Groundwater computer model constructed in 1999 (see Section 5.3.4) has been a major tool in forming this groundwater resources strategy.

THE RIVER RAVENSBOURNE GROUNDWATER CATCHMENT

This is a complex Chalk groundwater catchment in that the River Ravensbourne is sourced almost entirely from

high level springs on the Palaeogene strata which overlie the dip slope of the North Downs in south-east London and are not significantly in contact with the Chalk aquifer. Several tributaries start from the dip slope of the London Clay, Harwich, Woolwich, Reading, and Thanet formations just north of Shirley, Addington and Keston. The surface water catchment on the Palaeogene strata bears little relationship to the underlying Chalk groundwater catchment which obtains recharge from the North Downs Chalk outcrop area around Addington and Biggin Hill. The boundary with the River Wandle groundwater catchment is very flat and difficult to define. Most Chalk groundwater flows north, either directly to the Thames or under the Thames to the Chalk groundwater depression in central Essex. A smaller inlier of Chalk exists near the lower end of the River Ravensbourne at Deptford. It is unclear if Chalk groundwater would naturally feed the river over this short length as a very large groundwater source is operated at Deptford by Thames Water. In total, six Chalk sources are licensed in the extended Chalk catchment of the Ravensbourne. These total 58.4 Mld⁻¹ and have virtually no effect on the River Ravensbourne. A large source is operated on the unconfined Chalk at Addington with a smaller source at Stroud Green. The area is one of dry Chalk valleys with no dip slope or scarp slope Chalk springs. In the extremely high rainfall event of 2000/2001, Chalk groundwater levels rose to exceptionally high levels. Springs appeared in these normally dry Chalk valleys and overland flow and groundwater flooding occurred. Section 5.3.7 briefly describes the groundwater model that has been constructed for this area. However, the exact relationship between the Chalk and the Palaeogene is unclear. Also, because of the uncertainty of catchment boundaries, the neighbouring Darent unit needs to be considered in future management plans.

5.2.2 Southern Region

The Southern Region of the Environment Agency divides the part of the North Downs for which they have responsibility into three aquifer blocks for management purposes; where appropriate these are further subdivided into their constituent 'resource areas' (Figure 5.1).

THE NORTH-WEST AQUIFER BLOCK

The effective recharge area comprises approximately 330 km² of unconfined White Chalk Subgroup lying west of the Medway estuary and dipping north toward the axis of the London Basin. To the north-west and north-east, the aquifer is overlain by the Thanet Sands Formation and London Clay Formation. Although having low permeability, the Thanet Sands Formation also contributes to recharge.

DARENT RESOURCE AREA

The rivers Darent and Cray are the only permanent watercourses of any size draining the dip slope although minor dry-valley features in the east of the block are taken as marking the alignment of zones of relatively high transmissivity discharging to the Medway. Until recently the total volume abstracted each year from boreholes was only slightly less than the average rate of aquifer replenishment by rainfall and records show, furthermore, that for drier than average years there is a substantial deficit (Table 3.2). At such times, summer flows have been severely

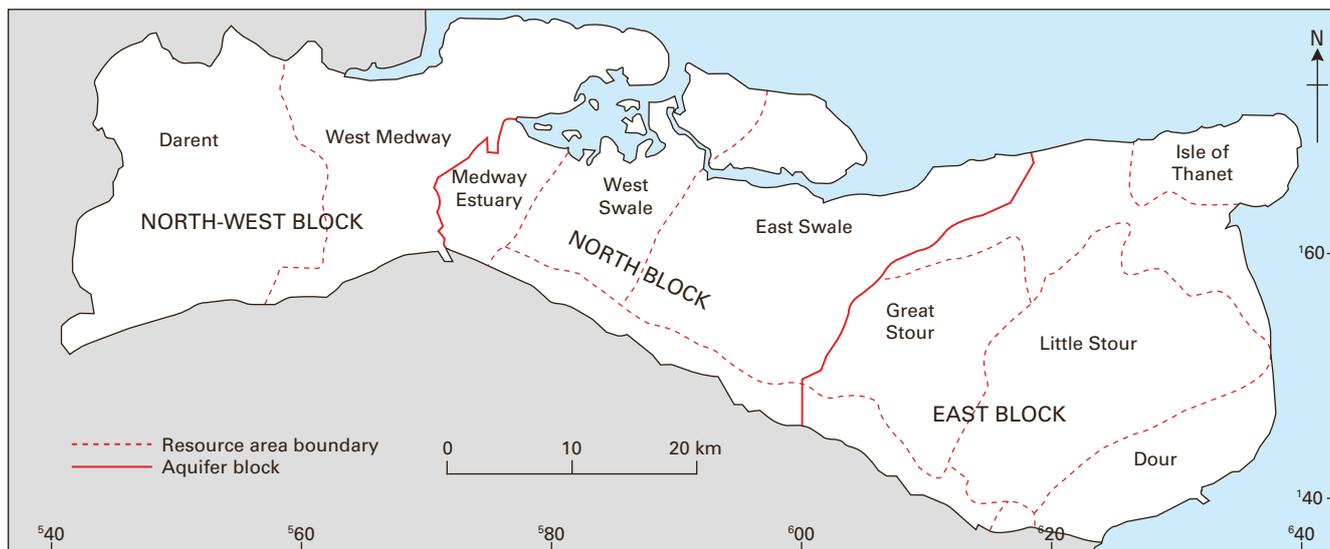


Figure 5.1 The Environment Agency Southern Region's subdivision of the North Downs into aquifer blocks and resource areas.

depleted and under the more extreme drought conditions such as those experienced during 1989 to 1992 and 1995 to 1997, springs have failed and the lower courses of the river have dried out completely.

The middle and lower reaches of the river are sustained almost entirely by spring discharges from the Upper and Middle Chalk (White Chalk Subgroup). It has been estimated that prior to the implementation of the low flow alleviation scheme (see Box 5.1), the average daily flow at Hawley, near Dartford, was only 40% of what would normally be expected of the river at this point in its natural state if no abstractions were taking place anywhere within the catchment. The impact of flow depletion is illustrated by the loss of biodiversity and the disappearance or at least a substantial reduction in numbers of key invertebrates. Recent years have also seen the abandonment of watercress beds and a general increase in the depth and extent of siltation of the river-bed gravels. This has had its effect in the loss of native brown trout from the middle and lower reaches. Silt deposition has also resulted in the encroachment of reed beds and a consequent reduction in channel capacity.

The total recharge area of 231 km² is taken as corresponding to the unconfined White Chalk Subgroup with some allowance for the moderately permeable Thanet Beds outliers. Annual rainfall varies across the area from a maximum of more than 840 mm in the extreme south-west near the top of the scarp to a minimum of around 530 mm in the lowland belt bordering the Thames estuary. A long term average (LTA) of 680 mm has been estimated for the Meteorological Office standard period 1961 to 1990 with effective rainfall estimated at approximately 260 mm; equivalent to an average annual recharge rate of $6 \times 10^4 \text{ Ml a}^{-1}$. As can be seen from Table 3.1, this amounts to approximately 65% of the total quantity authorised for abstraction from the Chalk under licences currently in force (approx. $9.3 \times 10^4 \text{ Ml a}^{-1}$). About 80% of this is allocated for public supply with most of the remainder for industry. In practice, for most years the total abstracted falls between 60% and 70% of the licensed quantity. This means that on average, uptake accounts for about 95% of recharge and under severe and protracted drought conditions this can result in a substantial depletion of groundwater storage.

WEST MEDWAY RESOURCE AREA

This comprises 127 km² of unconfined White Chalk Subgroup with a confined extension dipping north-east beneath approximately 170 km² of Palaeogene cover. Development of the resource has, until recent years, been strongly influenced by the growth in demand accompanying industrial expansion along the Thames and on the Isle of Grain. Since the mid 1970s however, there has been a progressive reduction associated with the decline in industrial demand to a point where today, abstraction accounts for less than 15% of the total taken from the Chalk; but this excludes the relatively high rates of aquifer dewatering (estimated at more than 20 Ml d⁻¹) maintained by Blue Circle Industries in order to prevent interference with quarrying operations at Northfleet. This represents a substantial resource loss but it has not been included in the summary balance as there are, as yet, no reliable figures for the long-term discharge. However, taking a realistic estimated minimum of 15 Ml d⁻¹ would increase the authorised total to more than 153 Ml d⁻¹, making this catchment the most heavily committed unit in the North Downs. However, because of the cut-backs in industrial abstraction elsewhere in the catchment, a degree of dewatering is likely to prove necessary as a means of controlling water-table levels and preventing groundwater flooding in the Northfleet area. Blue Circle Industries are planning a new £180 million works on the River Medway at Holborough near Snodland in the early 21st century. The Northfleet site is likely to cease operation within a year of commissioning of the new works and thus the future control of groundwater levels is likely to become a priority aquifer management issue. Cessation of dewatering will, in any event, mark a significant change in the groundwater regime of an area which in the early 1960s supported such high rates of industrial abstraction that attention had to be given to the risk of saline intrusion and subsequent contamination of paper mill boreholes. However, Thames Water Utilities Ltd are investigating the area up groundwater gradient from this quarry as a future source of supply to replace reduced abstraction in the Darent catchment (see Box 5.1).

THE NORTH AQUIFER BLOCK

The scarp slope of the Downs forms a prominent feature rising to approximately 200 m OD. To the north-east, the

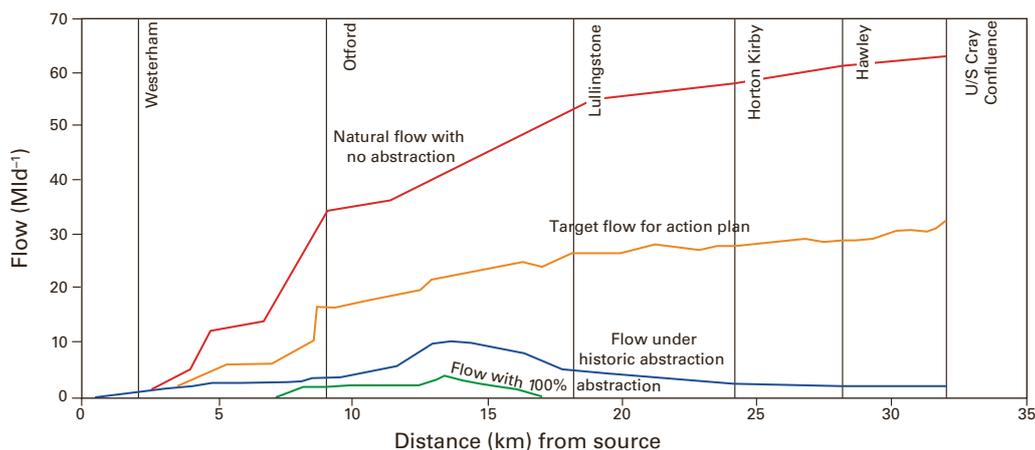
BOX 5.1 THE DARENT COMPENSATION SCHEME

The River Darent is fed by springs from the Lower Greensand and the Chalk aquifers of the North Downs. Groundwater was developed progressively during the last century reaching some 113 Ml d^{-1} (half the recharge rate) of which 50 Ml d^{-1} were exported from the catchment to supply parts of London. The abstractions reduced spring flow and the river dried up during the early 1970s and from 1989 onwards. It was thus classified as one of the top 40 low flow rivers at the time of privatisation of the water industry and Thames Water accepted that the problem was one of over abstraction (Acreman and Adams, 1998). In 1992 Thames Water formed a joint project team with the NRA to find a solution. The objective was to restore the basic amenity value of the river by returning flow to the channel in sufficient quantities for brown trout to return. By 1994 a two-phase scheme was under way to deliver an environmentally acceptable flow regime (EAFR) of 50% of the natural flow — a figure which had been established through ecological study and modelling (see Section 5.3.8). To achieve this Thames Water reduced abstraction from sensitive boreholes and extended the flexibility of its distribution network. The figure below illustrates the scheme by a comparison of actual and target flow accretion

profiles for August, the former being based on 1976 and 1989/92 observations and, therefore, representing a late-summer drought condition.

Phase 1 completed in mid 1999 achieved a 30% reduction in the total quantity of water licensed for public supply abstraction within the catchment, a 60% reduction in actual winter-period abstraction and a 30% cut in all-year usage from those boreholes sited close to the river and considered to have the most direct impact on baseflows. The Environment Agency also commissioned three shallow bank-side augmentation boreholes (effectively ‘artificial springs’) designed to come into operation at times when the flow falls below target rates and these are capable of delivering an additional 15 Ml d^{-1} . Phase 2, due for completion in 2008, will achieve a further reduction in licensed abstraction from the catchment at two more public water supply sources in the lower part of the catchment. This reduction will be met by developing new groundwater sources in the Swanscombe Chalk to the south of Bluewater Park and the large quarries near Dartford. These sources will utilise available groundwater which is currently being pumped to waste for dewatering purposes as part of the quarry operations. Once Phase 2 is complete, the scheme will have achieved an overall reduction of 70% in licensed abstraction from the Darent catchment with consequent benefit to flows in the River Darent.

Changes in flow for the river between Westerham and Dartford



escarpment dips gently toward the Swale which is here bordered by broad coastal lowland crossed by spring-fed streams draining the northern margin of the downland area. Elsewhere the area is heavily dissected by a complex of interconnecting dry valleys trending south-west to north-east. There are no surface water courses apart from the Medway which follows a meandering course through the gap cut in the escarpment between Snodland and Rochester, forming the western boundary. The 352 km^2 recharge area comprises unconfined Upper Chalk dipping north-north-east at approximately 2° beneath a cover of Palaeogene sands and clays. Of these, the London Clay Formation is the most important aquiclude in the area reaching a thickness of more than 130 m. The general dip of the Chalk is modified, albeit only slightly, by folding on an axis at right angles to the dip and by a second structural set parallel with the dip. The latter is characterised by fracturing and minor displacement.

It is this set which appears to form the zones of high permeability reflected at the surface in the development of dry valleys. These features have provided the most productive sites for groundwater abstraction. The greatest yields and highest rates of groundwater flow are encountered in the fracture zones associated with the dry-valley systems. They also occur throughout the outcrop of the White Chalk Subgroup within the zone of water-table fluctuations where solution activity has been most intense. Groundwater movement in the Chalk follows a predominantly north-easterly path toward the Swale coastline. Much of the flow breaks out as spring discharge at the contact with the overlying Palaeogene strata, most of the constituent formations having relatively low permeability. The major fracture zones developed in the White Chalk Subgroup are separated by areas of relatively low transmissivity running sub-parallel with the dry valleys and acting as partial groundwater barriers.

Average annual rainfall varies across the area from less than 580 mm in the extreme north-west to a maximum of 720 mm in the south-east near the top of the scarp above Charing. The corresponding effective rainfall rate of 230 mm translates into an average annual recharge of $8.1 \times 10^4 \text{ Ml a}^{-1}$. Authorised abstraction stands at $6.7 \times 10^4 \text{ Ml a}^{-1}$, drawn predominantly from the outcrop Chalk but small supplies are taken from the confined extensions underlying the Isle of Sheppey and the coastal margins of the Swale. This represents an average year commitment of 83%. This was notwithstanding the control and conservation measures adopted by the National Rivers Authority and water companies in a concerted campaign to reduce consumption. Borehole abstraction progressively out-stripped aquifer replenishment and the extent of resource depletion was such that even at the end of the first winter of recovery (1992 to 1993), groundwater storage throughout the central region of the block was still only 25% of normal.

The north Kent model (see Section 5.3.3) was developed to make recommendations about the future development of the groundwater resources of the part of this block between the rivers Medway and Stour.

The North Kent Marshes are designated as part of the Swale Special Protection Area (SPA) and RAMSAR site and the Environment Agency is required, under the European Habitats Directive, to review any abstractions likely to have an adverse impact on the constituent wetlands. Special attention will be given to those instances where baseflows are likely to have been reduced by abstraction from boreholes located near the northern extremity of the dip slope, close to the spring line. The review will identify whether any licensed abstraction has a significant effect on the conservation status of any part of a designated site. If an unfavourable effect can be demonstrated, remedial measures will need to be developed and implemented in order to restore these internationally important wetlands to a more favourable conservation status.

THE EAST AQUIFER BLOCK

This, the largest of the three blocks, comprises the greater part of the groundwater catchment of the River Great Stour, together with the Little Stour, Dour and the Isle of Thanet. The latter is separated from the main outcrop by the broad tract of marshland overlying Palaeogene deposits marking

the axis of a shallow syncline. Table 3.1 provides separate water balance summaries for the constituent resource areas. Taken overall, borehole abstraction accounts for more than 95% of the total licensed quantity and, as the majority of the sources are located close to the main water courses, abstraction has a more direct impact on river baseflows than might be deduced from the overall balance. For this reason, the principal spring-fed water courses have proved to be particularly vulnerable to periods of below-average winter rainfall. Significantly, both the Little Stour and Dour feature in the Agency's National Environment Programme on grounds of the need for measures to alleviate low flows.

Conditions in the eastern block as a whole have changed very little from the situation summarised in the River Stour study (Mott MacDonald and Partners, 1973):

'At the present time, almost the whole of the existing demand is met either directly or indirectly by groundwater from the Chalk aquifer. The constraint on further development in this field is the need to maintain the existing ecology in the Chalk streams and it was suspected that present rates of abstraction were, in many cases, close to this limit the only areas where significant groundwater sources still remain are in the confined Chalk aquifer near Canterbury and in the catchments flowing to sea around St Margaret's Bay.'

GREAT STOUR RESOURCE AREA

In a year of average rainfall, between 40 and 50% of the total recharge to the Chalk is abstracted for public supply and industry. This constitutes what might generally be regarded as a sustainable level of usage but there is evidence of other influences which, taken together, could bring increasing stress on the resources of the aquifer. River flows recorded at Wye and Horton gauging stations since 1965 have provided the basis for monitoring changes in the water balance for the Chalk component of the Great Stour catchment (172 km² out of a total area of 403 km²). During the 35-year period, average annual flows at Horton (Figure 5.2) have decreased by approximately 25% while those recorded at Wye have remained steady at around 70 Mm³a⁻¹. Table 5.1 provides a summary comparison of data for 1965 to 1998 and this shows an apparent decrease in recharge, after allowing for the increase in abstraction, of $2.6 \times 10^4 \text{ Ml}$; equivalent to a loss in effective rainfall of about 4 mm a⁻¹ for each year since 1965.

Figure 5.2 River flows recorded on the River Great Stour at Horton.

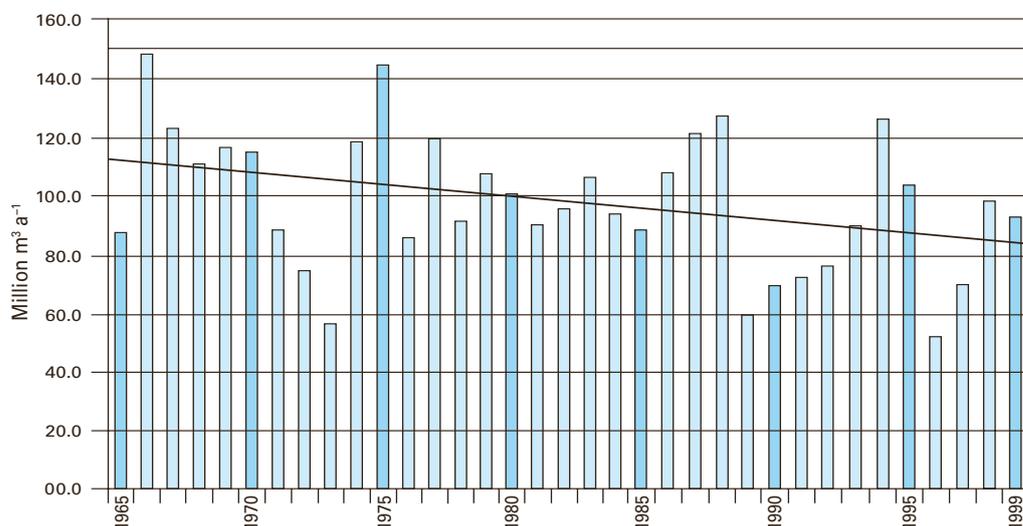


Table 5.1 Great Stour Chalk aquifer comparative water balances in mm³a⁻¹ (catchment area 172 km²).

Average annual totals	1965	1998	35 year loss
Inflow at Wye	70	70	0
Abstraction from Chalk	14	23	9
Outflow at Horton	117	82	35
Apparent annual recharge*	61	35	26

* Derived as (Horton-Wye)+ abstraction from Chalk

As to the most likely cause, the daily-read rain gauges at Canterbury, Wye and Charing (Figure 5.3) all show a progressive decrease of more than 50 mm in average annual rainfall over the last 90 to 100 years. The rate of decline appears to have slowed in recent years and the total

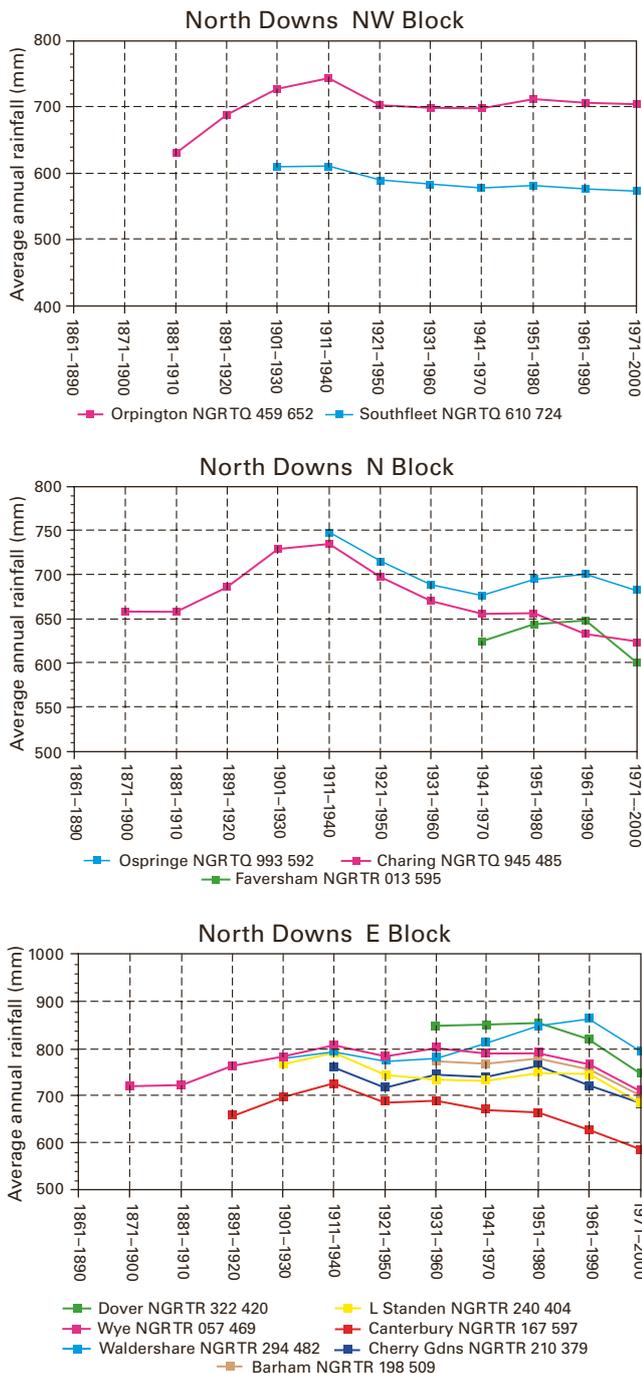


Figure 5.3 Changes in average annual rainfall for the north-west, north and east blocks of the North Downs.

since 1965 is estimated at not more than 0.4 mm a⁻¹, most of this being confined to the summer months. The decrease in terms of effective rainfall would, therefore, probably not exceed 0.1 mm a⁻¹. This leaves the apparent 4 mm a⁻¹ decrease largely unaccounted for and the question arises as to whether this could reflect other aspects of climate change. For example, although no systematic inspection of the evaporimetric records has been undertaken for the area, records for some stations in the south-east suggest an increasing trend in annual potential evapotranspiration rates (Figure 5.4). Whilst a direct relationship between climate change and river flow cannot necessarily be assumed, if the historic trend is taken as a general indicator, then further decreases in annual run-off can be expected and the point may be reached within the next 20 years when the flows at Horton and Wye will be almost equal with no significant intervening baseflow contribution to the river from the Chalk. This may have important environmental quality implications for the middle and lower reaches of the river.

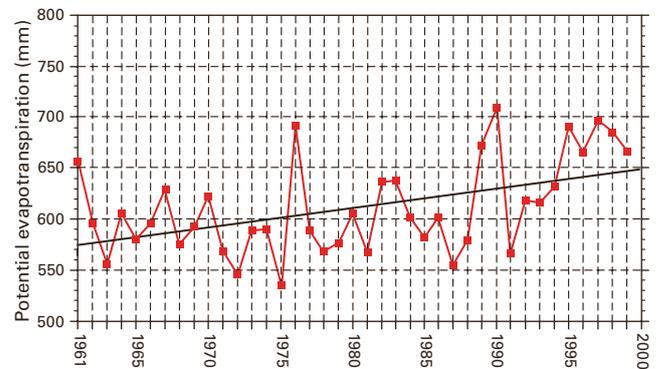


Figure 5.4 Annual potential evapotranspiration for the east aquifer block.

LITTLE STOUR RESOURCE AREA

The condition of the Little Stour is typical of the surviving Chalk streams of East Kent. The delicate balance of resources was highlighted early on in the long drought of 1989–92 when the lower course of the stream dried up completely over a distance of more than 2 km. Records of minimum summer flows near the river's confluence with the Stour indicate rates equivalent to between 15 and 20% of what would be expected for this catchment in its natural, undeveloped, state. Together with the Nailbourne, the Little Stour drains a catchment area of 287 km² of Chalk downland with the main course of the stream running south-west to north-east across the dip slope of the North Downs. The total stream length, from the head of the Nailbourne at approximately 120 m OD near Lyminge to its lowest point (2.0 m OD) at the West Stourmouth land drainage pumping station, is estimated at 30 km. The river has its confluence with the Stour at Plucks Gutter [TR 269 634], 2 km downstream of West Stourmouth. Approximately 1.5 km below Seaton it receives the flow of the River Wingham which enters on the right bank and drains an area of approximately 38 km². Almost 90% of the catchment is underlain by unconfined Middle and Upper Chalk, dipping north-north-east at about 2°. Near the north-east extremity of the catchment, the Chalk dips beneath clays and silts of the Thanet Beds which cover most of the remaining catchment area. The contact between the two formations is marked by an irregular spring line.

Annual rainfall averages 740 mm, ranging from around 820 mm at the top of the scarp above Lyminge to 620 mm near the confluence with the Stour below West Stourmouth. With potential evaporation averaging 525 mm, the long term effective rainfall is estimated at 316 mm a⁻¹, corresponding to an annual recharge of 9.04 x 10⁴ Ml a⁻¹. Current authorised abstraction from groundwater totals 2.44 x 10⁴ Ml a⁻¹ (of which public supply accounts for 99%), giving a relatively modest resource commitment of approximately 27%, rising to between 30 and 40% under drought conditions. This however masks the effect of the sources of supply located close to the river. Conclusions drawn from a comprehensive survey of the water resources of the Stour basin carried out by MacDonald and Partners (1973) include the observation:

‘There are special circumstances in the Little Stour and Wingham river valleys where it is estimated that full development of existing licensed sources would result in unacceptable river conditions every few years. It is recommended, therefore, that the existing sources in these catchments are resited in the confined parts of the aquifer and that compensation wells should be developed so as to supply the river with say, 30% of the combined minimum reliable yield of the newly sited sources’.

As a consequence, in any year with below-average rainfall, the section between Littlebourne and Seaton is likely to display near-zero flow conditions throughout the late summer and autumn months as the river flows in an artificial channel which is perched above the Chalk groundwater levels. The deterioration in flow regime is shown by the environmental degradation of the river below Littlebourne, marked, for the greater part, by the loss of most of the key invertebrate species normally associated with a healthy Chalk stream environment.

RIVER DOUR RESOURCE AREA

The Dour is a spring-fed Chalk stream draining nearly 90 km² of downland to the north-west of Dover. A further 40 km² to the north-east of Dover comprises an area of dip slope with groundwater draining sub-parallel with a south-west to north-east trending dry valley system. The strong rectangular configuration of the main watercourses and dry valleys is a reflection of the fracture pattern developed in the underlying Chalk. For the most part, the main river follows the line of a north-west to south-east trending set while the Alkham Valley, a major tributary feature, runs parallel with a south-west- to north-east-set which also controls the alignment of a number of coastal dry valleys in the Dover/Deal area. The catchment reaches a maximum elevation of approximately 130 m OD at its northern extremity near Lydden and a maximum of 180 m OD in the extreme west on the crest of the scarp slope. For much of its length, the southern watershed runs subparallel with the Lydden Valley which separates the catchment from the coastal cliff margin. Most of the catchment is underlain by the White Chalk Subgroup dipping gently north-east. A small area of the Grey Chalk Subgroup forms the floor of the Alkham Valley above Lower Standen. Away from the valleys, much of the Chalk is overlain by a low permeability capping of clay-with-flints and head brickearth, the total sequence locally reaching thickness of up to 5 m. These deposits cover more than 40% of the catchment and are considered to exert a strong influence on the distribution and intensity of aquifer recharge.

Average annual rainfall varies from a minimum of 740 mm in the coastal strip east of Folkestone to a maximum of over 850 mm at the head of the Alkham and Dour Valleys. Aquifer recharge for the western subcatchment has been determined from model studies (see Section 5.3.6) as averaging 2.85 x 10⁴ Ml a⁻¹; equivalent to an effective rainfall of 325 mm. The corresponding figure for the total catchment area is estimated at 4.26 x 10⁴ Ml a⁻¹. Current authorised abstraction, of which public water supply accounts for about 85%, stands at 3.56 x 10⁴ Ml a⁻¹ representing a resource commitment of 83%. Actual abstraction in recent years however averages less than half this, amounting to approximately 38% of the resource. Mean annual minimum flow (Q₉₅), as measured at the main gauging station at Crabble Mill has been determined at less than 20% of the natural rate. The recorded instances of dry channels and zero flows have been concentrated mainly on the Dour between Watersend Lake and Kearsney and on the Alkham Bourne above Bushy Ruff Lake. Following a below average recharge winter, the reach between Watersend Lake and Kearsney is one of the first to dry out or display low flow conditions. The process can start as early as July and depletion usually progresses downstream through Temple Ewell and Kearsney Abbey Lake. Here the impact of water-table depletion usually has its maximum effect sometime around September or October. Abstraction from the public supply boreholes sited in the east of the catchment between Dover and Deal seems to have had little influence on Dour baseflows. This may be partly because development of this part of the aquifer has been constrained by the risk of saline intrusion. However, local geological structural control also constrains flows to the Dour from the area. The most productive boreholes are located in the dry valleys which run sub parallel with the coast and these are associated with zones of high transmissivity. As a result, they generally display strong seaward flows even under relatively low hydraulic gradients and this allows the aquifer to recover fairly quickly following localised intrusions. Additional protection is, however, provided by a network of ‘early-warning’ boreholes which monitor water-table levels and salinities.

The River Dour was identified as one of the top 40 low flow rivers at the time of privatisation of the water industry. A joint investigation by Folkestone and Dover Water and the National Rivers Authority/Environment Agency resulted in the Dour Low Flow Alleviation scheme, Phase 1 of which was licensed in July 2006. Under Phase 1, abstraction at the company’s headwater sources is reduced when groundwater levels fall below a defined level linked to a target flow in the Dour. To compensate for this, an equivalent amount of water has been licensed for abstraction from boreholes at the lower end of the catchment. The aim is to reduce the impact of abstraction on the headwaters of the Dour and make the most use of the available resource in the lower reaches of the catchment before it is lost to the sea. Monitoring and reporting arrangements are in place to assess the effectiveness of the scheme.

THANET RESOURCE AREA

Although showing a heavy commitment on paper (authorised abstraction currently stands at 138% of drought-year resources), actual abstraction seldom exceeds 50%. This however, conceals the impact on the aquifer of the very high summer peak demand which accompanies

the annual tourist influx to the coastal resorts. Long term pumping rates are also severely constrained by high groundwater nitrate concentration and the risk of coastal saline intrusion. As a result, reliable output for most public supply boreholes falls short of the authorised rates and the area has become increasingly dependant on supplies developed throughout the 20th century further south.

5.3 DIGITAL MODELLING AS A MANAGEMENT TOOL

Groundwater models have been used extensively as resource management tools in the North Downs. They provide a means of both indicating weaknesses in the conceptual models and integrating the available data, thus highlighting any deficiencies, for a particular region. Calibration of the digital model to known field conditions provides a degree of confidence for it to be used in predictive mode as a management tool. A number of models have been produced for parts of the North Downs, including the following.

5.3.1 The Tilmanstone model

The use of settling lagoons for the disposal of minewater from 1907 to 1974 has resulted in the pollution of groundwater below an area of approximately 30 km² in east Kent (Box 4.1). A study undertaken by the then Southern Water Authority in the 1970s resulted in the cessation of the practice (Headworth et al., 1980). A numerical model of the groundwater flow and contaminant transport for the area was undertaken by the Water Research Centre (Bibby, 1981). It allowed for the first time the simulation of a large scale contamination event in the Chalk by including both rapid movement of the water through the fractures with retardation of the solute load through diffusion into the matrix pore water.

The prediction of future changes in the contamination concentration in the aquifer indicated that by 2008 there would still be 30% of the original 318 000 tonnes of chloride discharged from Tilmanstone Colliery in the aquifer. However, it was predicted that chloride concentrations would diminish to WHO limits for potable water (250 mg l⁻¹) by around 2004. See Figure 5.5 for chloride concentrations at Tilmanstone compared to levels predicted by the model. Clearly the model predictions were overly optimistic. A study by University College London (Burgess et al., 2002) indicated that this has a number of causes. Field studies and modelling revealed the effective transport parameters to be: a fracture aperture range of 0.4 to 3.8 mm, effective groundwater flow velocities ranging from 9 to 73 m d⁻¹ and matrix block sizes increasing

exponentially with depth from approximately 14 cm at 10 m depth to 7 m at 100 m depth. Most significantly the research by University College London has demonstrated the importance of the detailed Chalk lithostratigraphy in influencing the movement of the saline plume through the aquifer (Watson, 2006). The newly measured effective transport parameters have been incorporated in a one-dimensional dual porosity model and a three-dimensional integrated flow model and dual porosity solute transport model, MODFLOW and MT3DMS respectively (McDonald and Harbaugh, 1984; Zheng, 2002). Depending on the timescale of interest, the dispersive spreading will be limited by fracture orientations and diffusion into the matrix pore waters. The subsequent simulations showed that by 2074 high concentrations are diminishing in the upper part of the profile, but are only just appearing in deeper layers, a function of the variability of effective transport parameters for different Chalk lithologies.

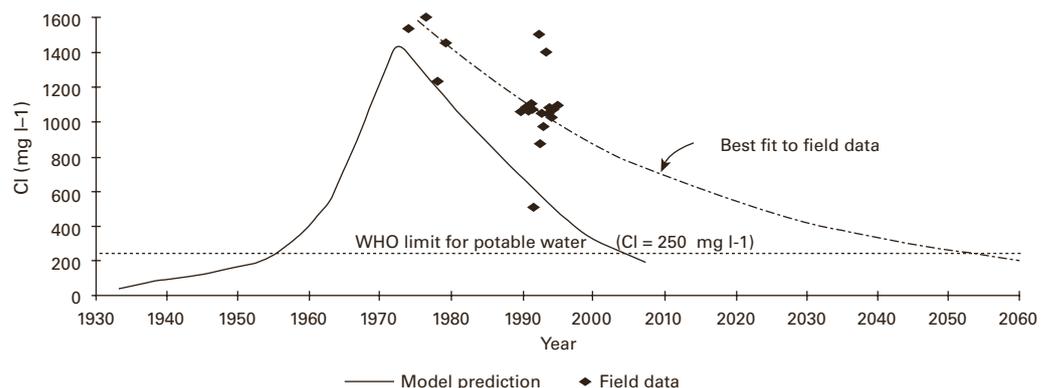
5.3.2 The Swanscombe model

Thames Water Utilities Ltd is exploring new groundwater resources in part of the North Downs to the west of the River Medway including the Darent catchment and part of the Cray catchment. Interest in this area stems largely from the large-scale dewatering operation within a major Chalk quarry 2 km south of the River Thames, and the possibility of intercepting the groundwater before it reaches the quarry (see Section 5.2.2, West Medway Resource Area). A regional groundwater model was developed by the British Geological Survey using the groundwater modelling code ZOOMQ3D (Jackson, 2001) which is capable of representing local-scale features within a regional context. The model was originally developed to assess the sustainability of major new groundwater abstractions within the regional system. However, as the objectives of the study and the spatial scale of interest changed, the model was modified and successfully used to simulate a group pumping test in a locally complex aquifer system (Jackson et al., 2003).

5.3.3 The North Kent model

Constructed by Southern Water Authority and Mid Kent Water Company (1989) in order to investigate and develop the groundwater resources of the north Kent Chalk, it was part of a wider study that included investigation (but not modelling) of the Lower Greensand Group aquifer. The boundaries were taken as the River Medway in the west, the River Stour in the east and the base of the outcrop of the Lower Chalk on the North Downs scarp slope

Figure 5.5 Chloride concentrations at Tilmanstone compared to levels predicted by the model.



to the south while the northern boundary lay under the Thames Estuary. The model was successfully calibrated against field data derived from the hydrometric network and abstraction records from 1960 to 1985 which enabled recommendations to be made about the future development of the groundwater resources.

More recently another groundwater model has been commissioned by the Environment Agency for the north Kent area (Water Management Consultants, 2006). Using the MODFLOW model code it covers essentially the same area as the earlier model. It was assessed and refined through comparison of simulated and observed conditions over the period from 1970 to 2004. A total of 158 abstractions are represented within the model. Of these 36 are for public water supply which, along with six abstractions for the Kemsley Paper Mill and the Faversham Brewery, account for over 95% of abstraction within the modelled area.

It was found that the introduction of a facility to represent the variation of permeability with depth was necessary to successfully simulate the form of groundwater recession curves in a large number of observation boreholes within the study area. Additionally it was found necessary to include lateral flow in the unsaturated zone beneath the top of the North Downs to be able to simulate groundwater conditions. Further research has been recommended as no field evidence was found to indicate that such flow actually occurs. A strike-parallel zone of high transmissivity was introduced in the model adjacent to the surface contact between the Chalk and early Palaeogene formations which improved the model's capacity to simulate observed conditions. Again, further work was recommended to investigate whether such a zone actually exists. It was also recognised that the model did not sufficiently represent the known complexity of the Palaeogene deposits and this would need to be addressed for the model to adequately simulate the groundwater conditions of the North Kent marshes.

5.3.4 The London Basin model

This model was completed in early 2000 as a joint venture between the Thames Region of the Environment Agency and Thames Water Utilities Ltd., and was constructed by Mott MacDonald. It focuses on the confined Chalk aquifer of the Central London Basin but was specifically extended to cover the North Downs unconfined Chalk between Epsom and Orpington. The model is conceived as a four-layer system (the Chalk as two layers to simulate variable permeability with depth, the Basal Sands and London Clay Formation / Woolwich and Reading Formations) although of course only the Chalk is present in the North Downs section. The model was developed in order to assist with the management of all the Chalk groundwater resources of the modelled area and particularly to help with management of rising groundwater levels in London.

From observations and inferences of geology, groundwater hydraulics and hydrochemistry, the Chalk appears to comprise a series of fault bounded aquifer blocks, having boundaries of variable permeability. The result is that these aquifer blocks have variable interconnection, and are a critical control on the impact of abstraction on groundwater resources and with the River Thames. Since its initial development, the model has been enhanced to include these aquifer blocks and boundaries thus providing an important tool to support Thames Water's wider resource development

programme. Thames Water Utilities Ltd has an extensive on-going resource development programme within the modelled area, including:

- The Central London Rising Groundwater programme
- The North London Artificial Recharge Scheme
- The South London Artificial Recharge Scheme
- The East London Resource Development

5.3.5 The East Kent Chalk aquifer model

In 1990 The University of Birmingham Civil Engineering Department and Acer Consultants Ltd. were commissioned by Folkestone and District Water Company to carry out mathematical modelling of the east Kent Chalk aquifer around Folkestone and Dover (Folkestone and District Water Co., 1991). Funding was provided by Folkestone and Dover Water Company, Mid Kent Water Company, the National Rivers Authority and Southern Water Services Ltd. The work was carried out in three phases. Phase 1 examined the future development of groundwater in three broad zones: the Little Stour (including the rivers Nailbourne, Acrise-Denton and Wingham), the River Dour catchment, and the Dover–Deal area. Phase 2 extended the model to include the Great Stour catchment. Phase 3 concentrated on concerns specific to Folkestone and Dover water supply. The model was calibrated to data from 1980–1990. In 1996 the model area was truncated to the west, essentially using the Great Stour as the boundary – this model was calibrated against data from 1980–1996.

The modelling studies concluded that for the Dover–Deal area, if all licences were to be utilised at their permitted maximum, significant saline intrusion would occur. No solution to a viable pumping regime with increased abstraction was determined. For the Dour area the model predicted difficulties in obtaining licensed output during droughts for the inland sources coupled with significant reductions in the Dour flow. It was determined that additional abstraction may be possible from central Dover and that surface/groundwater interactions in the Nailbourne and Little Stour may potentially provide a gain in overall resources.

In 2003 the Environment Agency commissioned another East Kent Groundwater Model (EKGM) which was completed in 2006 (Mott MacDonald, 2006). Its objective was to ascertain the likely impacts of abstraction and discharges on groundwater levels and streams flowing from the Chalk aquifer on the wider aquatic environment and to explore groundwater management options. It covers an area between the Chalk scarp east of Ashford to the coast around the Isle of Thanet and includes the catchments of the rivers Great Stour below Wye, and all the Little Stour, Wingham Stream, Dour, North-South Streams and various rivers and streams flowing in areas of Palaeogene strata.

The East Kent Groundwater Model uses the MODFLOW code with the Environment Agency's option to simulate variation of permeability with depth (VKD). The model was accepted as providing a generally good representation of groundwater levels and river flows. Coastal and scarp spring flows are also considered to be reasonably represented. Under a separate study for drought forecasting, the model was extended to mid 2006. It is expected that further extensions will be undertaken in the future.

5.3.6 The River Dour model

In 1998 the Environment Agency commissioned Mott MacDonald to develop a groundwater model of the River Dour in order to evaluate the impact of groundwater abstraction on sensitive areas of the river. The model was also to be used to assess potential strategies for low flow alleviation. The model indicated that a combination of abstraction cutbacks in the upper catchment, and corresponding increases in abstraction around Dover, along with limited river augmentation provided the most beneficial flow regime.

5.3.7 The Ravensbourne model

The Ravensbourne catchment groundwater model was developed for Thames Water by Hydrogeological Services International in order to:

- consolidate hydrogeological understanding of the catchment
- determine the impact of increased abstraction on the Ravensbourne and on other abstractors within the catchment.

The groundwater system was conceived as a three-layer system consisting of London Clay Formation, Lower London Tertiary Sands and the Chalk. The base of the Chalk was taken as a depth of 100 m below the potentiometric surface under recent average hydrometric conditions on the assumption that groundwater flow occurs in the upper 100 m of the Chalk, although in practice most flow probably occurs in the upper 30 to 40 m.

5.3.8 The Darent and Cray catchments mathematical model

An integrated groundwater/surface water model of the Darent and Cray catchments was developed by Mott MacDonald, approximately over the period 1994 to 1997 for the (now) Environment Agency as part of the River Darent low flow alleviation scheme (see Box 5.1). The code was based on the integrated finite difference method (Narasimhan and Witherspoon, 1976) which has been extensively developed and incorporated into the Mott MacDonald Integrated Catchment Management Modelling (ICMM) package on many projects. The code used to input recharge data to the ICMM was a modified version of the Stanford Watershed Model (Crawford and Linsley, 1966). The model calibration period extended from 1970 to 1997 and was subsequently updated by the Environment Agency to include 1999.

The Darent ICMM has six model layers. The lowest is the Hythe Formation (limestones), followed by the Sandgate Formation (an aquitard) and the Folkestone Formation (sands), all of which outcrop in the upper Darent catchment. The model then represents the Gault Clay Formation and the Chalk aquifer and finally an overlying alluvium layer. The Chalk is represented as a single layer without a depth dependent permeability profile. A feature of the model is the definition of a submodel in the mid Chalk catchment area. This has a refined grid and allows closer approximation of the river and lake system in this part of the catchment. Both main and submodels incorporate special routines to simulate the operation of augmentation boreholes according to rules which are based on the achievement of target flows in the Darent.

5.3.9 Source protection zone models

A set of steady-state groundwater flow models was used to help define groundwater source protection zones in the North Downs in support of the Environment Agency's Groundwater Protection Policy (Environment Agency, 1998). The general approach taken was to use steady state groundwater flow models on a catchment scale to estimate the average groundwater flow fields. These provided the framework for reverse particle tracking with the travel times along these traces being used to define the source protection zone limits. Model calibration was based on applying average recharge estimates and varying the permeability distribution to match simulations with observed average groundwater levels and baseflows. In predictive mode, the source abstractions were set to protected yield levels and uncertainty levels were applied. A general feature of these models is the representation of the Chalk, for particle tracking purposes, using an effective aquifer thickness. A value of 50 or 60 m was adopted, based mainly on geophysical log profiles.

For that part of the North Downs within Thames Region of the Environment Agency, two large steady state models using the FLOWPATH groundwater modelling package were constructed. The western area model covered the River Wey to the River Mole and included the complex group of sources at Leatherhead. The eastern model extends to the eastern limit of the Thames Region.

The Darent ICMM was modified by Mott MacDonald to allow greater mesh refinement around groundwater sources which is required to define flow paths and hence travel times with sufficient accuracy. The Darent ICMM was also interfaced with the USGS MODPATH code for particle tracking. The ICMM code modifications were first verified against more conventional MODFLOW and FLOWPATH solutions.

Two MODFLOW/MODPATH steady state models were constructed by the Environment Agency to cover the north Kent Chalk from the Darent catchment boundary eastwards to the English Channel at Dover. The average flow fields were calculated using the USGS MODFLOW code and representing the Chalk as a single layer of 50 to 60 m effective thickness. Considerable mesh refinement around groundwater sources was applied to achieve sufficient definition. These models applied an average recharge pattern which was modified to represent recharge routing off the extensive cover of low permeability clay-with-flints. High chalk permeabilities were applied in the major valleys and dry valleys with much lower values in the interfluvial areas. Notably, the modelled permeability contrast had to take place over a short distance and by a factor, typically, of about 20 to 40:1.

The Isle of Thanet Chalk was modelled using the FLOWPATH code by Southern Science Ltd for the Environment Agency. This follows the same principles as the MODFLOW/MODPATH codes but within the one package. Most of the Chalk sources on Thanet have long adits as collectors and these were represented in FLOWPATH by distributing the abstraction along them.

5.4 MANAGEMENT ISSUES AND DRIVERS

Five key issues have been identified that will drive water resource management over the coming decades, namely:

- the substantial resource deficit reflecting the long history of water supply development concentrated mainly on Chalk groundwater

- the future impact of climate change processes and the likelihood of a continuing deterioration in the balance of resources
- additional stress resulting from future growth in public supply demand
- a general and continuing increase in the scope of national and EC legislation aimed at environmental protection and enhancement which, in turn, demands increasingly stringent control over water abstraction and use
- diffuse pollution and groundwater protection.

Of all the factors influencing the development of water resource management strategy, climate change probably represents the most uncertain element, in both the nature and degree of its impact. It could for example, influence all of the major components of the water balance including the target flows and levels adopted for the designated spring-fed streams and wetland sites. The increased frequency and severity of droughts in recent years have been cited as evidence of progressive climate change and forecasts by the Climate Change Impacts Review Group indicate that the south-east could become drier with lower summer rainfall totals and higher evaporation loss rates. Although winter rainfall is expected to increase, the corresponding gains to groundwater storage and the resultant spring-fed baseflow may not fully compensate for the high deficits accumulated during the summer months. There is therefore some concern that for those areas of higher demand where sources of supply are already under stress (and the North Downs Chalk is a conspicuous example), sequences of deficit years could become increasingly frequent features of the regional climate.

The long-term trends in annual rainfall exemplified by the small sample of North Downs rain-gauge records presented in Figure 5.3 would suggest that if there is an influence for change it would seem to be operating differently for coastal and inland sites. Without drawing too many conclusions from the limited dataset, the record for the Stour catchment indicates a reduction of about 7% in average annual rainfall over the 90 year period; the likely implications of this are discussed in Section 5.2.2.

At the other climatic extreme, and representing a completely different aquifer management challenge, are the recent instances of the heavy rainstorms and floods of October to December 2000. Rainfall during the four month period September to December was estimated for the North Downs at more than double the long-term average and by the end of the period the region was reporting record high water-table levels with substantial flows in the Nailbourne, Petham Bourne and other dry valleys throughout north and east Kent. Communities remote from any permanent watercourses and with no previous record of groundwater flooding have had properties inundated by springs and seepages breaking out through the foundations and defeating all the normal protective measures (including sand bagging and channel diversion works) that would be routinely employed to good effect against surface run-off. By mid summer of 2001, observation boreholes were still recording groundwater levels significantly above the seasonal average throughout the eastern block.

The European Water Framework Directive (2000/60/EC), which came into force in December 2000, is the most significant piece of European legislation relating to water management for at least two decades. The Directive is a response to the fragmented nature of existing legislation relating to water and provides a framework to pull this

together and expand the scope of water protection to all waters. The main aims of the Directive are to prevent further deterioration of, and promote enhancement of, the status (quality and quantity) of water bodies and related ecosystems. This includes the progressive reduction in the pollution of groundwater.

The management of waters under the Directive will be based on the concept of integrated river-basin management: all waters will be managed within 'river-basin districts', with groundwater assigned to 'groundwater bodies' within these. The delineation and initial characterisation of these groundwater bodies was completed by December 2004. The status of each river basin district will be assessed, monitoring programmes put in place, and issues and objectives identified in a river basin management plan.

Catchment abstraction management strategies (CAMS) are water resource management plans which are developed by the Environment Agency on an area-by-area basis as part of the work being carried out to meet the requirements of the Water Framework Directive. The CAMS areas have been based mainly on surface water catchments, complementing the existing local environment action plans (LEAPS). Although defined for the most part by river catchment boundaries, the resource areas falling either wholly or largely within the North Downs region are assessed primarily in terms of the balance of groundwater resources for the Chalk aquifer. This will also have to take into account the implications for the baseflow regime of any spring-fed streams or wetland areas. The environmentally acceptable flow regime (EAFR) can then be given definition in terms of the total in-river need and this will then provide the basis for a threshold or 'hands-off' flow for the control of abstraction. To put the strategy into effect requires:

- an update of all water balance estimates (taking into account the influence of climate change on demand growth and resource replenishment)
- assessment of the environmental requirements for each aquifer block
- determination of EAFR target flows and levels and
- outline of scheme options for achieving target flows.

The CAMS operate on a six-year review cycle, during which time the Environment Agency undertakes a detailed assessment of the resource, including total available resource, environmental requirements, licensed quantities, actual abstracted quantities. The balance between the committed and available resources determines the 'resource availability status' for each water resource management unit within the area, i.e. whether further abstraction licences can be granted without derogating the environment or other users (Table 5.2). The following 'sustainability appraisal' process considers what the resource availability status for each unit should be at the end of the six-year cycle. For example, in a catchment which is 'over abstracted' the Environment Agency may attempt to recover some licences.

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

Table 5.2 Definition of the CAMS ‘resource availability status’ classifications.

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

The North Downs Chalk aquifer is covered by the following CAMS areas:

London CAMS	Completed April 2006	Next review 2010 to 2012
Darent and Cray CAMS	Completed May 2007	
Medway CAMS	Completed April 2005	Next review 2009 to 2011
North Kent and Swale CAMS	Completed April 2004	Next review 2008 to 2010
Stour CAMS	Completed May 2003	Next review 2007 to 2009

Within the CAMS framework, new licences will be of finite duration, usually of the order of 15 years. Although renewal after this period is intended to be the norm, the Environment Agency is required to give abstractors several years notice if a licence is not likely to be renewed. Existing licences will gradually be brought under this new system and converted to time-limited status, with the Environment Agency beginning with those licences deemed to have most potential to cause adverse effects on the environment or the sustainability of resources. This new licensing system gives the Environment Agency more flexibility and enables it to respond more efficiently to future changes in demand or resource quantity or quality.

The impacts of current and future developments will need to be managed with the help of increasingly sophisticated integrated surface/groundwater models that can also incorporate baseline quality and pollutant

transport. These models will need to be developed to demonstrate compliance with the Water Framework Directive as well as predicting the impacts of climate change and altered abstraction regimes. For these models to be credible and defensible the data on which they are based needs to improve dramatically. Recent desk-based revision mapping of the Chalk in parts of the North Downs (Farrant and Aldiss, 2002; Aldiss et al., 2004) has used the new Chalk stratigraphy and in conjunction with borehole and seismic reflection data has led to the production of three-dimensional geological models for much of the area. The Thames Gateway development and the Channel Tunnel Rail Link (CTRL) are major initiatives that affect the water resources in this region through increased demand and the potential for groundwater pollution. The high-speed rail link from London to the Channel Tunnel poses risks to groundwater resources in general, and to individual sources of supply which had to be assessed. Having a total length of 109 km, the route passes through the full sequence of the Chalk of the North Downs. Preliminary investigations of various possible alternative routes and detailed ground investigation for the route provided a wealth of new data on all aspects of the Chalk (Warren and Mortimore, 2003); more than 5000 investigation holes including boreholes, trial pits and probes were sunk. The information gained from these sources has primarily been analysed to gain information on the engineering properties of the Chalk for the design and construction of the CTRL — including a 3.2 km long tunnel beneath the Chalk hills of the North Downs — but also provided valuable data to improve the understanding of Chalk hydrogeology in this region.

6 References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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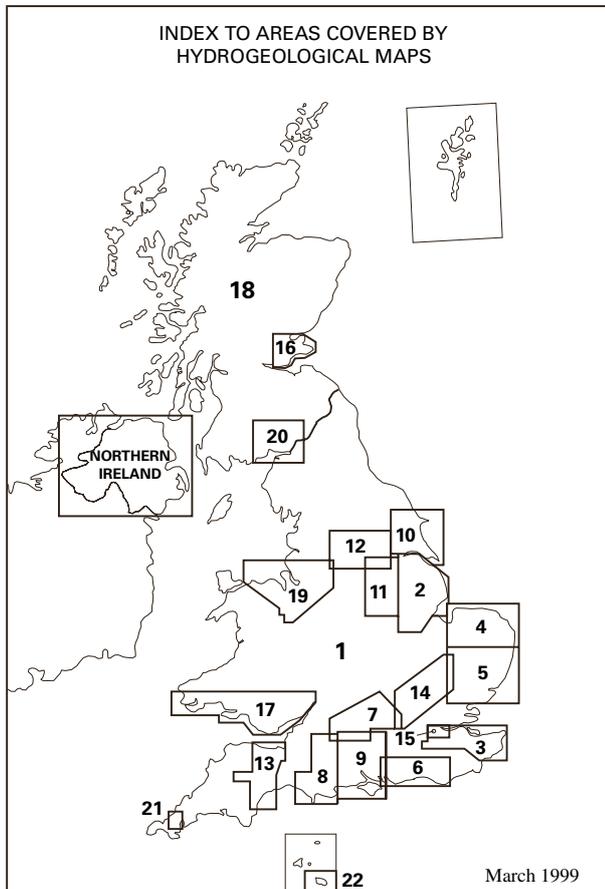
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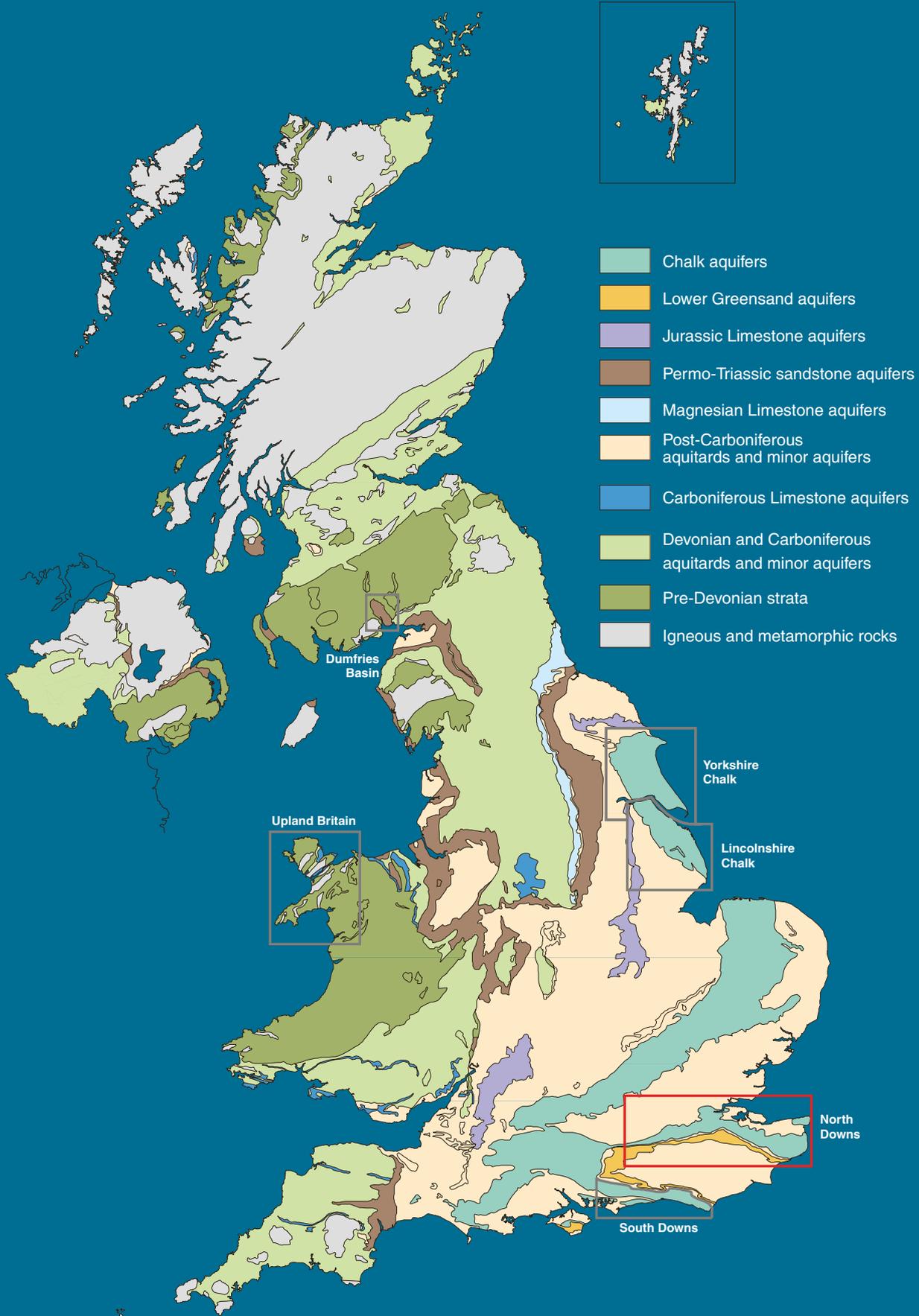
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