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The Chalk aquifer system of Lincolnshire

Research Report RR/06/03

BRITISH GEOLOGICAL SURVEY

RESEARCH REPORT RR/06/03

The Chalk aquifer system of Lincolnshire

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Front cover

The view from the Lincolnshire Wolds towards the Lincolnshire Marsh.

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Preface

This study, which was largely a review of previous work, was undertaken as part of the National Groundwater Survey (NGS), which aims to meet identified needs for the comprehensive description of the major British aquifers and their groundwater resources. This includes the characterisation of the physical and chemical properties and processes that govern groundwater flow and pollutant transport and attenuation, in both the unsaturated and saturated zones. The NGS commenced with a study of the Chalk aquifer, divided into eight regions. Completed studies are listed in the back of this report.

Although much work has been undertaken on the Lincolnshire Chalk aquifer system, there is a need for current knowledge to be brought together into a convenient format in the public domain. This study aims to compile available hydrogeological information and provide a summary of this information in report form, and furthermore to produce improved conceptual models of the aquifer system. This report is intended as a source of reference that will benefit and interest researchers, students and those in the water industry (suppliers, regulators and consultants) as well as the general public.

To meet the objectives of the study it has been necessary to go beyond a straightforward review of existing information. An interdisciplinary approach has been taken, where our understanding of the geology and recent geological processes have been integrated with our knowledge of the groundwater flow system, water chemistry and residence times. Understanding the fundamental geological, physical and chemical processes that have led to the development of the aquifer enables us to predict the distribution of aquifer properties more accurately. In turn, this improves predictions of the response of the groundwater systems to external changes such as increased abstraction or reduced rainfall.

The NGS brings together hydrogeologists with a diversity of interests and roles, mapping geologists, structural geologists and hydrogeochemists. This report reflects this multidisciplinary approach so that the Lincolnshire Chalk aquifer is portrayed as a dynamic and renewable resource that is managed to meet the demands of users and the environment.

The British Geological Survey has collaborated with the Environment Agency–Anglian Region, Anglian Water Services plc, and the University of Birmingham. An Advisory Panel involving members of the above organisations ensured that the work was relevant to them, as well as contributing much valuable information and acting as reviewers.

Acknowledgements

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Executive summary

The Lincolnshire Chalk aquifer system comprises the Chalk Group, the underlying permeable Lower Cretaceous formations (including the Spilsby Sandstone) and the overlying permeable Quaternary deposits. The Chalk has developed into a major aquifer as a result of a series of events and processes since its deposition in the Cretaceous Period. The Lincolnshire Chalk, which belongs to the Northern Chalk Province, has a lower matrix porosity than the Chalk of southern England; the greater hardness of the Chalk in this province has resulted in a higher degree of fracturing and, therefore, the potential for higher transmissivities. The Chalk possesses high transmissivity as a result of solution enhanced fractures, but has only low storage. The latter characteristic is a consequence of the small pore neck size in the matrix which precludes drainage of the pores so that only fractures contribute to the storage capacity of the Chalk. The combination of high transmissivity and low storage makes the aquifer susceptible to drought because the limited water stored can be depleted by rapid discharge to the coast. Fortunately the Quaternary sands and gravels play an important role in the aquifer system by contributing valuable additional storage. These superficial deposits provide a critical buffer during periods when outflows from the aquifer exceed inflows (recharge). The transmissivity of the Chalk is variable both spatially and perhaps more importantly with depth, the bulk of the permeability development being in the upper 30 m or so of the saturated zone of the Chalk.

There are two distinct Chalk groundwater systems in Lincolnshire. North of Louth, groundwater is recharged beneath the higher ground of the Wolds, where the Chalk is unconfined, and flows eastwards and north-eastwards where it becomes confined by Quaternary deposits. Groundwater is discharged from the confined aquifer by pumping from abstraction boreholes, by flow out to sea and, to a lesser degree, by upward leakage to spring-fed wetlands where the confining layers are more permeable. South of Louth the Chalk groundwater flow is very different. As the Chalk has been removed by erosion along part of a previous coastline, the unconfined Chalk beneath the Wolds is in effect disconnected from the confined Chalk to the east. The area where the Chalk is absent due to erosion is termed the Louth Window. Recharge to the southern unconfined Chalk is largely discharged as springs. Some groundwater may be transferred from the southern unconfined Chalk to the confined Chalk either through the underlying Lower Cretaceous formations or through the overlying permeable Quaternary deposits although the quantities are believed to be small.

Groundwater in the southern confined Chalk has a different chemical composition than that in the north. Evidence for only limited transfer of modern water from the unconfined Chalk is provided by the longer residence times of the confined groundwater (based on geochemical residence time indicators). Most of the groundwater abstracted from the Chalk is pumped from the confined aquifer north of Louth.

Leakage between the Lower Cretaceous and Chalk formations undoubtedly does occur although the quantities remain uncertain. This is mainly because the area where the more permeable Lower Cretaceous formations are in hydraulic continuity with the Chalk is difficult to define accurately due to overstepping of the Lower Cretaceous formations by the Chalk and due to variability in both lithology and thickness of the Lower Cretaceous formations. The continued decline in groundwater levels in the Spilsby Sandstone in the south eastern part of the area (in response to pumping from this aquifer) suggests that downward leakage from the Chalk may be less than previously thought.

The quality of groundwater in the Lincolnshire Chalk aquifer system is variable; groundwater is typically of good quality, but problems of high nitrate, and elevated arsenic and iron concentrations exist in some parts of the aquifer. Saline waters are present in some coastal areas of the aquifer. The chemistry of the groundwater is controlled both by natural processes, such as water–rock interaction, and by human influences, primarily abstraction, agriculture and industrial activities.

The groundwater has been categorised into four broad hydrochemical types, of which Types I to III are fresh waters, and Type IV is saline. Type I is modern water, of meteoric origin, with anthropogenic inputs; Type II is slightly older meteoric water, which was also recharged in modern times, but concentrations of solutes derived from anthropogenic sources (e.g. NO_3) are lower. Type III is considerably older, low total dissolved solids (TDS) groundwater, believed to have entered the aquifer system during the Flandrian; and Type IV is saline water. The Type IV waters can be further subdivided on the basis of their age and composition. This analysis of the hydrochemistry has revealed much about the present and historical flow systems in the aquifer.

The groundwater in the outcrop zone is modern (Type I). This modern water has also penetrated the confined Chalk of north Lincolnshire, as demonstrated by the high nitrate concentrations observed in this area. The groundwater in the confined Chalk of south Lincolnshire is old due to lack of flow across the buried cliff, which eroded completely through the Chalk in this area. Saline water exists in some parts of the coastal zone.

The Lincolnshire Chalk aquifer system is a valuable resource which has been used for potable and industrial use for the last 200 years. The properties of the Chalk aquifer make it susceptible to saline intrusion. Groundwater management was focussed on this issue and the need to control abstraction during the mid twentieth century. This concern provided the impetus for developing a regional groundwater model capable of forecasting the amount of groundwater than can be abstracted while restricting the inland movement of seawater. This was the first time that a regional groundwater model was used as a management tool in the UK and it enabled the saline intrusion problem to be successfully controlled with the cooperation of the major abstractors.

A second, later concern was the rise in groundwater nitrate concentrations observed in many abstraction boreholes during the past 30 years. This problem is widespread in many aquifers in the UK, especially in

southern and eastern England, and is a consequence of the leaching of nitrate from fertilisers applied to arable soils. Treatment works have been installed by Anglian Water Services and, while they are effective in reducing nitrate concentrations, they are costly. Nitrate is a particular problem in this aquifer as rainfall recharge is relatively low and provides little opportunity for dilution. Most of the outcrop of the north Lincolnshire Chalk has now been designated a nitrate vulnerable zone (NVZ). Farmers who are farming land within NVZs are required by law to comply with measures to control leaching of nitrate to surface water and groundwater. More recently, the aquifer system faces the threat of contamination by a wide range of synthetic organic compounds, principally pesticides and hydrocarbons. These compounds typically have low acceptable concentrations in drinking water (typically in the range 0.1 to 50 mg l^{-1}) and their occurrence in groundwater is frequently a result of casual disposal to the ground and accidental spillages or leakages.

During the past 20 years it has become widely recognised that the management of groundwater resources needs to be more than maintaining and protecting water supplies and the water resource and must also consider how best to safeguard and enhance the environment. Recognition of the wider importance and role of groundwater is reflected in the integrated basin management approach to managing groundwater which places emphasis on conjunctive use of water resources and the importance of balancing the needs of the abstractor with the need to safeguard the amenity and environmental value of the water resource. The European Water Framework Directive provides the legislative basis for applying these strategies in the UK. This is a challenging task and is made more difficult by uncertainties regarding the impact that climate change may have on water resources in the future.

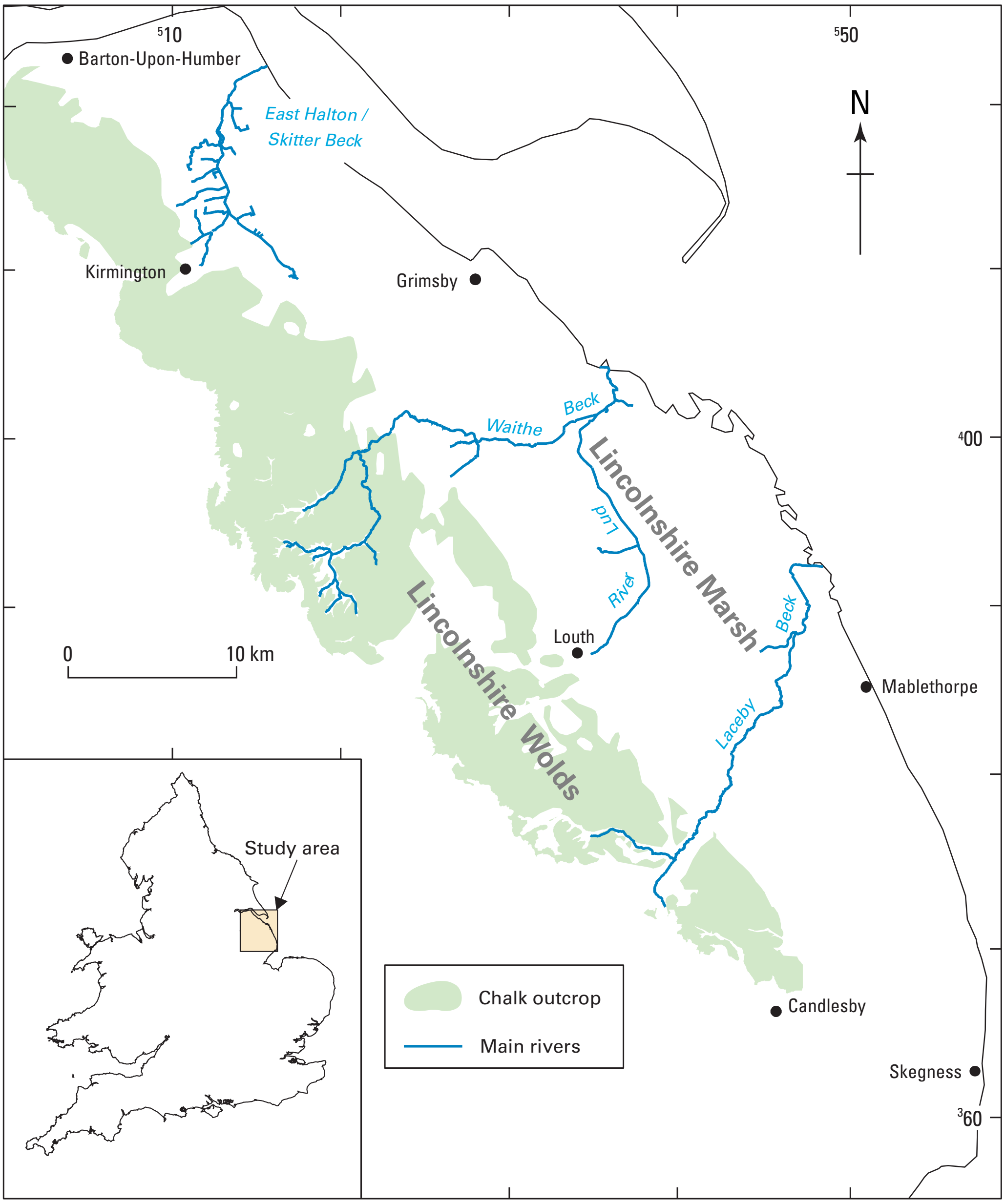
1 Introduction

The Chalk of Lincolnshire forms low rolling hills known as the Wolds which stretch from the Humber Estuary in the north to Skegness in the south. The area covered by this report is shown in Figure 1.1: the western boundary is the limit of the outcrop of the north-easterly dipping Chalk, and the eastern boundary is the present day coastline, although the Chalk extends out beneath the North Sea. The study area is approximately 80 km long and 25 km wide.

The Lincolnshire Chalk is part of the Chalk Group of the northern province and typically has lower porosity than, and is harder than, the Chalk of southern England. Northern province Chalk is also more thinly bedded and contains more frequent tabular flints. The structure of the Chalk in Lincolnshire is fairly simple, however, Quaternary erosion formed a wave-cut platform and associated cliffline in the east of the area. In an area near Louth the erosion removed the full thickness of Chalk, creating a feature known as the Louth Window (Chapter 2). These erosional features have since been buried beneath superficial deposits.

The main hydrogeological features of the Lincolnshire Chalk aquifer system are shown in Figure 1.2. It is pertinent to describe an *aquifer system*, as in some areas hydraulic connections exist between the Chalk and underlying formations such as the Spilsby Sandstone and permeable deposits above. The aquifer system is unconfined beneath the Wolds, but is confined by till in most of the eastern part of the region. Recharge occurs on the Wolds, from where groundwater generally flows to the

Figure 1.1 Location map, showing the Chalk outcrop and the extent of study area.



north east, discharging naturally as springs at the western edge of the till and to the sea. Flow patterns in the Chalk south of Louth are less well known as the Louth Window effectively separates the unconfined and confined parts of the Chalk. Saline water is present in some coastal areas of the aquifer, such as in the Grimsby–Immingham area. The major outflows are baseflow to rivers, springflow and abstraction.

The Chalk can store and transmit large quantities of water, and is thus a major aquifer that is extremely important for public water supply. Chalk is a fine-grained rock and only slight drainage of the matrix occurs under gravity due to the small size of the pores and the pore throats, so the matrix contributes little to effective storage and flow. The hydraulic properties of the Chalk are controlled by the network of fractures, particularly where they have been enlarged by solution. It is a highly transmissive but relatively low storage aquifer and these characteristics present significant problems to those managing the aquifer system. Firstly, the low aquifer storage may result in significant reduction in borehole yields, reduced stream flow, and saline intrusion during periods of limited recharge. Secondly, the aquifer is susceptible to contamination because contaminants can migrate rapidly through the aquifer (reducing the opportunity for attenuation) and there is little effective storage to provide dilution. As a result, high groundwater nitrate concentrations have become widespread over large areas of the aquifer as a result of intensive agriculture during the past 30 years. The Environment Agency, Anglian Region is responsible for regulation and protection of the Lincolnshire Chalk aquifer system (Chapter 5).

1.1 TOPOGRAPHY

The Chalk is exposed in the western part of the study area, forming the downland scenery of the Lincolnshire Wolds, which extend from the Humber to Candlesby [TF 45 67]. The Wolds run approximately north-west to south-east, with a steep escarpment on the western side, leading to an upland area, and a more gentle easterly dip slope (Figure 1.3). This Chalk outcrop is about 70 km long and up to 15 km wide. The upland areas reach elevations of around 165 m OD (above Ordnance Datum), but are lower around the Humber

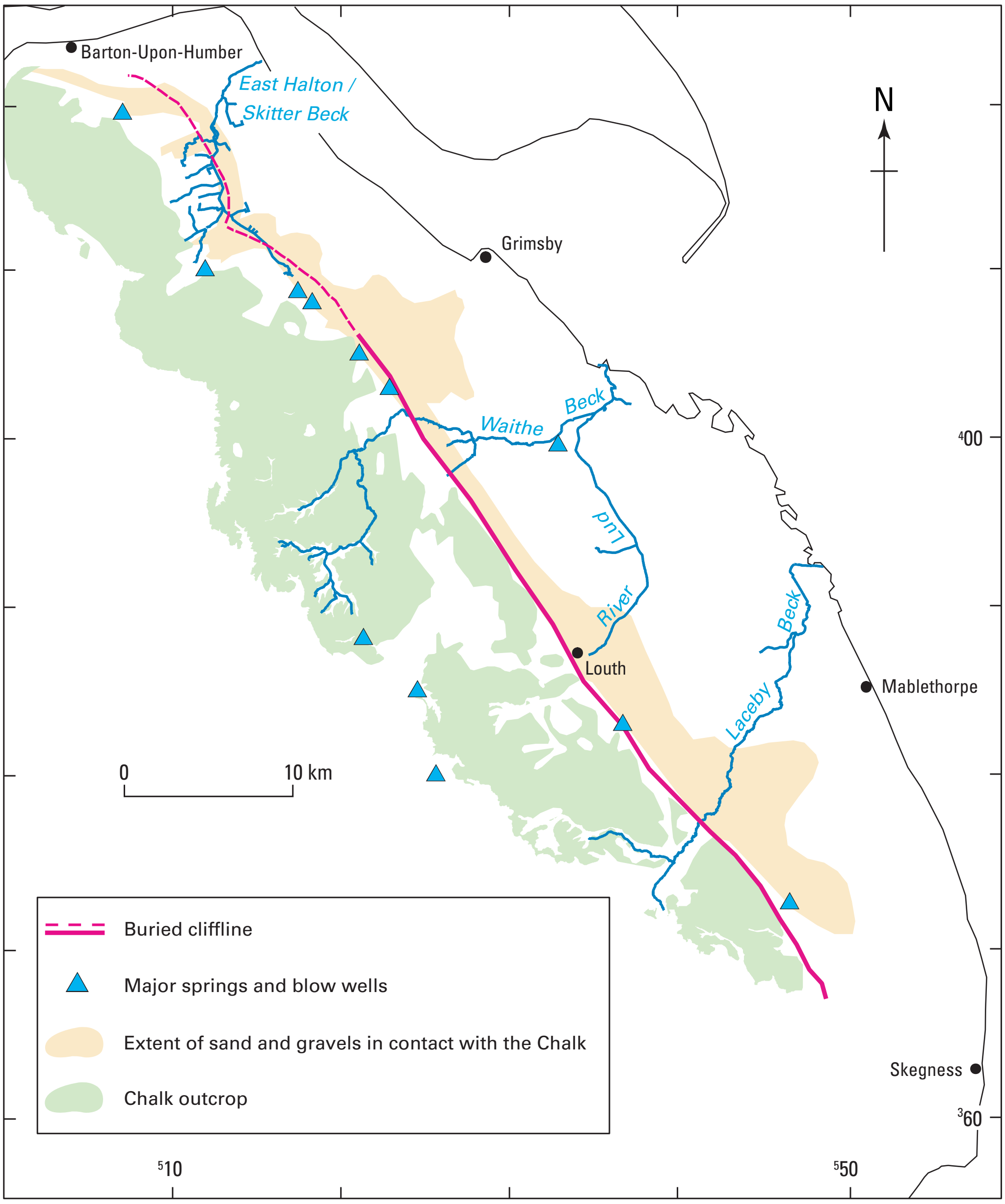
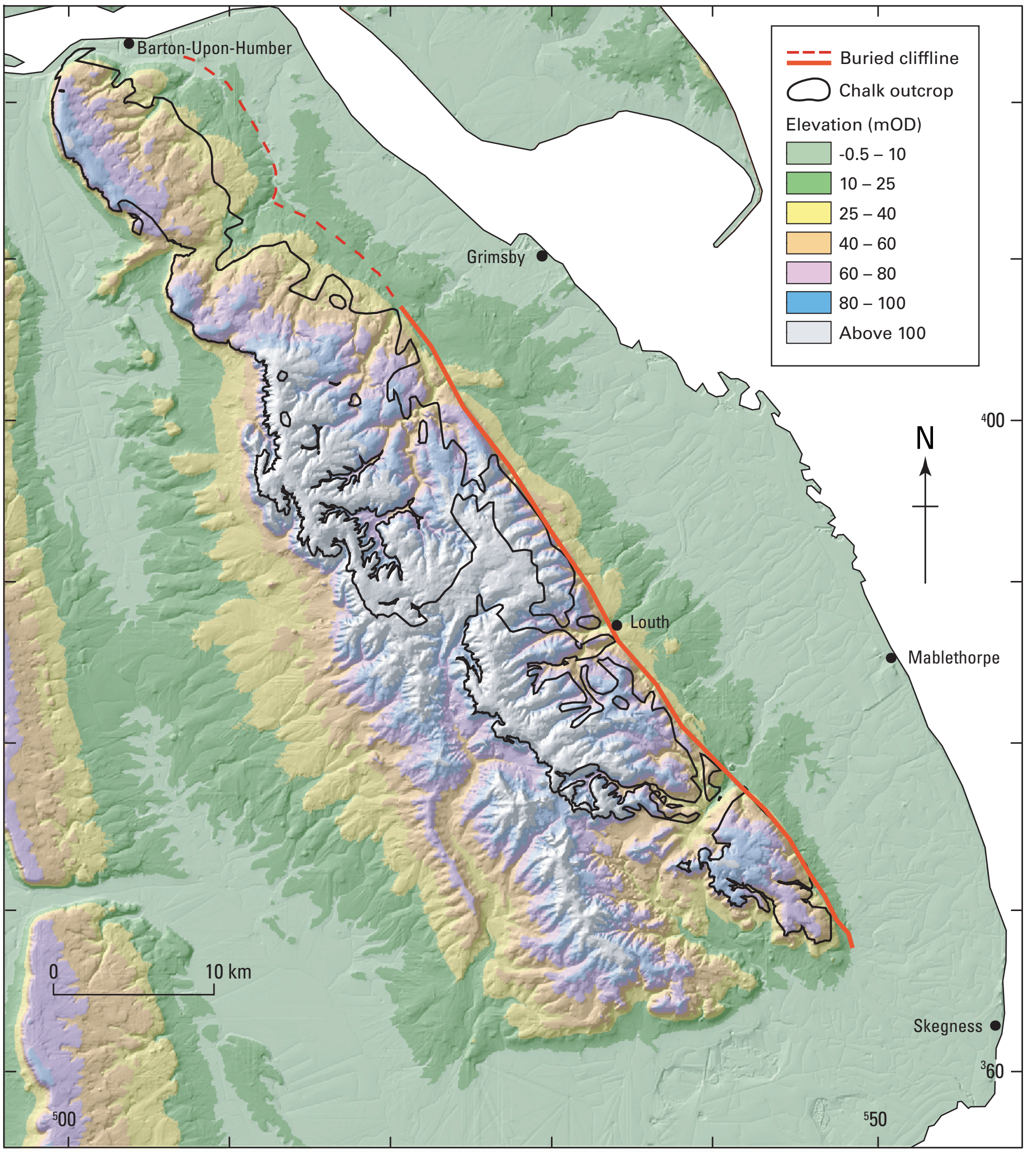


Figure 1.2 Hydrogeological features of the Lincolnshire Chalk aquifer system.

Figure 1.3
Topography in plan view.



Estuary and in south Lincolnshire, where the elevation rarely exceeds 100 m OD. The Wolds are incised by numerous dry valleys. East of the Wolds, the Chalk is covered by glacial till, which becomes thicker towards the coast. This area is the relatively flat, low-lying coastal plain known as Lincoln Marsh which is only 1 to 2 m above OD in places, and is up to 15 km in width.

1.2 DRAINAGE

There is little surface drainage on the Wolds, as the topography rarely intersects the water table. Stretches of 'Chalk' streams such as the Waithe Beck (Figure 1.4) flow on a mixed Lower Cretaceous sequence, predominantly of sandstones which provide baseflow to the streams, but with some stretches on clays and limestones.

In the north of the area, ephemeral springs from the Chalk feed streams which flow across the till to the sea. Lincoln Marsh drains towards the Humber Estuary and the North Sea. There are areas where the confining layer is relatively permeable allowing groundwater from the Chalk to rise up through Quaternary deposits to the surface forming large springs (known locally as blow wells) which feed important wetland sites and streams.

1.3 CLIMATE

MORECS (Met Office Rainfall and Evaporation Calculation System) data from 1961 to 2002 aggregated across the study area gives annual average precipitation of about 680 mm, annual average potential evaporation of about 614 mm and annual average actual evaporation of about 530 mm.

The distribution of annual average rainfall for 1961 to 1990 is shown in Figure 1.5.

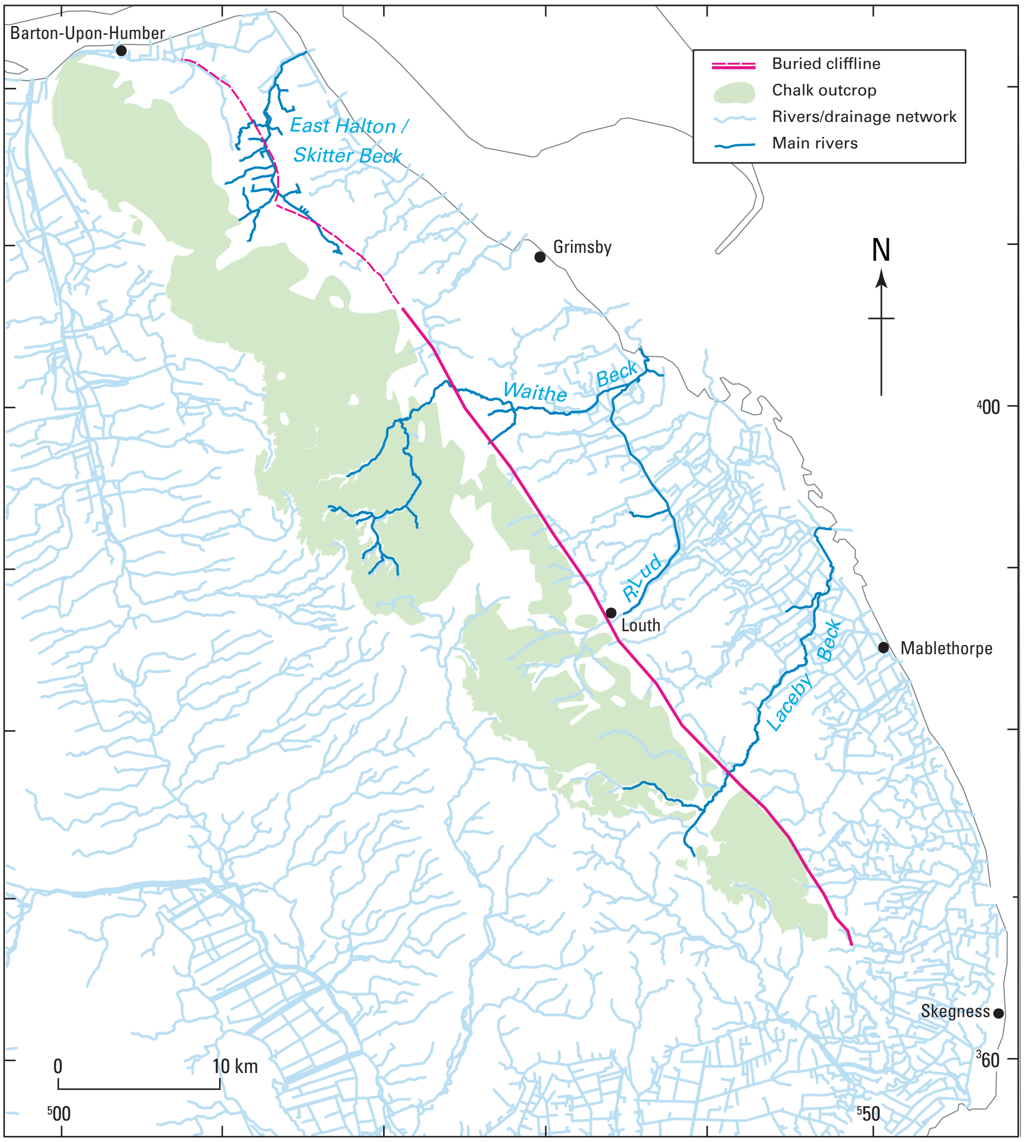
1.4 LAND USE AND DEMOGRAPHY

Lincolnshire as a whole is very rural and sparsely populated, however, there are some sizeable urban areas, and the population of the county is growing at a rapid rate (e.g. a projected increase of 4% from 1996 to 2001 compared to 1.4% nationally; Lincolnshire County Council, 1999). The most important towns in the area are Grimsby, Skegness and Louth.

Land use in the region is dominated by agriculture. Cereals dominate on the thin soils of the Wolds, whereas on the heavier soils of the Lincoln Marsh, sugar beet, potatoes and cereals are important.

Industry and urban areas are mainly located along the coast, especially in the Grimsby–Killingholme area. Much

Figure 1.4 Drainage network.



of the industry is related to food processing and packing. The service sector is the largest employer in the county. Tourism is also important to the county's economy and causes a substantial increase in population during the peak holiday season (Lincolnshire County Council, 1999). Land use in the area is shown on Figure 1.6. The simplified land use classification has been derived from the Land Cover Map 2000 (LCM2000: see Centre for Ecology and Hydrology, 2004, for further details) by aggregating land use categories. The LCM2000 data are obtained by analysing spectral reflectance data from Earth observation satellites.

1.5 WATER USAGE AND THE SIGNIFICANCE OF GROUNDWATER

Groundwater is the most important source of water in the area. Chalk boreholes for public supply were first drilled during the second half of the 19th century and abstraction from the Chalk aquifer for public supply and industry increased rapidly during the 20th century.

Groundwater from the Chalk aquifer system is the cheapest source of water in the area, typically requiring little treatment, and as such is in great demand. In fact, the aquifer is significantly over-committed, i.e. if all the licensed abstractions (which total c.182 Ml d^{-1}) were fully utilised they would exceed recharge and the resource would not be sustainable. However, the Environment Agency and major abstractors work together to reduce abstraction during periods of low recharge. This is discussed in more detail in Chapter 5. In a normal year the actual quantity abstracted from the aquifer system is about 60 to 70% of the licensed quantity. Most public supply abstractions are located just off outcrop or in the confined Chalk, mostly in the northern part of the study area. Large abstractions for industrial use are taken from the Chalk in the coastal areas between Grimsby and Killingholme.

Anglian Water Services (AWS) is responsible for public water supply in the study area. The raw water resource is obtained from a combination of groundwater and surface water sources in the area and imported water from adjacent catchments. The company operates 13 sources in the Lincolnshire Chalk and nine in the Spilsby Sandstone.

Key issues regarding the Lincolnshire Chalk aquifer system today are: quantifying the groundwater resource; understanding the permeability distribution; balancing groundwater abstraction with environmental demands; and quality issues, particularly diffuse pollution from nitrate and pesticides.

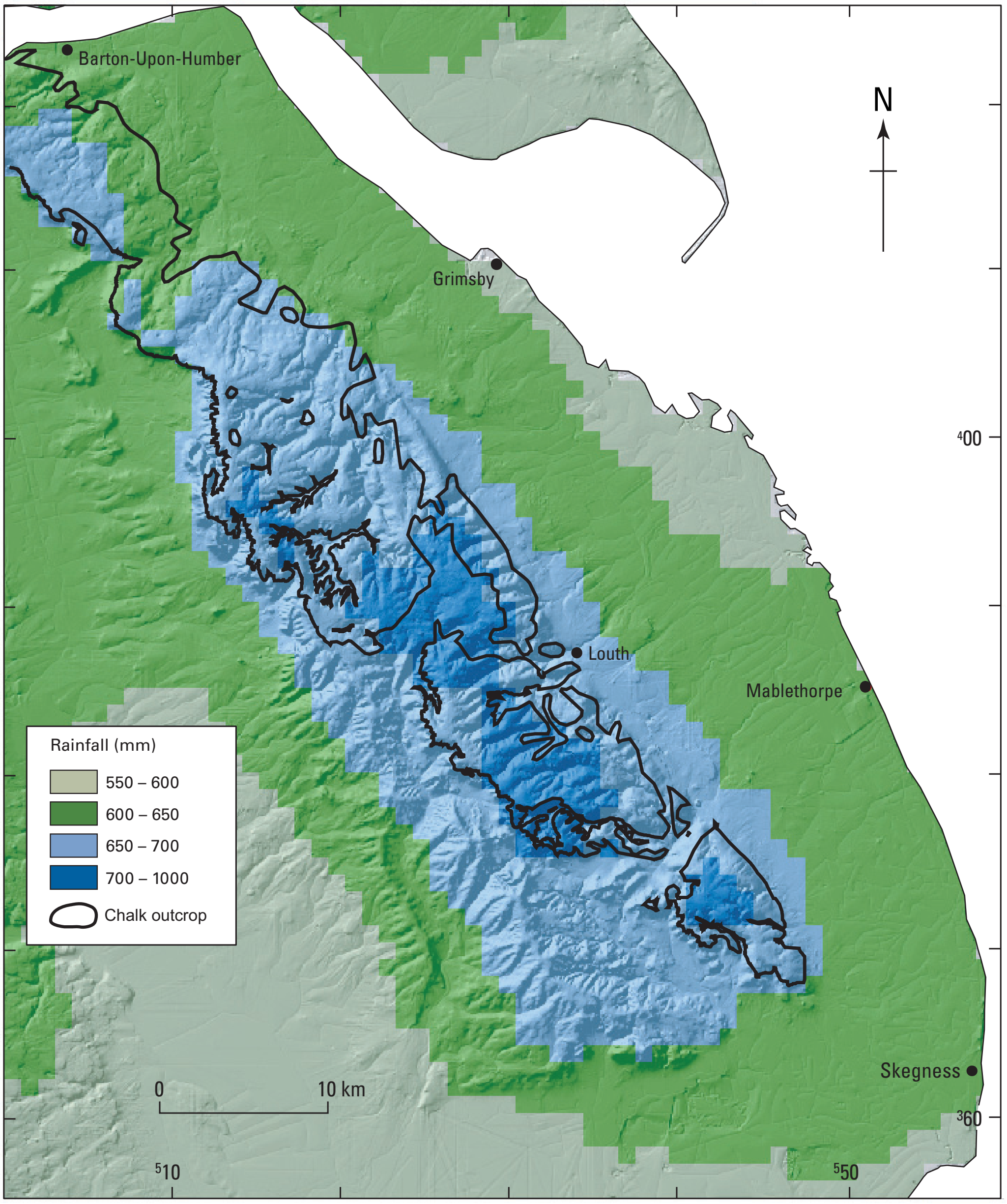


Figure 1.5 Annual average rainfall for the period 1961 to 1990.

1.6 PREVIOUS WORK

This report collates various research studies and investigations undertaken on the Chalk aquifer over the past 50 years. These include a series of studies of the hydrogeology of the Grimsby district, and of saline intrusion in that area, in the 1950s and 60s (Gray, 1954, 1955, 1956, 1958, 1964).

Later, a major research project evaluating the Lincolnshire Chalk aquifer system was undertaken by the University of Birmingham in collaboration with Anglian Water Authority (University of Birmingham, 1978, 1982, 1987, 1993). This research had a broad scope including geology, hydrochemistry, geophysics, hydrogeology and numerical modelling. Much of the information contained in this report originates from this investigation.

More recently, a number of studies of relevance to this report have also been undertaken. These include a study of the baseline geochemistry of the Lincolnshire Chalk aquifer (Smedley and Brewerton, 1998), and a review of the various changes in the lithostratigraphical classification of the strata in the area (Sumbler, 1999). The findings of these studies have been incorporated into this report.

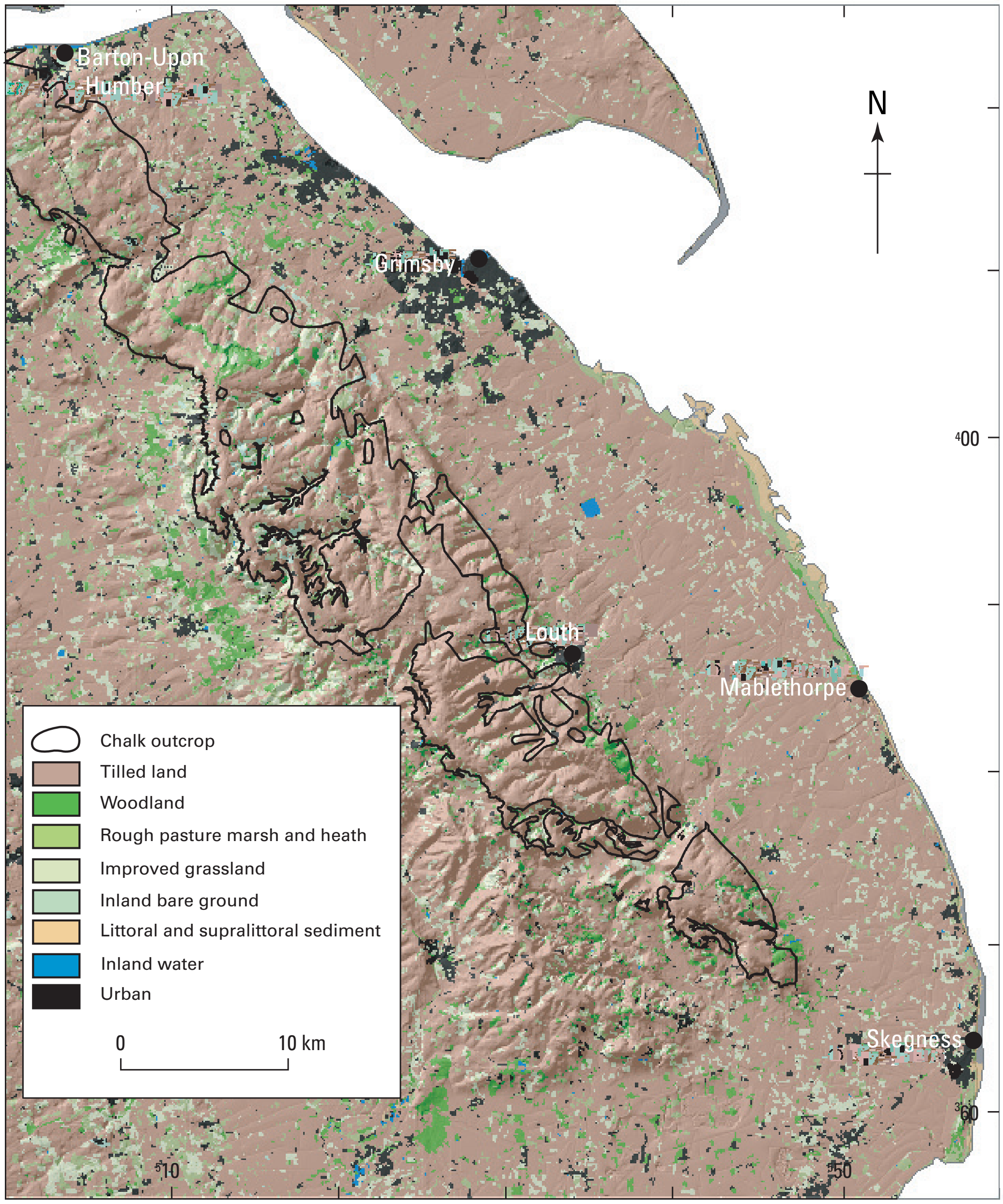


Figure 1.6 Map of land use.

2 Geology and structure

2.1 INTRODUCTION

Only Mesozoic and Quaternary formations occur at the surface within the area. Precambrian rocks have been proved in a deep borehole in Lincolnshire and Lower Palaeozoic sediments are locally present at depth (Kent, 1980). However, the most extensive basement rocks across much of the region are of Carboniferous age. These ancient rocks are covered by considerable thicknesses of Mesozoic strata, of Triassic, Jurassic and Cretaceous age. The geological succession of the Upper Jurassic and Cretaceous periods is given in Table 2.1. These beds were laid down in a region of moderate subsidence known as the East Midlands Shelf. The Mesozoic succession tends to be thickest in mid or north Lincolnshire: it thins both southwards towards the stable structural high of the London Platform, and northwards towards the Market Weighton High, a zone of reduced subsidence in Yorkshire. The oldest rocks exposed in the study area are Late Jurassic in age and crop out to the west of the Wolds escarpment (Figure 2.1). The Jurassic strata are overlain by a series of Lower Cretaceous formations; these older strata thin out to the north, as illustrated in Figure 2.2. Towards the end of the Early Cretaceous a period of uplift produced an erosion surface that cuts down northwards through the underlying beds towards the Market Weighton High. As a result, most of the Lower Cretaceous succession is absent in the northern part of the region. The Carstone Formation, of Albian age, was deposited on this surface when a transgression over the region led to sublittoral reworking. As inundation proceeded, the supply of clastic sediments declined and the Hunstanton Formation (formerly known as the Red Chalk) was deposited. The transgression continued into Late Cretaceous times, during which white chalk was deposited in clear seas that extended over much of Britain. There are no rocks of Palaeogene age known in the district.

The combined effects of uplift of central England and subsidence of the North Sea Basin during the Late Cretaceous and Palaeogene resulted in the gentle tilting of the region such that today the Lincolnshire Chalk dips at 1 to 2° to the north-east. Contours on the base of the Chalk, shown on Figure 2.3, are slightly offset by the Caistor Monocline, a broad, minor fold which trends west–east from Grasby [TA 08 04] to Grimsby [TA 27 09]. In the west of the region the Caistor Monocline has a substantial downthrow to the north (Berridge and Pattison, 1994), but the displacement dies out towards the coast. Minor folding and faulting are common throughout the Chalk, in addition to pervasive jointing.

In the Quaternary the land surface was greatly modified by episodes of glacial erosion and deposition. During the Ipswichian interglacial stage a cliffline and wave-cut platform were eroded in the eastern part of the region, and were later buried beneath thick deposits of till, sand and gravel dating from the last (Devensian) glaciation. These features, the scale of which are illustrated in Figure 2.2b, are of great significance to the present-day hydrogeology (Chapter 3). Holocene (recent) deposits from the postglacial epoch include the silts and peats of Lincoln Marsh and reworked coastal material that is being deposited on the sandbanks at Grimsby and Immingham.

Table 2.1 The Upper Jurassic and Cretaceous succession in Lincolnshire. Aquifers are shown in bold.

PERIOD	CHRONOSTRATIGRAPHY	[sub] GROUP	FORMATION	MEMBER	
UPPER CRETACEOUS	Maastrichtian	CHALK GROUP White Chalk Subgroup	Rowe Formation Chalk (Holderness and North Sea)		Lincolnshire Chalk aquifer system
	Campanian		**Flamborough Chalk Formation**		
	Santonian				
	[Coniacian?]		**Burnham Chalk Formation**		
	Turonian		**Welton Chalk Formation**		
	Cenomanian	CHALK GROUP Grey Chalk Subgroup	**Ferriby Chalk Formation**		
LOWER CRETACEOUS	Albian		**Hunstanton Formation**		
			Carstone Formation		
			Sutterby Formation		
	Aptian		Skegness Clay Formation		
	Barremian		Roach Formation		
	Hauterivian		Tealby Formation	Upper Tealby Clay	
				Tealby Limestone Member	
				Lower Tealby Clay	
	Ryazanian		Claxby Ironstone Formation	HundlebyClay Member	
			Spilsby Sandstone Formation		
JURASSIC	Portlandian				
	Kimmeridgian	ANCHOLME GROUP	Kimmeridge Clay Formation	**Elsham Sandstone Member**	
	Oxfordian		Ampthill Clay Formation		
			West Walton Formation		
	Callovian		Oxford Clay Formation		
			Kellaways Formation etc.		

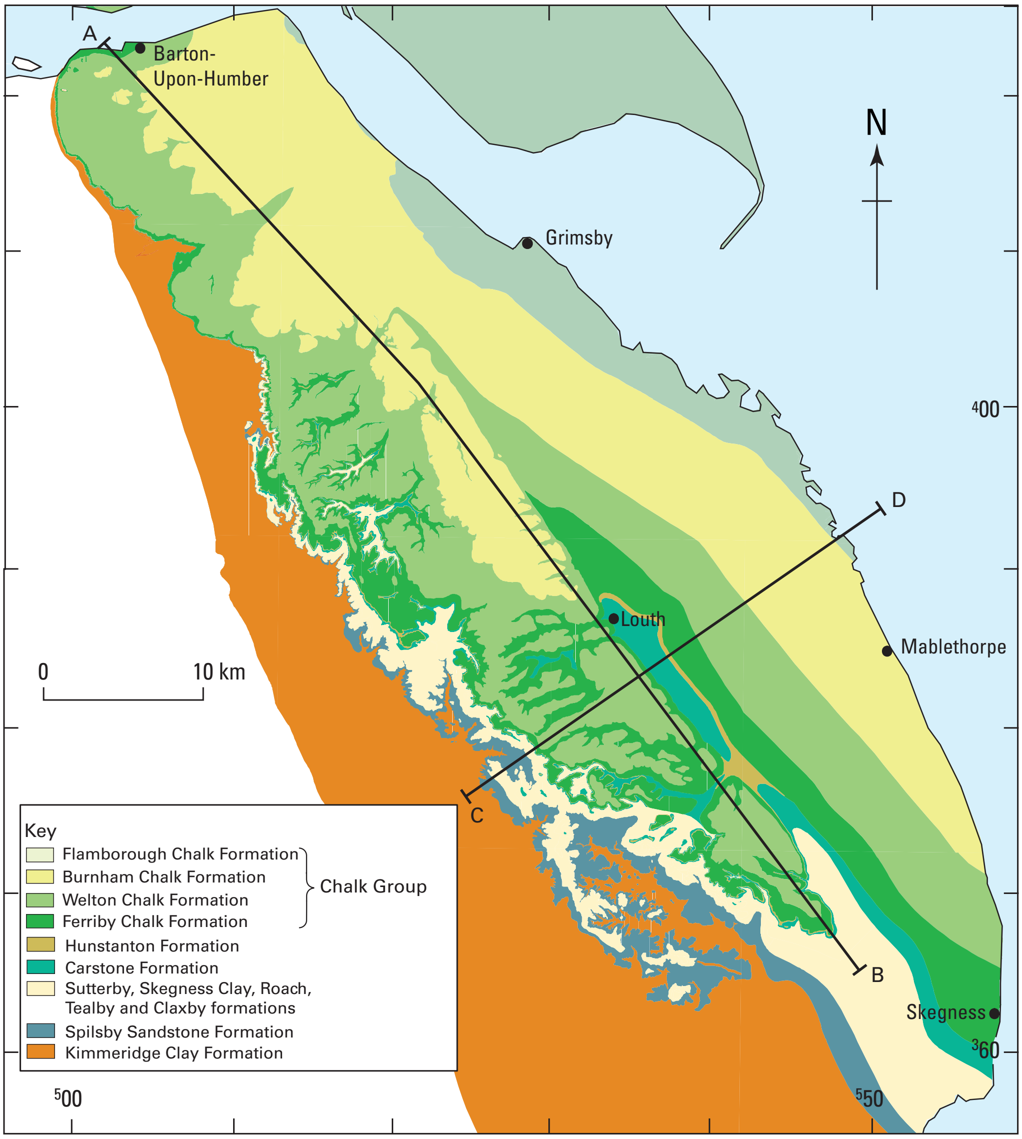


Figure 2.1 Map of bedrock geology (1:50 000).

2.2 STRATIGRAPHICAL SUCCESSION

2.2.1 Introduction

The stratigraphical positions of the formations discussed below are shown in Table 2.1. The Lower Cretaceous formations that underlie the Chalk form part of the Lincolnshire Chalk aquifer system, although the degree of hydraulic connectivity is variable. The Upper Jurassic clay formations form the base of the aquifer system. It is, therefore, worth considering these strata in some detail. There have been several changes to the classification of the Chalk Group in recent years; these are discussed below.

2.2.2 Jurassic formations

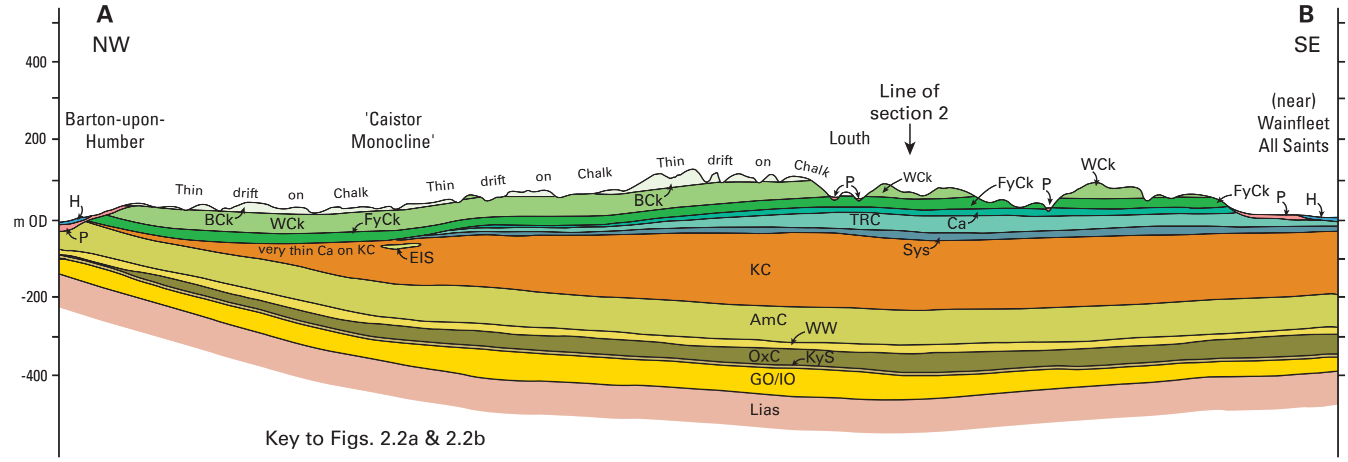
The upper part of the Jurassic succession, the Ancholme Group, mainly comprises argillaceous rocks of low permeability that form the base of the Lincolnshire Chalk aquifer system and separate it from the underlying Lincolnshire Limestone Formation.

Near the base of the Ancholme Group, the Kellaways Formation, comprising silty sands and clays, is succeeded by the Oxford Clay, West Walton, Ampthill Clay and Kimmeridge Clay formations, which are all dominated by grey, more or less silty mudstones. Near the top of the Kimmeridge Clay Formation, the Elsham Sandstone Member, a calcareous sandstone up to about 9 m in thickness, is developed in a restricted area of north Lincolnshire.

2.2.3 Lower Cretaceous formations

Resting upon the Kimmeridge Clay, the Spilsby Sandstone Formation comprises medium- to coarse-grained weakly cemented pebbly sandstone with better cemented calcareous sandstone nodules (‘doggers’), and is typically 10 to 20 m thick. It forms a shelf-like outcrop to the west of the Wolds. Where fully developed (in the south), the Spilsby Sandstone spans the Jurassic–Cretaceous boundary. It rests erosively on the Kimmeridge Clay and cuts down to somewhat lower horizons when traced northwards.

Above the Spilsby Sandstone the Lower Cretaceous beneath the Chalk is a rather complex succession, typically less than 50 m thick, which forms a narrow outcrop at the foot of the main Wolds escarpment. The Claxby Formation at the base comprises up to about 14 m of muddy ooidal ironstone (Gaunt et al., 1992). In the south, it locally includes a median mudstone unit known as the Hundleby Clay. The succeeding Tealby Formation comprises up to about 30 m of pale grey mudstone with ferruginous ooids including, towards the top, up to 4 m of hard, shaly, thinly bedded limestone (the Tealby Limestone Member). Above, the Roach Formation



Key to Figs. 2.2a & 2.2b

H	Holocene deposits	KC	Kimmeridge Clay Formation
P	Pleistocene deposits	EIS	Elsham Sandstone Member (schematic)
FCk	Flamborough Chalk Formation	AmC	Ampthill Clay Formation
BCk	Burnham Chalk Formation	WW	West Walton Formation
WCk	Welton Chalk Formation	OxC	Oxford Clay Formation
FyCk	Ferriby Chalk + Hunstanton formations	KyS	Kellaways Formation
TRC	Tealby, Roach & Claxby Ironstone formations	GO/IO	Great + Inferior Oolite Groups (undifferentiated)
Ca	Carstone Formation (schematic)	Lias	Lias Group
Sys	Spilsby Sandstone Formation		

0 10 km
(Vertical exaggeration x 12.5)

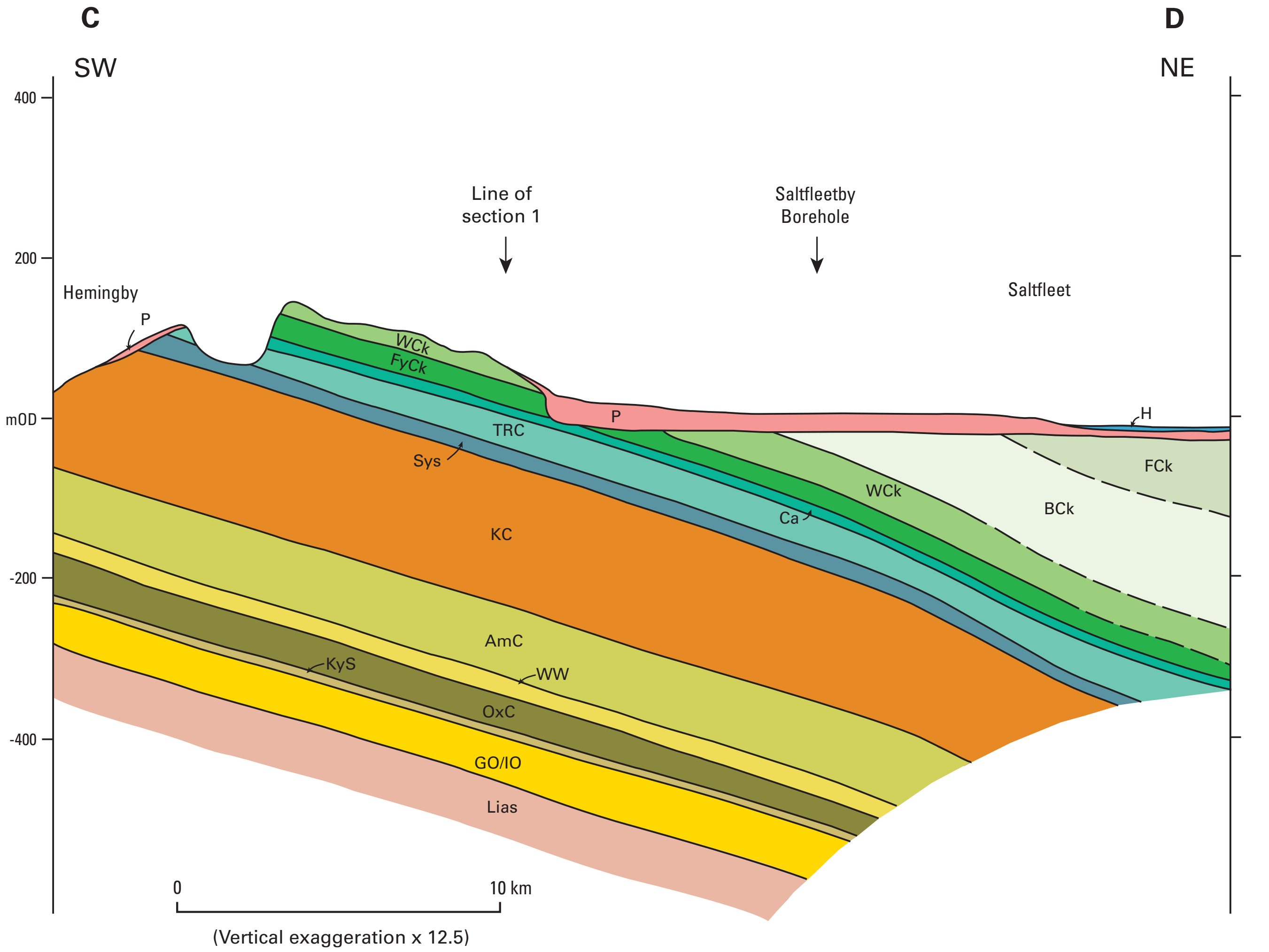
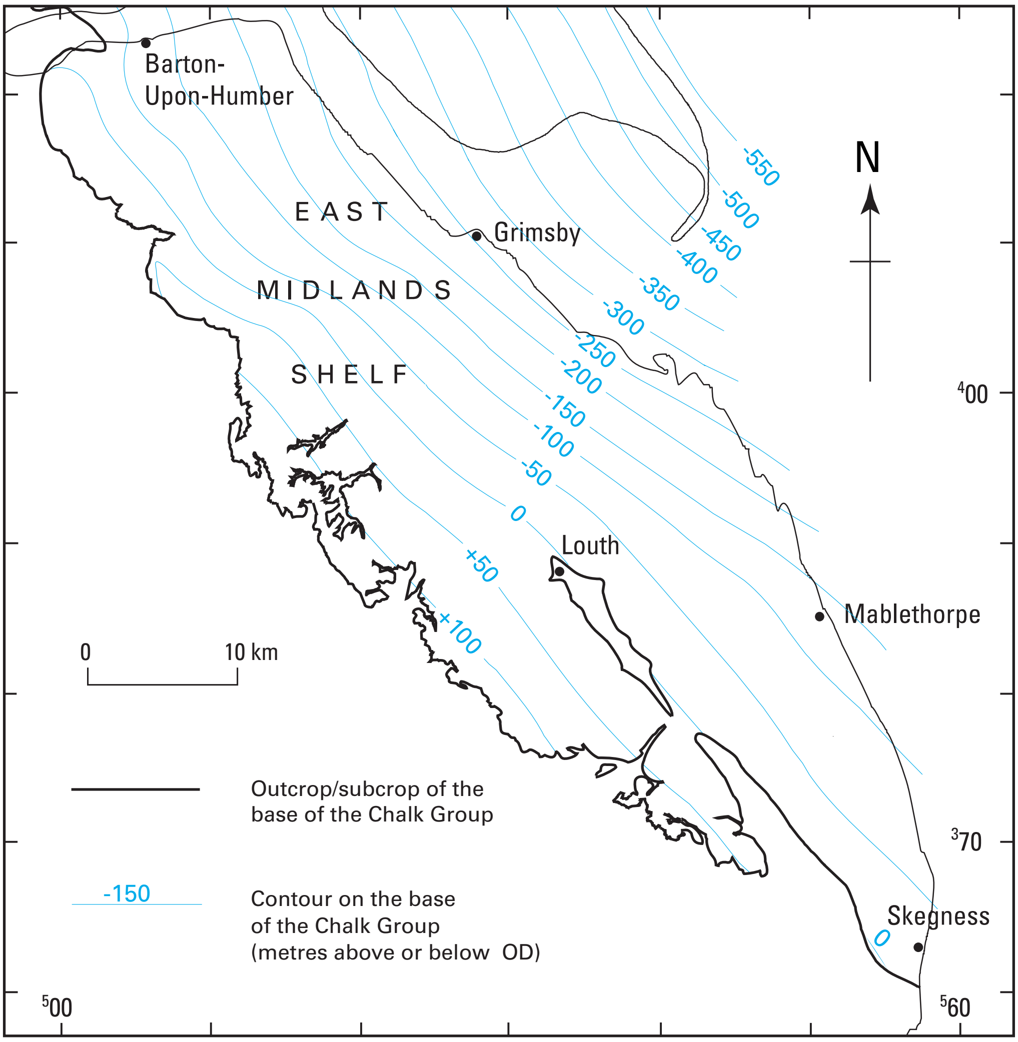


Figure 2.2 Cross-sections illustrating the geometry of the strata in Lincolnshire, showing thinning and overstepping of strata.

Figure 2.3 Contours on the base of the Chalk of Lincolnshire and Yorkshire (m OD) and major structural features (Sumbler, 1999).



consists of up to 20 m of rather ferruginous mudstone, limestone and sandstone. In south Lincolnshire, it is overlain by the locally developed Sutterby and Skegness Clay formations.

The Spilsby Sandstone, Claxby Ironstone, Tealby and Roach formations are all restricted to the southern part of the region, being cut out progressively northwards by the unconformity at the base of the succeeding Carstone Formation. This unit, consisting of up to 10 m of rusty-brown or greenish coarse-grained and commonly pebbly sandstone, thus comes to rest on the Spilsby Sandstone in the neighbourhood of Caistor [TA 12 01]. The Spilsby Sandstone itself is cut out near Grasby [TA 09 05]. Farther north the Carstone is only 1 m or so thick, and cuts down further through the Jurassic succession so that at the Humber it rests on the Ampthill Clay and over the Market Weighton High in Yorkshire it rests on the lowest part of the Lias Group. The Carstone is succeeded by the Hunstanton Formation, formerly known as the Red Chalk. The Hunstanton Formation is made up of reddish, somewhat sandy and more or less marly (argillaceous) chalk. The basal boundary with the Carstone is generally quite sharp, but the upper boundary with the Ferriby Formation, though strictly defined by a non-sequence at the base of the Upper Cretaceous, may be hard to identify as the lithologies of the two formations are similar and the boundary does not coincide with the upper limit of reddish chalk. The Hunstanton Formation is generally about 3 m thick, but thins somewhat in South Lincolnshire, and is only 1 m thick at the type section on the Norfolk coast. The Hunstanton Formation is therefore included with the Fernby Chalk Formation in Figures 2.2 and 3.12, and within the area of chalk outcrop on other figures.

2.2.4 The Chalk Group

The Chalk succession reaches over 250 m in thickness in north-east Lincolnshire. Overall, individual units of the Chalk Group tend to thin slightly to the south, towards the stable shelf area of the London Platform, and there is a hint of thinning in the northernmost part of the region as the Market Weighton High is approached. In addition, a slight eastwards thickening towards the North Sea Basin is apparent.

The Chalk Group of England is divided into two lithological and faunal provinces, which result from differences in depositional and diagenetic conditions; the Chalk of Lincolnshire belongs to the northern province. In parts of the succession, the chalks of the northern province are relatively hard and thinly bedded and contain beds of flint (tabular flints), and so contrast with the softer, massive chalks of the southern province, in which tabular flints are rare (Rawson, 1992). However, the boundary between the northern and southern provinces is somewhat diffuse, and in southern Lincolnshire the Chalk Group acquires many of the characteristics of the southern province succession (Sumbler, 1999). The Chalk Group has historically been divided into the Upper, Middle and Lower Chalk, but the criteria used to define these divisions are not entirely relevant to the Chalk of the northern province. The group was originally subdivided into three parts, based essentially on the presence or otherwise of flint. Wood and Smith (1978) introduced a more refined lithostratigraphical scheme, an updated version of which is used in this account (Hopson, 2005). The Chalk Group in Lincolnshire is now divided into four formations: the Ferriby Chalk, Welton Chalk, Burnham Chalk and Flamborough Chalk formations (Table 2.2). Table 2.2 also shows the chronostratigraphical classification of the Chalk Group of the northern province.

2.2.4.1 Ferriby Chalk Formation

The Ferriby Chalk Formation comprises generally soft, grey, marly chalks with some discrete marl bands and is flint-free throughout. It includes a number of marker beds including the Totternhoe Stone, a dark grey or brown, hard shelly limestone in the middle part of the succession, and the Nettleton Stone, a hard gritty chalk a few metres higher. Above, the upper part of the formation is generally a fairly pure chalk with some pink-stained bands at the top. The Ferriby Chalk Formation crops out along the lower slopes of the Wolds escarpments in south-west Lincolnshire, and along valley sides and bottoms within the Wolds. It also occurs beneath thick Quaternary deposits at the foot of the buried Ipswichian cliffline. The Ferriby Chalk Formation is typically about 20 to 25 m thick, being 23 m at the type locality (South Ferriby Quarry). It is a little thicker (c.30 m) in south Lincolnshire, contrary to the general trend.

2.2.4.2 Welton Chalk Formation

The Welton Chalk Formation crops out on the Wolds escarpment and forms the upper plateau surface of much of the Wolds. It is dominated by extremely pure, white chalks which are typically massive, thickly bedded, and generally softer than those of the overlying Burnham Chalk Formation (Sumbler, 1999). It contains a few well-developed nodular flint bands, which form marker beds, but otherwise the flints are small and quite sparse. Widespread marl seams, which are also useful markers, occur throughout the formation. The base of the formation is marked by the Plenus Marls Member which comprises greenish grey marls and marly chalk, and includes a thin dark grey to black bituminous marl known as the Black Band. The Plenus Marls are succeeded by about 4.5 m of a hard grey and yellowish grey shelly chalk, which is the approximate equivalent of the Melbourne Rock of East Anglia and the Chilterns. The Welton Chalk Formation, typically about 50 m thick, is about 53 m at outcrop in the Humber area, and 48 m thick near Killingholme. It thins southwards, probably to some 40 m in southernmost Lincolnshire, the equivalent beds in Norfolk being only 33 m thick.

2.2.4.3 Burnham Chalk Formation

The Burnham Chalk Formation forms some of the highest ground of the Wolds, but much of the outcrop is concealed beneath the thick Quaternary deposits of east Lincolnshire. It is characterised by hard, thinly bedded chalks with frequent tabular flints and discontinuous flint bands (Sumbler, 1999). The basal part of the formation is particularly flinty, with individual flint bands of up to 0.3 m or more in thickness. The Burnham Chalk Formation is about 130 m thick in the Killingholme area but thins southwards, the equivalent beds being only c.100 m thick in Norfolk.

2.2.4.4 Flamborough Chalk Formation

The Flamborough Chalk Formation is the youngest part of the Chalk Group represented in Lincolnshire. It occurs only in the north-east coastal area, where it is entirely concealed beneath Quaternary deposits. The formation is characterised by white chalk, softer than the underlying chalks, with frequent thin marl beds and negligible flint. Only the basal c.50 m of the Flamborough Chalk Formation occur in Lincolnshire. The formation totals about 265 m where complete in Holderness, Yorkshire (Sumbler, 1999).

2.2.5 Geophysical log correlation

Barker et al. (1984) demonstrated that downhole geophysical borehole logs can be used to help identify chalk lithologies and stratigraphy where no other information is available. In particular, some persistent marl bands, erosion surfaces and flint beds form marker bands that can be distinguished on resistivity and gamma logs. Figure 2.4 gives an example of the strong resistance signature produced by marl bands and also shows the consistency between resistivity logs from boreholes that are many kilometres apart. As well as allowing the stratigraphic range of a borehole to be determined, this method also aids the delineation of geological structures (University of Birmingham, 1978).

2.2.6 Quaternary deposits

2.2.6.1 Introduction

Quaternary deposits are largely present to the east of the buried Ipswichian cliff line and directly overlie the Chalk. Figure 2.5 shows the generalised superficial geology of the area. The Quaternary sediments were deposited over several glacial–interglacial periods and can reach a total thickness of more than 20 m. The history of Quaternary deposition is discussed later in this chapter; a description of the nature and distribution of the various deposits is given below in a general chronological order.

2.2.6.2 Wragby Till

The Wragby Till is a pre-Devensian (probably Anglian) glacial deposit that occurs as scattered remnants on the Chalk Wolds and is widespread on the low ground to the west of the Wolds. Generally these chalk and flint-rich till deposits are absent beneath the Devensian tills to the east, having been eroded during the Ipswichian Stage, however, remnants may be present in buried valleys (e.g. the Kirmington Channel).

2.2.6.3 Chalk bearings and chalk head

The chalk bearings and chalk head are similar in composition, both consisting of broken chalk, but differ in their genesis and distribution. The processes which formed these deposits are described in Chapter 3.

The chalk bearings is a layer of fragmented chalk which occurs above the relatively unweathered, structured chalk where it is overlain by glacial deposits to the east of the Ipswichian coastline. The chalk bearings are also found on the Wolds outcrop, particularly in dry valleys. At a local scale the thickness and nature of this heavily weathered horizon may vary significantly, and it is difficult to define the thickness as the bearings grade into the underlying chalk. However, the chalk bearings are between 1 and 5 m thick over most of the study area (University of Birmingham, 1978), with a reported maximum thickness of about 10 m (Allen et al., 1997). The chalk bearings

Table 2.2 Chronostratigraphical and lithostratigraphical classification of the Chalk Group of Lincolnshire and Yorkshire (Northern Province) compared with that of southern England (Southern Province). Not to scale. Both the traditional (Jukes-Browne and Hill, 1903, 1904) and newer (Bristow et al., 1997) lithostratigraphical schemes are indicated (Sumbler, 1999). The base of the Chalk Group is now defined as the base of the Ferriby Chalk Formation (Hopson, 2005).

STAGE	BIOZONES North (traditional)	BIOZONES South (current standard)	LITHOSTRATIGRAPHY Northern Province Formation	Northern Province Lithology	Southern Province	Southern Province Formation
CAMPANIAN	*Belemnitella mucronata*		ROWE CHALK	Chalk with flints	UPPER CHALK	Portsdown Chalk
CAMPANIAN	*Sphenoceramus lingua*	*Gonioteuthis quadrata*	FLAMBOROUGH CHALK	Chalk without flints	UPPER CHALK	Culver Chalk
CAMPANIAN	*Uintacrinus anglicua*	*Offaster pilula*	FLAMBOROUGH CHALK	Chalk without flints	UPPER CHALK	Newhaven Chalk
SANTONIAN	*Marsupites testudinarius*		FLAMBOROUGH CHALK	Chalk without flints	UPPER CHALK	Newhaven Chalk
SANTONIAN	*Uintacrinus socialis*		FLAMBOROUGH CHALK	Chalk without flints	UPPER CHALK	Newhaven Chalk
SANTONIAN	*Hagenowia rostrata*	*Micraster coranguinum*	BURNHAM CHALK	Chalk with flints	UPPER CHALK	Seaford Chalk
CONI-ACIAN	*Micraster cortestudinarium*		BURNHAM CHALK	Chalk with flints	UPPER CHALK	Lewes Chalk
TURONIAN	*Sternotaxis plana [Holaster planus]*		BURNHAM CHALK	Chalk with flints	UPPER CHALK	Lewes Chalk
TURONIAN	*Terebratulina gracilis*	*Terebratulina lata*	WELTON CHALK	Chalk with flints	MIDDLE CHALK	New Pit Chalk
TURONIAN	*Rhynchonella cuvieri*	*Mytiloides labiatus*	WELTON CHALK	Chalk with flints	MIDDLE CHALK	Holywell Chalk
CENOMANIAN	*Sciponoceras gracile*	*Neocardioceras juddi*	WELTON CHALK (Plenus Marls Member)	Marly chalk without flints	MIDDLE CHALK	Holywell Chalk
CENOMANIAN	*Actinocamax plenus*	*Metoicoceras geslinianum*	WELTON CHALK (Plenus Marls Member)	Marly chalk without flints	LOWER CHALK	Plenus Marls Member
CENOMANIAN	*Holaster tecensis*	*Calycoceras guerangeri*	FERRIBY CHALK	Marly chalk without flints	LOWER CHALK	Zig Zag Chalk
CENOMANIAN	*Holaster subglobosus*	*Acanthoceras jukesbrownei*	FERRIBY CHALK	Marly chalk without flints	LOWER CHALK	Zig Zag Chalk
CENOMANIAN	*Holaster subglobosus*	*Acanthoceras rhotomagense*	FERRIBY CHALK	Marly chalk without flints	LOWER CHALK	Zig Zag Chalk
CENOMANIAN	*Holaster subglobosus*	*Mantelliceras dixoni*	FERRIBY CHALK	Marly chalk without flints	LOWER CHALK	West Melbury Chalk
CENOMANIAN	*Holaster subglobosus*	*Mantelliceras mantelli*	FERRIBY CHALK — Base of Chalk Group	Marly chalk without flints	LOWER CHALK	West Melbury Chalk / Glauconitic Marl Member
ALB-IAN			HUNSTANTON	Red chalk	Upper Greensand and Gault	

typically consist of unconsolidated broken chalk or chalk gravel, but are variable in composition. They locally contain angular flints, sands, or even soft putty chalk (University of Birmingham, 1978). The term 'putty chalk' usually refers to very fine-grained, structureless material that is cohesive when wet. Putty chalk has not been observed at outcrop in Lincolnshire but may be present beneath superficial deposits. The chalk bearings are hard to differentiate from chalk-derived head, so these deposits are generally categorised as part of the chalk bearings. Chalk head is frost-shattered chalk which was transported from the Wolds and deposited at the foot of slopes, in valley floors and at the base of the Ipswichian coastline.

2.2.6.4 Sands and gravels

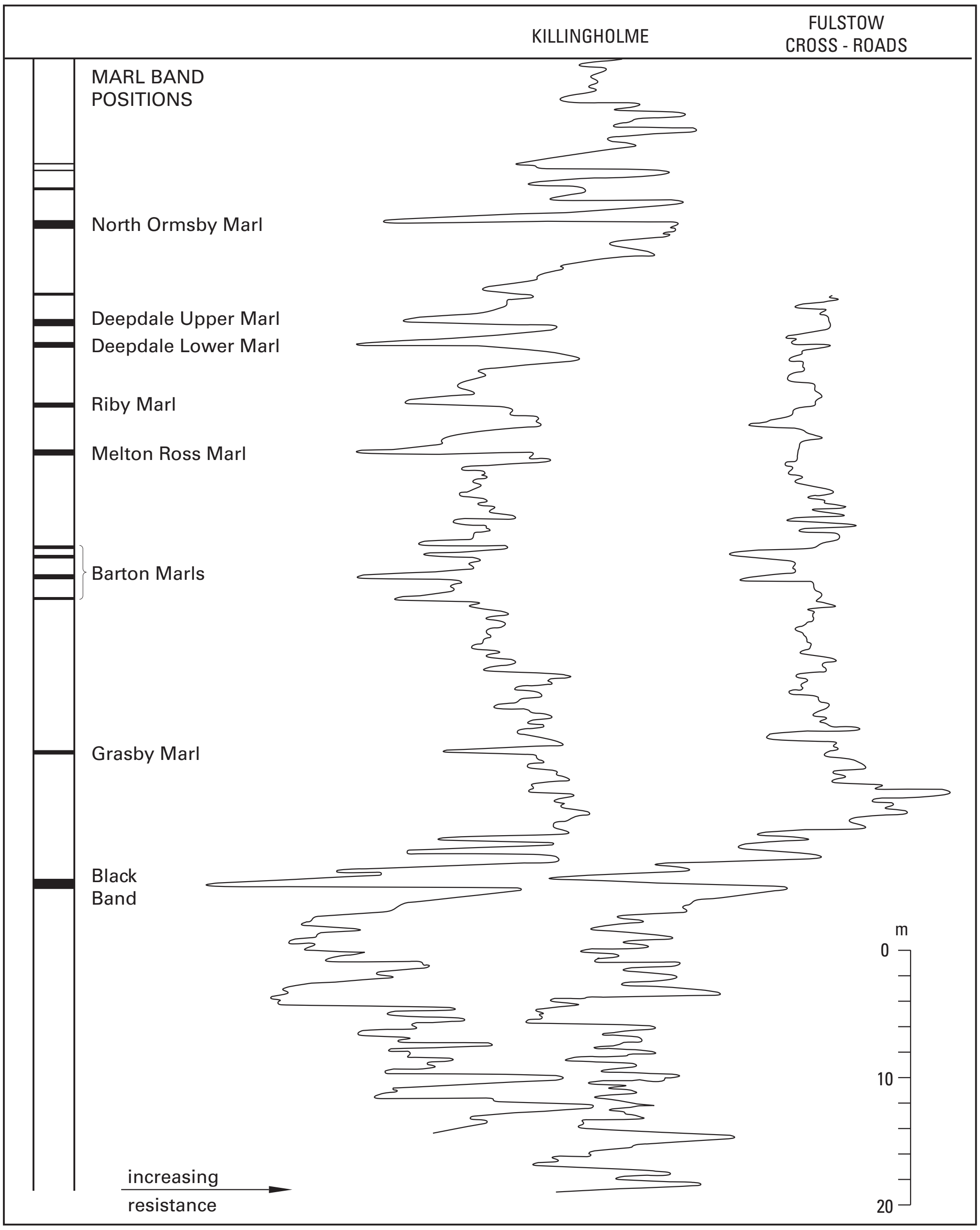
Sands and gravels were deposited during one or more pre-Devensian (probably Anglian) glacial episodes, and are associated with the Wragby Till. Fluvioglacial sands and gravels were also deposited during the Devensian Stage. These are exposed between Laceby [TA 21 06] and Brocklesby [TA 14 11] and near to the present course of the East Halton Beck (University of Birmingham, 1978). The deposits are typically no greater than 3 m thick. Another unit of fluvioglacial sands and gravels overlies the chalk bearings and the Chalk over some of the area where it occurs beneath the Marsh Till.

Deposition of beach sediments occurred during the Ipswichian stage; these are banked up against the cliff which marked an Ipswichian coastline. These sediments form a narrow belt which is typically less than a kilometre wide and are up to 12 m thick between Barnoldby-le-Beck [TA 23 03] and Louth, where the cliff is highest (University of Birmingham, 1978). They comprise fine- to medium-grained sands in the Grainsby [TF 26 98] area, while north of Barnoldby-le-Beck they are extremely similar in composition to overlying fluvioglacial sands and gravels. The distribution map (Figure 2.6) therefore shows undifferentiated sands and gravels.

2.2.6.5 Marsh Tills

The Marsh Tills were deposited during the Devensian glaciation. As it was the last glacial episode, the deposits and features have been better preserved than tills from previous glaciations, but are only found principally to the east of the buried coastline, as this was approximately the limit of the ice sheet (Figure 2.7). The Devensian Marsh Tills form a thick blanket over most of the land east of the Ipswichian coastline. The thickness is typically from about 20–30 m in the central part of the study area to about 10 m in the vicinity of Barrow [TA 07 21]. The Devensian till is commonly thickest adjacent to the Ipswichian coastline; for example, it is about 36 m thick around Barnoldby-le-Beck (Berridge and Pattison, 1994). The tills are relatively thin in some areas, such as the area west of Grimsby, and generally feather out just west of the buried coastline.

Figure 2.4
Comparison of single point resistance logs at Killingholme and Fulstow Cross Roads, a distance of 26 km apart (Barker et al., 1984).



These tills are particularly important hydrogeologically as they are of low permeability and confine the Chalk aquifer system.

2.2.6.6 Estuarine and tidal flat deposits

The estuarine and tidal flat deposits consist of a succession of peats, clays and silts that built up with the progressively rising sea level during the Flandrian[1]. They are present in a broad band along most of the Lincolnshire coastline and the banks of the Humber Estuary. Deposits are of variable thickness but are believed to reach 20 m in places, for example, between Donna Nook [TF 43 99] and Mablethorpe [TF 50 85] (University of Birmingham, 1978). The deposits are thinner near Skitter Ness [TA 13 25] but are hydrogeologically important as they overlie the Chalk in a channel cut into the Marsh Till by an earlier River Humber, confining the aquifer where discharge could otherwise occur. These deposits were mainly deposited during the Sub-Boreal period (5000–2500 years BP) and the Sub-Atlantic period (about 2000 years BP) (University of Birmingham, 1978).

2.2.6.7 Blown Sand

In very recent times a belt of sand dunes has formed along much of the Lincolnshire coastline, up to 5 kilometres inland, e.g. between Mablethorpe and North Somercotes [TF 42 96], and also near Humberston [TA 31 05] (University of Birmingham, 1978).

2.3 HISTORY OF THE CHALK AND ITS DEVELOPMENT AS AN AQUIFER

2.3.1 Introduction

Various processes have created and modified the Chalk, from deposition and diagenesis through uplift, erosion and weathering. The spatial distribution of the effects of these processes, and the extent of modification, have a fundamental control on the aquifer system of today. The

1 The most recent 10 000 years of the Quaternary belongs to the Holocene Epoch. This postglacial period of temperate climate is considered to be an 'interglacial', known as the Flandrian Stage.

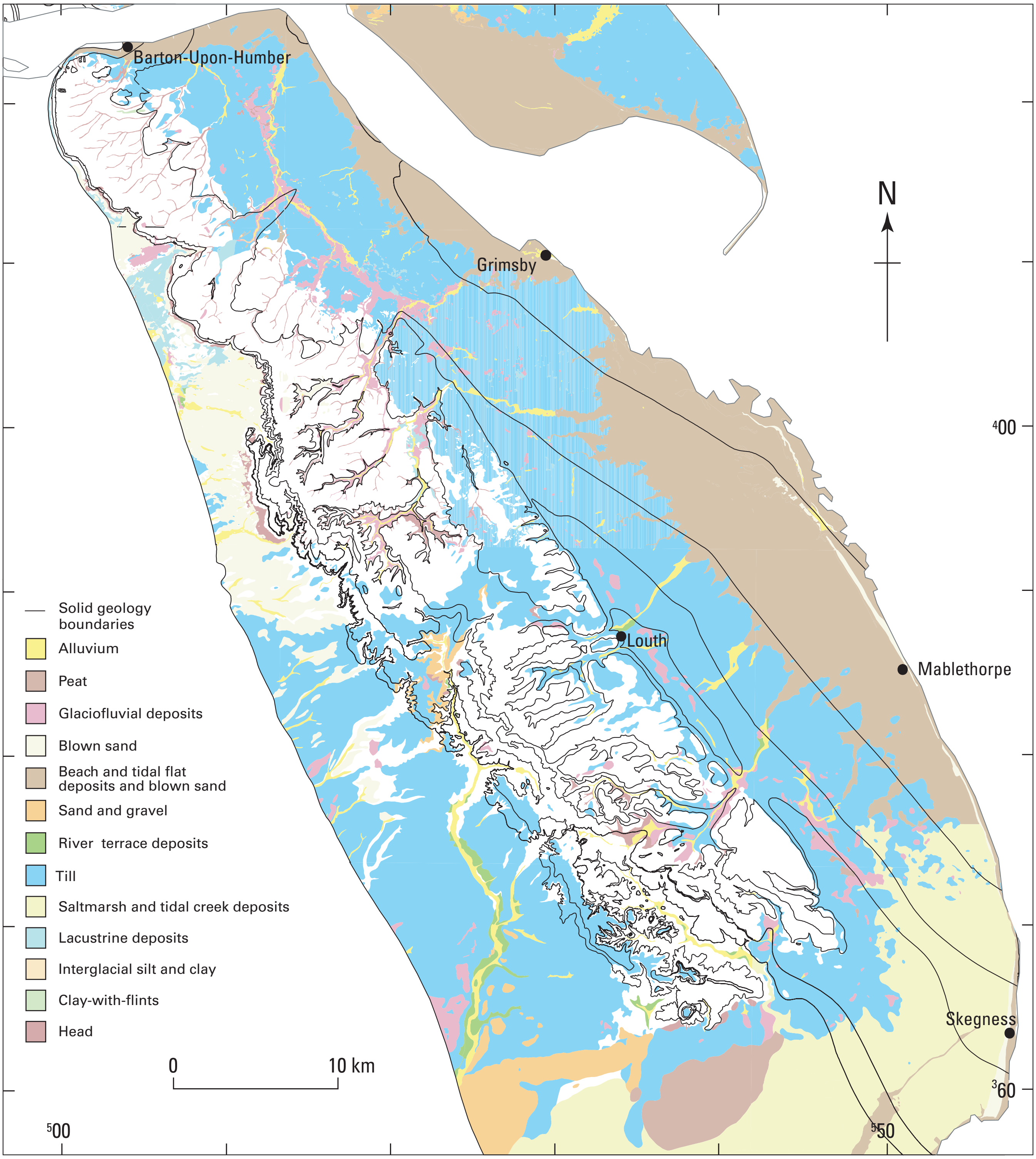


Figure 2.5 Simplified map of superficial deposits (1:50 000).

underlying Lower Cretaceous strata, which today form part of the aquifer system, are not considered in this section as they play a minor role in comparison to the Chalk. However, the deposition of the Quaternary deposits above the Chalk is described as these, in particular the till and sands and gravels, influence the present day hydrogeology.

2.3.2 Deposition and diagenesis

The Chalk Group comprises carbonate-rich sediments that were deposited in a shelf sea which covered much of north-west Europe during some 40 million years in the Upper Cretaceous period. Chalk is an extremely fine-grained micritic limestone, mainly composed of biogenic debris. The principal ingredient is a coccolith mud, made up of the microscopic skeletal calcite plates of coccolithophorids, a type of alga (Hancock, 1975). Other bioclastic components include microscopic calcispheres (from dinoflagellate algae), foraminifer tests, and shell debris from larger creatures such as bivalves and echinoderms. The fossils found in the Chalk indicate that the sediments were deposited in a fully marine subtropical environment.

The Chalk is thought to have been deposited at a fairly steady rate, although there were frequent pauses in

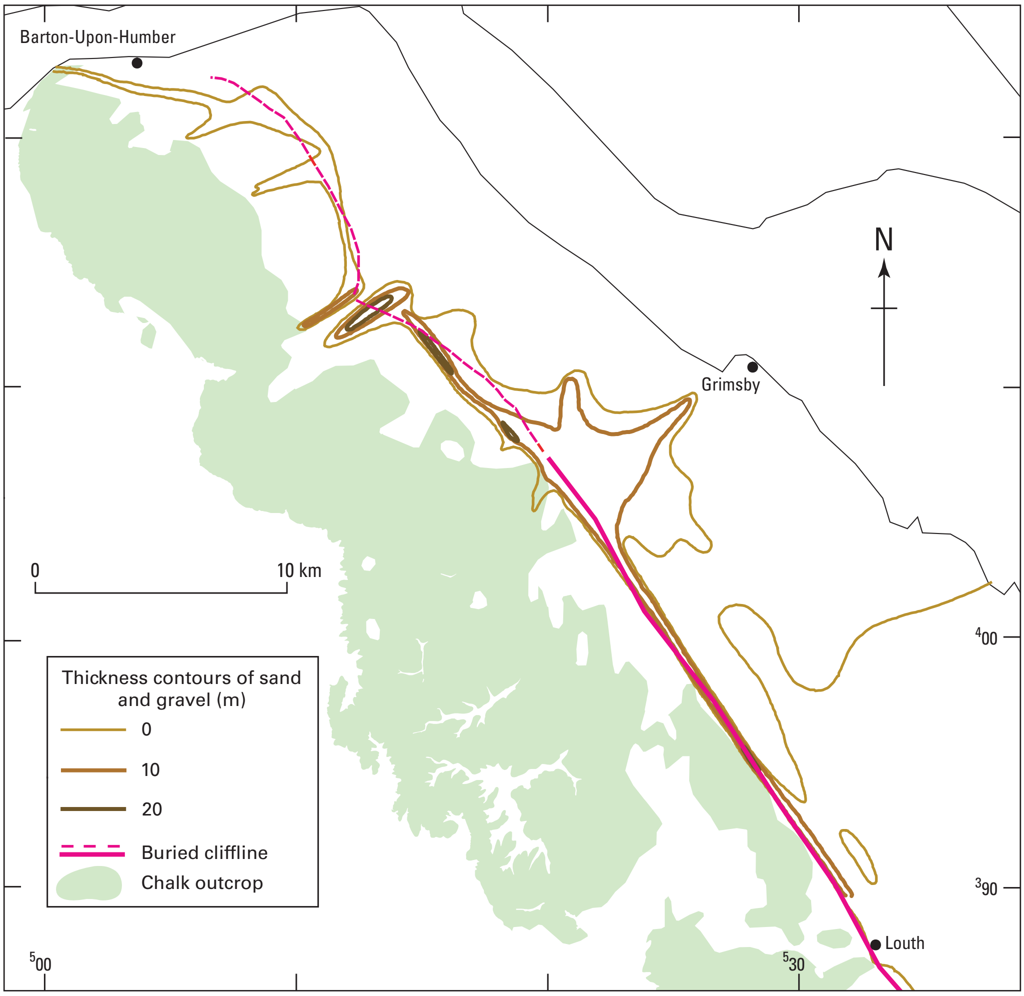


Figure 2.6
Distribution of sands and gravels.

sedimentation which have resulted in omission and erosion surfaces (Rawson, 1992). Omission surfaces can be mistaken for low angle jointing (University of Birmingham, 1978). Hardgrounds, such as that developed just below the Totternhoe Stone, are the result of major breaks in deposition, during which the sediment became hardened by cementation (Rawson, 1992). Paradoxically, although these harder chalks tend to have lower intergranular porosity than the underlying or overlying strata, they typically have higher permeability as they fracture more cleanly than the softer rocks (Price, 1987).

Some of the laterally continuous marl bands, which may be up to a few centimetres thick, may have formed from volcanic ash. Other marl horizons result from episodes when inputs of terrigenous material increased.

Flint, a form of cryptocrystalline quartz, formed at an early stage of diagenesis, though at some depth below the sea-floor (Clayton, 1984). The silica derives from the skeletons of sponges, radiolarians and diatoms, which dissolve in the generally alkaline environment on burial. Decomposing organic matter produced localised acidic conditions in which the silica reprecipitated, replacing calcium carbonate which went into solution. This process occurred preferentially in more permeable parts of the sediment, such as burrowed horizons. Consequently, the majority of flints are replacements of the chalk in and around burrows, and the shape of a flint nodule generally reflects the original burrow morphology. Flint nodules may be so abundant that they coalesce into a more or less continuous bed, forming a so-called tabular flint. Being related to sedimentary rhythms, many of the flint bands are widespread marker-horizons and, like marl seams, are often very prominent on geophysical logs (low gamma, high sonic, high resistivity).

Diagenesis has had a significant impact upon the nature and distribution of aquifer properties of the Chalk. The porosity of the chalk deposits was up to 80% prior to diagenesis (Downing et al., 1993). The hardness that is characteristic of the chalks of the northern province is a result of burial to greater depths than the chalk in southern England, which has produced pressure solution of carbonate and its redeposition as a calcite cement in the pore spaces of the sediment. The Chalk of the northern province thus also has lower matrix porosity than the southern Chalk. Stylolites, also common in northern chalks, are another manifestation of solution at specific horizons in lithified sediment. These pressure solution effects relate both to overburden pressure (i.e. depth of burial by later rocks) and to local and regional tectonic stresses (e.g. Mimran, 1977), as well as being dependent on the nature of the original sediment. In detail, the causes are complex, for the degree of cementation of the Chalk varies both vertically and horizontally, so that relatively soft chalk may be intercalated with, or pass laterally into, units of well-cemented chalk.

Diagenetic processes such as mechanical compaction and pressure solution interacted with primary sedimentary characteristics, e.g. grain size, fabric and mineralogical composition, to cause a general decrease in matrix porosity with depth (Scholle, 1977; Scholle et al., 1983). Mechanical compaction predominates during the early stages of burial diagenesis and a few hundred metres burial may result in the reduction of porosities from in excess of 60% to less than

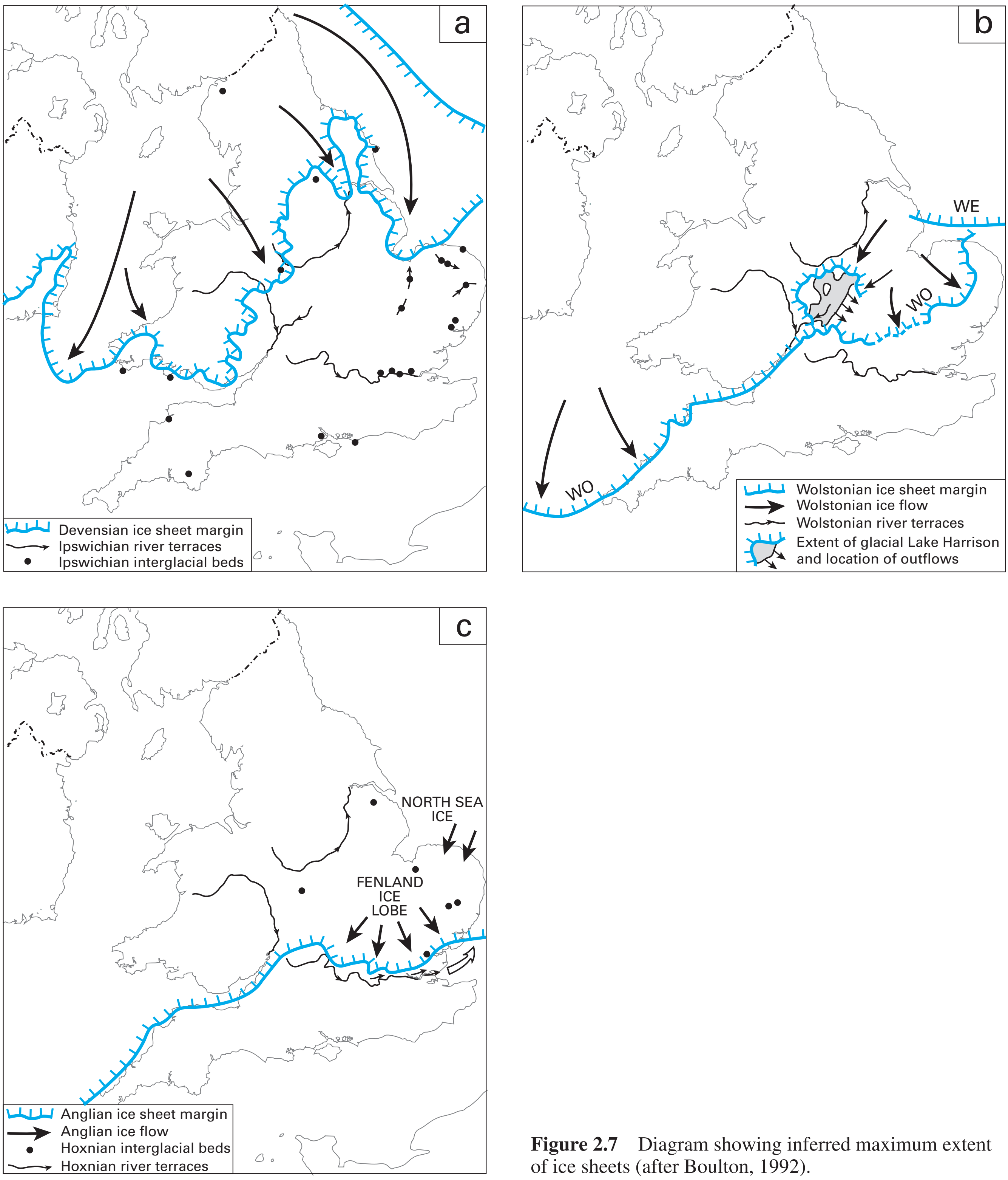


Figure 2.7 Diagram showing inferred maximum extent of ice sheets (after Boulton, 1992).

50%. Pressure solution or solution transfer diagenesis reduces matrix porosity through the dissolution and re-precipitation of minerals under conditions of non-hydrostatic stress. This mechanism predominates during the later stages of diagenesis under conditions of greater overburden.

A statistical analysis of aquifer properties data shows that the Welton and Ferriby Chalk formations have porosities less than 30% and gas permeabilities less than 1 mD, while some samples of the Flamborough and Burnham Chalk Formations have higher values (Bloomfield et al., 1995; Allen et al., 1997). There is a distinct grouping which indicates that there are two diagenetically controlled porosity regimes on a regional scale within the Chalk of Lincolnshire and Yorkshire; the dominant process of diagenesis shifted from mechanical compaction to pressure solution due to variation in maximum burial depth. The porosity evidence suggests that the boundary between mechanical compaction and pressure solution lies somewhere in the Flamborough or Burnham Chalk Formation. The entire sequence of Welton and Ferriby Chalk formations have undergone pressure solution (Scholle, 1977; Scholle et al., 1983).

Diagenesis drastically reduced the primary porosity of the Chalk after deposition, but it remains relatively high at between 12 and 34% (Chapter 3). After deposition and diagenesis the Chalk had relatively high porosity but the permeability was still low due to the small pore size and the absence of fracturing, and the Chalk would not yet have constituted an aquifer.

2.3.3 Uplift: tilting, fracturing and erosion

A period of extended uplift occurred throughout the Late Cretaceous and Palaeogene, with folding and tilting of the main Wolds syncline. These movements were the result of a change in the tectonic regime from one of dominant crustal extension to one of dominant compression (Berridge and Pattison, 1994). The Caistor Monocline was also formed during this time (University of Birmingham, 1978).

The majority of the jointing and fracturing observed in the Lincolnshire Chalk probably originates from this period. Conjugate sets of joints are common and high-angle joints are often observed in quarries, however, regional joint trends have not been identified (University of Birmingham, 1978). While much of the jointing has been attributed to regional and local structural controls in the Palaeogene, other mechanisms of formation, such as cambering and valley bulging, may also have contributed.

The University of Birmingham (1978) found no evidence of faulting at the core of the Caistor Monocline at depth, however, some minor faulting is associated with this structure. Strike faults have been observed at Claxby [TF 44 71] near Alford, in the South Ferriby Cement Quarry [SE 992 204], and near Louth (University of Birmingham, 1978).

During the Palaeogene uplift the Chalk underwent prolonged denudation and considerable thicknesses of the uppermost divisions of the Chalk were removed. By the end of the Palaeogene the Chalk was fractured, introducing secondary porosity. However, the hydraulic conductivity of fractured chalk which has not undergone enhancement by solution is generally low, for example, some confined areas of the Chalk in the UK have a transmissivity of less than 15 $m^2 d^{-1}$ (Water Resources Board, 1972). Thus, although the structural changes in the Chalk during the Palaeogene period would have increased its permeability, this permeability was probably still too low to enable significant flow of water, i.e. the Chalk still did not have the properties which today make it a major aquifer.

2.3.4 Glacial–interglacial history

The Lincolnshire region was greatly affected by the cyclic climatic fluctuations of the Quaternary Period, covering the last two million years or so. These glacial–interglacial cycles were especially important in the development of the Chalk aquifer, firstly because it was during this time that most of the permeability was developed. Secondly, glacial deposits were draped over large areas of the Chalk, and these selectively restrict modern recharge and modify the groundwater flow pattern accordingly.

During the cold, glacial phases, ice-sheets advanced, eroding vast quantities of material as they flowed over the rocks. This material was deposited at the sole of the advancing ice-sheet as till. As the ice-sheets grew the sea level fell, although this would have been offset to a minor extent by isostatic depression of the land. When the climate warmed at the beginning of interglacial phases, the ice-sheets melted and retreated, releasing large volumes of meltwater and deposited outwash sands and gravels. Sea levels rose again, though the effects were reduced by the slow isostatic rebound of the land as the weight of the ice was removed. Ice-sheets covered the Lincolnshire region on at least two, and perhaps several more, occasions and periglacial conditions affected it during many other cold phases.

The sequence of Quaternary events recorded in Lincolnshire is summarised in Figure 2.8, and the succession of Quaternary deposits is listed in Table 2.3. During the Devensian Stage (the 'last glaciation'), ice sheets advanced over the eastern part of the region, abutting a cliffline which formed during the temperate Ipswichian Stage, an interglacial which occurred about 125 000 years ago (Figure 2.8). The Devensian ice retreated as recently as 14 000 years ago, and extensive glacial deposits remain. Remnants of glacial deposits which occur to the west of the Devensian limit date from one or more older glaciations, during which the whole of Lincolnshire was covered by ice. The chronology of these pre-Devensian glaciations is still the subject of considerable debate, but most workers believe that the majority of the deposits date from the Anglian Stage, nearly half a million years ago.

2.3.4.1 Periglacial processes and deposits

Across the region the surface layers of the Chalk have been affected by Pleistocene cryoturbation and solifluction and to a more limited extent by contemporary weathering processes, causing pervasive fragmentation of the chalk matrix and the formation of vuggy porosity (Younger, 1989). This topmost layer of fragmented chalk, which occurs between the relatively unweathered, structured, chalk and the overlying glacial deposits, are known as the chalk bearings. The chalk bearings and the putty chalk (very fine-grained, structureless material) are thought to have been formed by alternate freezing and thawing under periglacial conditions.

Chalk head is a solifluction deposit which also formed under periglacial conditions and is hard to differentiate from chalk bearings in terms of composition, although the distribution of these deposits is different.

Periglacial processes would have occurred during each glacial episode and it is, therefore, difficult to attribute the resulting deposits to a particular stage.

2.3.4.2 Dry valleys

Dry valleys were incised when glacial meltwaters were unable to infiltrate the ground due to permafrost and instead formed incised streams in the Chalk. As the permafrost melted, water infiltrated to deeper levels, and the streams ceased to flow so that their old courses became dry valleys.

The University of Birmingham (1978) recognised several generations of dry valleys in the Lincolnshire Wolds. The earliest generations are represented by the Kirmington Channel and the dry valleys seen at Barrow upon Humber [TA 07 21] and Thornton Curtis [TA 09 18]. Further south, few traces of the early generation valleys are present east of the buried coastline. The Kirmington Channel (also known as the Kirmington Fjord), a major buried channel, is thought to be a preglacial valley enlarged by catastrophic localised escape of glacial meltwaters near the periphery of the Anglian ice sheet (Berridge and Pattison, 1994). The Kirmington Channel is comparable to the buried tunnel valleys of East Anglia. It is located 4 km south of Killingholme and trends east-north-east. It is about 8 km in length, 2 km wide and up to 50 m deep.

The youngest generation of dry valleys are glacial meltwater channels, which have smooth steep sides and flat floors, presumably formed at the end of the Devensian glacial event, when the ice melted. The University of Birmingham (1978) identified over 70 of these channels, for example between Beelsby [TA 20 01] and Wold Newton [TF 24 97] and between Swallow [TA 18 03] and Riby [TA 18 07].

Table 2.3 Quaternary succession in Lincolnshire (after University of Birmingham, 1978).

Stage	Oxygen isotope stage	Deposit	Thickness (m)
Flandrian	1	Estuarine and tidal flat deposits	10
Devensian	2–5d	Glacial sands and gravels	25
		Upper and Lower Marsh Till	25
		Lake and spillway deposits	
		Chalk Bearings	2
		Head	
Ispwichian	5e	Beach sediments	15
Pre-Ipswichian		Chalky Till	15
		Bain Valley Gravels	
		Chalk Bearings	3
		Silt, peat and clays at Kirmington	>5

2.3.4.3 Erosion

Some significant erosional features are attributed to the Ipswichian interglacial. Most importantly, a wave-cut platform and former coastline, now buried beneath thick Devensian and Flandrian deposits, are believed to date from this period. The buried coastline runs along the length of Lincolnshire and the wave-cut platform extends eastwards from its base (Figure 1.3). The coastline is less distinct around the Humber, but it reaches approximately 30 m in height around Tathwell [TF 32 82] and about 45 m high further to the north-west. In the Louth area, the Chalk has been completely eroded at the base of the cliff, so that the subjacent Lower Cretaceous beds underlie the Devensian glacial deposits (Figure 2.1). In this report this feature is referred to as the Louth Window; geophysical investigations have shown that it extends as far north as Fotherby [TF 31 91]. A strip of Chalk was also removed along the Calceby valley from the buried cliff area to the foot of the Chalk escarpment; this feature trends to the south-west, from Belleau [TF 40 78] to Driby [TF 38 74]. These channels almost isolate the southernmost area of exposed Chalk from the main mass of the Chalk (Figure 2.9). The Ipswichian erosion, which reduced the thickness of the Chalk aquifer and in some areas cut through it completely, has had major hydrogeological influence; these issues are discussed in Chapter 3.

2.3.4.4 Deposition

As each glacial episode ended the ice sheets melted and retreated, leaving in their wake the clasts that had been entrained in the ice. Subsequent ice sheets reworked some of the earlier deposits; the younger Devensian deposits are, therefore, more prevalent today than those of pre-Devensian glaciations. The glacial deposits range from extremely poorly sorted tills to better sorted fluvioglacial sands and gravels.

Deposition also occurred during interglacial times, most notably of the Ipswichian beach sediments and Flandrian estuarine and tidal flat deposits.

The Quaternary deposits range from low permeability tills and silts to highly permeable sands and gravels. These deposits have an extremely important role in the hydrogeology of the Lincolnshire Chalk aquifer system today and are discussed in more detail in Chapter 3.

2.3.4.5 Permeability development

Permafrost, ice-sheets, till deposits and various other phenomena associated with glacial and interglacial events can significantly influence local and regional hydrogeology. The groundwater flow regime, groundwater chemistry, and the hydraulic characteristics of the aquifer are affected during the glacial/interglacial events. As well as affecting the hydrogeology at the time, some of these changes have had major implications for the present day groundwater system.

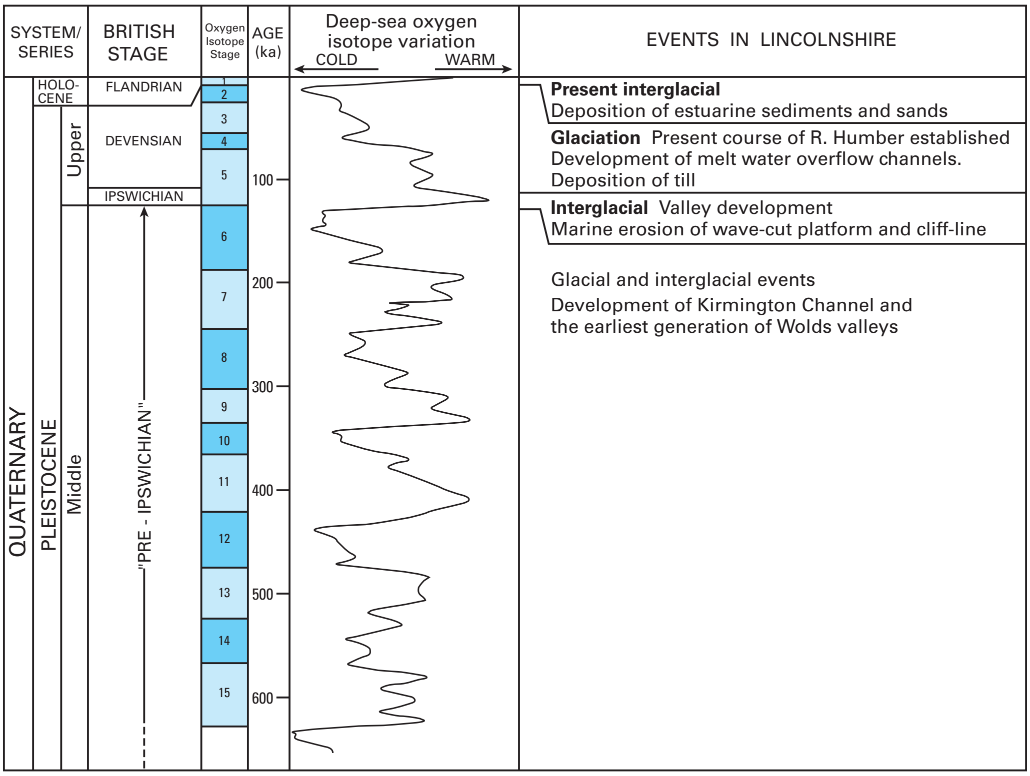
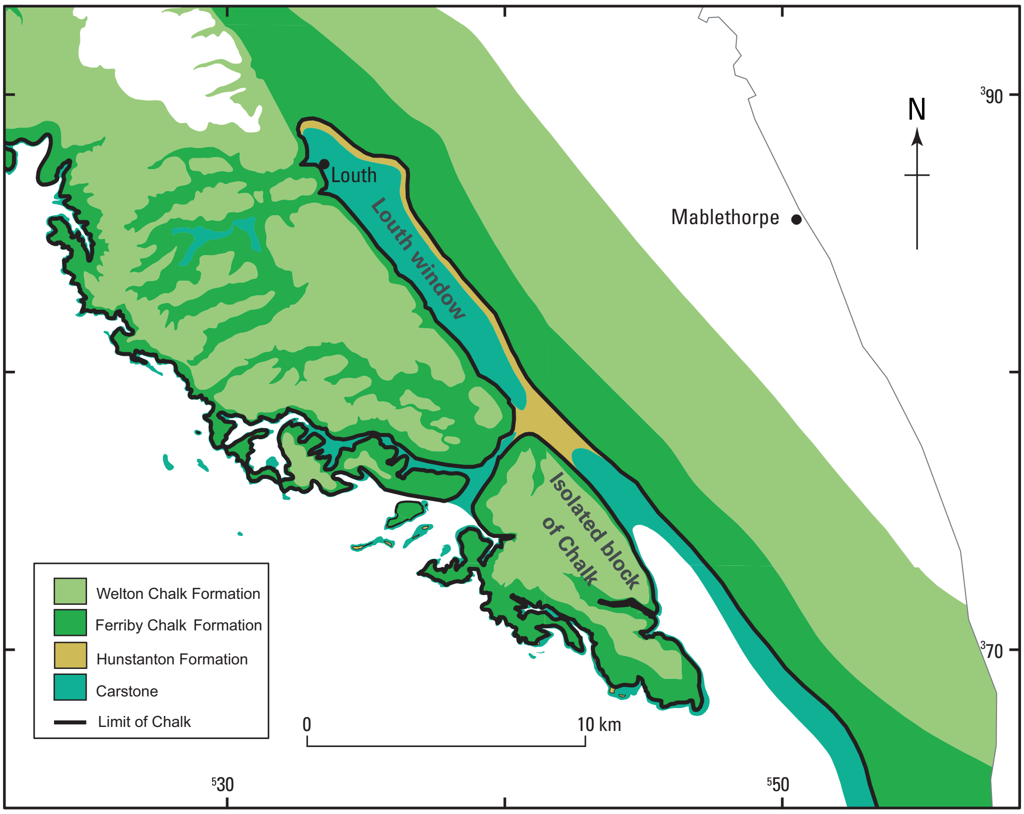


Figure 2.8 Sequence of Quaternary events in Lincolnshire.

Figure 2.9 The limit of the Chalk outcrop, showing the Louth Window and the isolated southern 'block' of Chalk (after University of Birmingham, 1982).



The most important effect of the glacial–interglacial cycles on the Chalk of Lincolnshire has been permeability development, which in the Chalk occurs primarily through solutional widening of fractures. Newly recharged groundwater is slightly acidic as carbon dioxide (CO_2) dissolves into water in the atmosphere and in the soil zone to form carbonic acid, a weak acid which can dissolve calcium carbonate. The amount of CO_2 dissolved in the water is sensitive to temperature. This is because the solubility of carbon dioxide in water increases with lower temperature, although this effect is countered by the fact that soil bacteria produce less CO_2 in colder climates. This process of solutional enhancement of permeability during the past two million years, and its spatial distribution, has had a fundamental impact upon the development of the aquifer system. This process was at a maximum during interglacial times when large volumes of fresh (low total dissolved solids) meltwater were released, providing a plentiful source of potential groundwater recharge.

Conversely, when permafrost conditions occurred during glacial periods the groundwater froze to tens of metres depth, inhibiting recharge, flow and discharge within this zone. Younger (1993) calculated that Devensian permafrost was approximately 210 m thick in the North Lincolnshire Chalk. He surmised that beneath the Devensian permafrost there would have been a thin confined zone of groundwater under considerable pressure: the groundwater remains unfrozen at depth due to the influence of the geothermal gradient. Shallow groundwater circulation was restricted to perennial talik (unfrozen) zones, such as rivers, and to the seasonal thawed layer, both of which only affected a relatively thin upper horizon. Younger discusses evidence from modern periglaciated environments that indicate that permafrost acts as an aquitard, rather than an aquiclude, i.e. slow movement of water can occur, and this may be significant over geological timescales. Nevertheless, he agrees with the findings of Hiscock and Lloyd (1992) that significant permeability development of the Chalk during glacial periods was restricted to the shallow suprapermafrost zones (perennial and seasonal taliks).

This reasoning was supported by models which simulated the influence of climatic change on the hydrogeology of the Lincolnshire Chalk aquifer in the area of Killingholme over the past 140 000 years (the Ipswichian interglacial to the present day) (Hiscock and Lloyd, 1992). Groundwater models are usually calibrated against observed head distributions but as prehistoric head data are not available, the accuracy of the palaeo-hydrogeological models was judged by seeing if they reproduced the position of the saline water interface that is observed in the modern aquifer. Hiscock and Lloyd found that little recharge occurred during the Devensian glacial period; consequently, permeability development would have been negligible at this time. They also concluded that the last 5000 years were the most important time for permeability development due to forest clearance and a wetter climate. The aquifer permeability had to be reduced by 26% (from present day values) for the model to give credible results for the Ipswichian interglacial period, which suggests that the current level of permeability was not fully developed until the Flandrian interglacial. The early Devensian transition vertical section model of Hiscock and Lloyd required a reduction in recharge rate to give sensible output simulations. Saline water intruded during the Ipswichian is present in parts of the aquifer today (Chapter 4), indicating that throughflow was restricted, probably because groundwater recharge was limited by extensive permafrost. They extrapolated these results to conclude that permafrost conditions must have been common throughout the Devensian, limiting recharge and permeability development. The early Flandrian model used Devensian permeability values, but a slight increase was required for the mid Flandrian model. A significant permeability increase of 33% in the upper layers of the

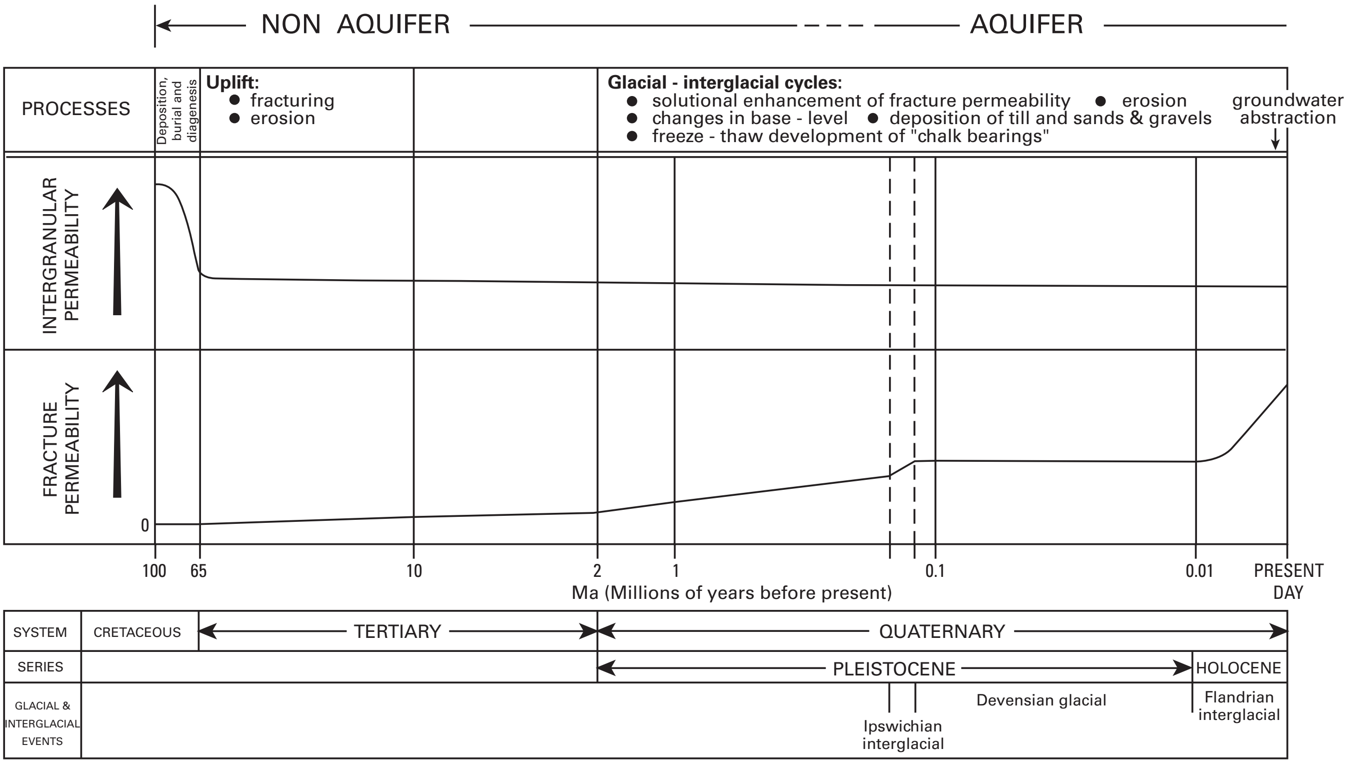


Figure 2.10 Schematic diagram of the development of permeability in the Lincolnshire Chalk.

Chalk is invoked from the mid Flandrian to present day models.

The development of solution-enhanced fractures produced an aquifer in which most of the permeability (although little porosity) is provided by the fractures while the matrix provides significant porosity but negligible permeability. The Chalk is, thus, often referred to as a dual-porosity aquifer.

The permeability development of the Lincolnshire Chalk is shown schematically in Figure 2.10.

2.3.5 Weathering

Weathering of the Chalk has affected its permeability. The top few tens of metres have undergone weathering, resulting in an up-profile increase in joint frequency and aperture. In the uppermost 10 m or so the chalk becomes friable and rubbly. In the extreme case, the near-surface Chalk is structureless with angular blocks in a matrix of weathered chalk; when wet the matrix may take on a paste-like consistency (putty chalk). The existence and nature of this layer affects local infiltration and recharge.

3 Hydrogeology

3.1 INTRODUCTION

The Chalk forms a dual-porosity aquifer, with primary porosity in the matrix and secondary porosity in the form of solution-enhanced fractures. Fractures, and the solution-enhanced fractures in particular, contribute nearly all the aquifer permeability. The Chalk aquifer system of Lincolnshire includes the Chalk Group, the permeable Lower Cretaceous formations, which are in hydraulic continuity with the Chalk, and the permeable Quaternary deposits (sands, gravels and chalk bearings). The latter play a significant role in the Chalk aquifer system, providing valuable additional storage as well as being important in transmitting water laterally. For these reasons, the chalk bearings and associated sands and gravels must be considered as an integral part of the aquifer system.

This aquifer system can be conveniently divided into two: the Chalk aquifer system north of Louth and the Chalk aquifer system south of Louth. The northern groundwater system can be characterised as follows: rainfall recharges the aquifer where the Chalk outcrops in the Wolds. Groundwater moves northwards and eastwards down geological dip and becomes confined by the overlying Quaternary till deposits. Groundwater discharges from the confined aquifer by: abstraction from boreholes; upward leakage through permeable Quaternary deposits (to springs or blow wells); and flow towards the North Sea. The southern groundwater system behaves very differently. This is because the Chalk is largely cut away by the Louth Window, which effectively separates the unconfined and confined aquifers, limiting groundwater flow between the two blocks (Figure 2.9).

3.2 PHYSICAL DESCRIPTION OF THE CHALK AQUIFER

3.2.1 Matrix characteristics

The Chalk matrix is characterised by a combination of small grain size, small pore-throat size and high effective porosity. The relatively small dominant pore-throat size of the Chalk has significant implications for the drainage characteristics of the aquifer. Price et al. (1976) measured median (d_{50}) pore-throat sizes for fifteen samples of northern province Chalk which ranged from 0.275 to 0.575 microns with a mean of about 0.4 microns. Due to the small pore-throat sizes described above, matrix permeability in the Chalk is very low, typically in the range 0.1 to 10 mD (about 10^{-4} to 10^{-2} m d^{-1}). As a consequence pore water is relatively immobile and it is the fracture system which controls rapid groundwater flow and contaminant advection (Price et al., 1993).

The Chalk matrix is of importance to the understanding of the aquifer for two main reasons: firstly because despite its low permeability, the matrix is generally able to transmit the bulk of the infiltration through the unsaturated zone. Local differences in the properties of the matrix may influence water movement, thus in the harder less porous chalks, bypass flow (that is water movement in the fractures that bypasses the matrix) can be important. Secondly, the matrix porosity is high, typically 15 to 30%, and this can have a significant retarding influence on contaminant migration even in the saturated zone where groundwater flow is dominated by fractures, because of diffusion and exchange between the fracture and matrix porewater.

Matrix porosity and permeability vary systematically with the stratigraphical sequence at the regional scale. Trends in matrix porosity are principally a function of the maximum burial depth or the maximum diagenetic grade experienced by the Chalk, as depth-controlled compaction of the Chalk is largely irreversible (Scholle, 1977; Scholle et al., 1983; Hillis, 1995). At the local or site scale the regional matrix porosity and permeability trends may be masked by porosity variations associated with changes in lithology.

A composite porosity log for the Burnham, Welton and Ferriby Chalk formations of Lincolnshire, based on core analysis of samples from three boreholes at Barrow Haven [TA 0695 2317], Goxhill Haven [TA 1198 2540] and Immingham [TA 2128 1494], is presented in Figure 3.1. This log shows that matrix porosity generally increases with distance above the base of the Chalk, where local departures from the overall depth trend are associated with specific lithologies such as hardgrounds or marls. For example, Figure 3.1 shows that in the Ferriby and Welton Formations porosities are typically of the order of 15% to 25% but in the Burnham Formation porosity increases from approximately 20% at 80 m above the base of the Chalk to 40% at approximately 200 m above the base of the Chalk. The low porosities at approximately 25 m and 75 m above the base of the Chalk correspond to the Plenus Marls Member at the base of the Welton Chalk and the North Ormsby Marl at the base of the Burnham Chalk. The data presented in Figure 3.1 are summarised, at the formation level, in Table 3.1. On short porosity profiles, features such as pressure solution fabrics, tectonic hardening or hardgrounds may dominate variations in matrix porosity.

3.2.2 Fracturing

The Chalk is an aquifer because it is fractured and fracturing is, therefore, of fundamental importance to a discussion of chalk hydrogeology.

The Chalk of Lincolnshire shows a joint pattern similar to other flat-lying sedimentary sequences, with the most commonly observed joint pattern at surface exposures being of three approximately orthogonal joint sets, with one joint set parallel to bedding. These bedding plane fractures are regionally extensive and are generally laterally persistent structures that are located at discrete lithological boundaries. In the Chalk, bedding plane fractures may be developed in association with marl seams, flint bands, and hardgrounds, or can be localised by abrupt changes in the density of the chalk.

Geophysical logging of temperature and conductivity in several boreholes provided evidence which suggests that the clay bands within the Chalk may act as confining

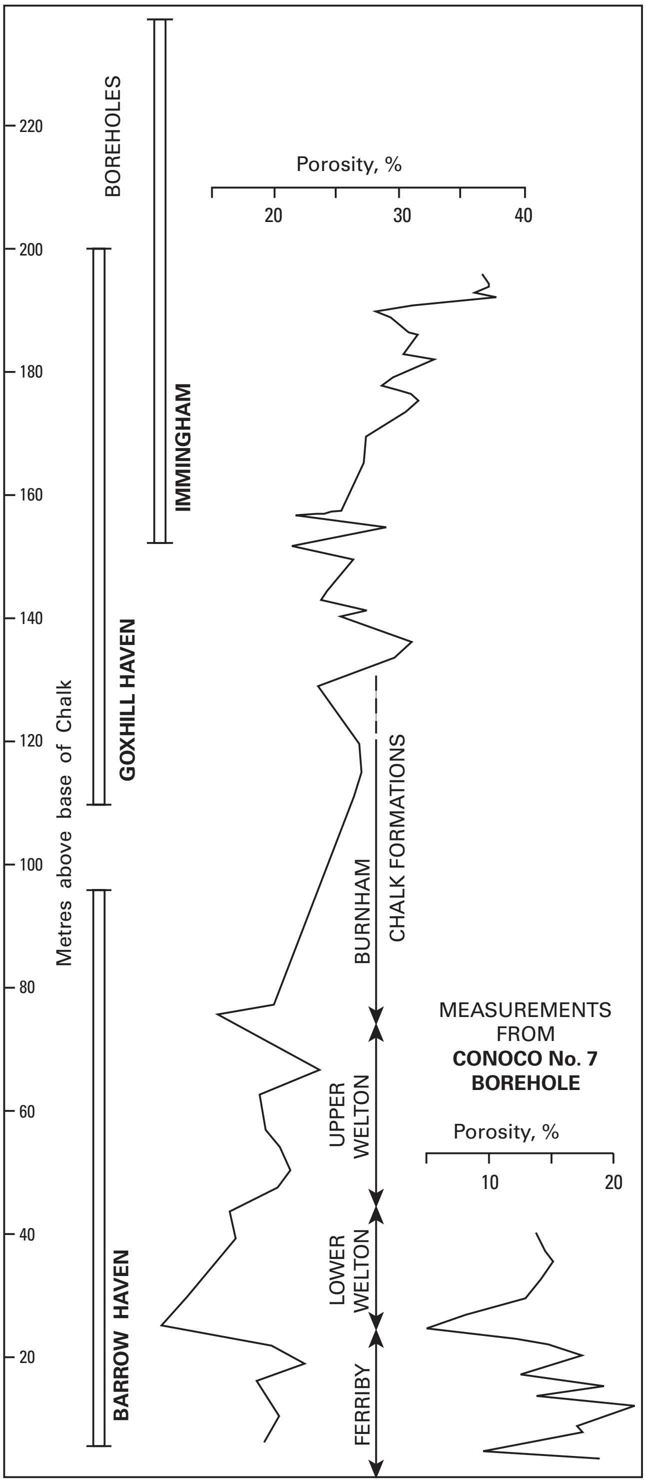


Figure 3.1 Composite porosity log showing the relative stratigraphic positions of the boreholes (Barker, 1994).

layers, at least locally (Barker et al., 1984). The North Ormsby Marl, in particular, is an effective barrier to groundwater flow. The adjacent flint bands, particularly the Ludborough Flint, may contribute to this barrier. Solution-enhanced fractures often develop just above lower porosity bands and tend to be parallel to bedding. The influence of flint bands in flow has also been demonstrated by flowmeter logging of four boreholes at North Killingholme (D. Buckley, personal communication). An example of the logs is given in Figure 3.2, and the inflow horizons, many of which were common to several or all of the boreholes, are labelled.

The other stratigraphical feature that can influence permeability development is the hardground, where solution-enhanced fractures are often better developed than surrounding horizons. This could be due to them being more cleanly fractured because they are harder. Alternatively, it may result from bedding plane fractures associated with the break in sedimentation with channel flow along the top/base of the lower permeability layer, causing preferential solution enhancement of the fractures.

The morphology of bedding plane fractures is highly variable and can range from relatively planar, laterally extensive single fractures with locally large apertures (in excess of a couple of centimetres) associated with massively bedded chalks, to thin zones of intense fracturing associated with finely bedded chalks with marls. However, in both cases the horizontal continuity of these structures provides the potential for rapid subhorizontal flow in the saturated zone.

Apart from bedding plane fractures, other fractures, joints and faults, are present. Joints are fractures with negligible displacement, while faults are fractures that exhibit a significant shear displacement parallel to the fracture surface at the scale of observation. Joints and faults form in response to specific stress states, and accommodate strain in fundamentally different manners; differences in their genesis are reflected in differences in their spatial distributions (Gillespie et al., 1993). These fractures are often high angle and can be important because they may connect across low permeable layers, e.g. hardgrounds or marl bands, and also because they may form enhanced solution features (tubes) where they intersect with bedding plane joints. There is very little data available on fracturing in Lincolnshire, although high-angle and conjugate sets are known to be common (University of Birmingham, 1978). Joint aperture as well as joint frequency is very variable. The University of Birmingham (1978) observed that in Lincolnshire quarry faces, the widening of joints by chemically aggressive groundwaters appears to be entirely random. In addition, frequently horizontal features such as bedding plane joints and stylolitic surfaces have been subjected to a greater degree of solution enhancement than the oblique joint sets. No major fault zones have been recognised.

3.3 AQUIFER PROPERTIES

3.3.1 Hydraulic conductivity and transmissivity

3.3.1.1 Introduction

As discussed earlier in Chapter 2, the development of the transmissivity of the Chalk of Lincolnshire has been influenced by many events such as cementation, jointing, marine transgression and glaciation. The Chalk aquifer has two components of permeability: the matrix permeability which is low due to the small size of the pore throats; and the fracture permeability which dominates.

The matrix permeability of Chalk core measured in the laboratory generally gives values in the range 9×10^{-5} to 9×10^{-4} m d^{-1} (Price et al., 1993). These values equate to a transmissivity of about 0.01 to 0.1 m^2 d^{-1} for a 100 m thick aquifer: comparing these values to field transmissivities, typically in the range 500 to 3000 m^2 d^{-1}, demonstrates the importance of fractures to the overall transmissivity of the aquifer. Furthermore, the Chalk is a heterogeneous and anisotropic aquifer, and it is important to be aware of the three-dimensional variation in hydraulic conductivity and transmissivity. The permeable Quaternary

Table 3.1 Average porosity of Chalk formations in Lincolnshire (from Barker, 1994).

Formation	Mean porosity (%)	Standard deviation from the mean	No. of measurements
Burnham Chalk Formation	29.2	4.5	52
Upper Welton Chalk Formation	20.5	2.0	14
Lower Welton Chalk Formation	14.8	2.4	10
Ferriby Chalk Formation	20.6	1.5	10

deposits also contribute to the transmissivity of the aquifer system, especially where the permeable sands and gravels attain thicknesses of 5 m or more.

The following sections describe our present understanding of the processes which have enhanced permeability and transmissivity throughout the Quaternary, as introduced in Chapter 2, and how these tend to exaggerate the heterogeneity and anisotropy initiated by fracturing. Current knowledge regarding the present day vertical and lateral distribution of permeability and transmissivity in the Chalk of Lincolnshire is then summarised.

3.3.1.2 Development of permeability and transmissivity by solutional widening of fractures

Transmissivity develops preferentially around groundwater discharge points in the Chalk. Flow lines become increasingly closely spaced towards outlets, such as springs and seepages, with a consequent increase in flow velocity. Groundwater flow converges towards these areas. Solutional enlargement of fractures occurs more rapidly in these horizons of higher flow, which, therefore, become high permeability zones. Once a high permeability zone has formed, flow tends to be concentrated along, and converge towards, this zone. The high permeability zone develops laterally as a result, extending further and further from the original focus, as shown schematically in Figure 3.3. This theory of focused permeability enhancement explains, in part, the higher permeability observed around valleys. The water table tends to lie within or near such a near surface high permeability zone as it buffers changes in water level. Water is discharged quickly from the high transmissivity zone at times of high

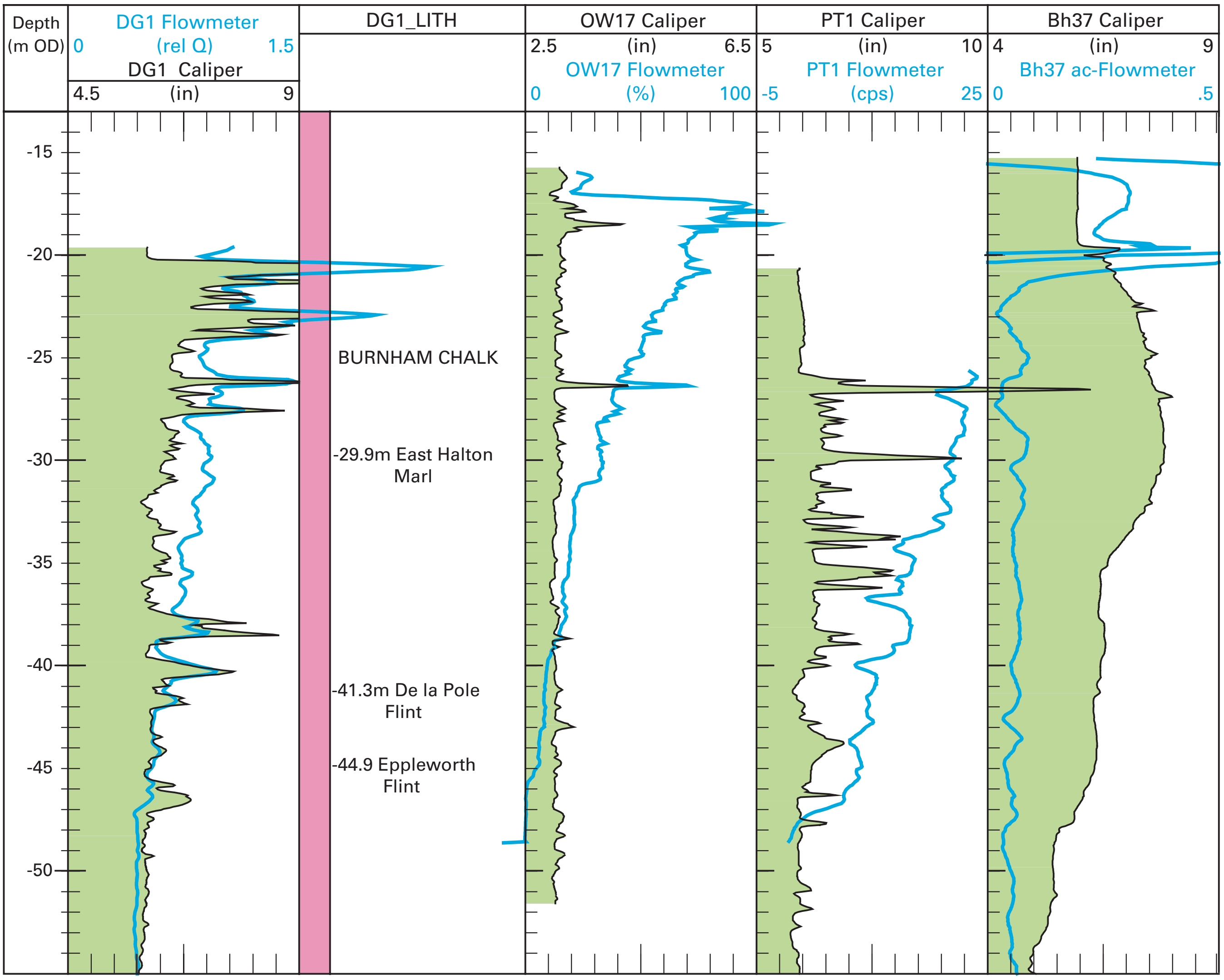


Figure 3.2 Flowmeter and caliper logs for North Killingholme boreholes.

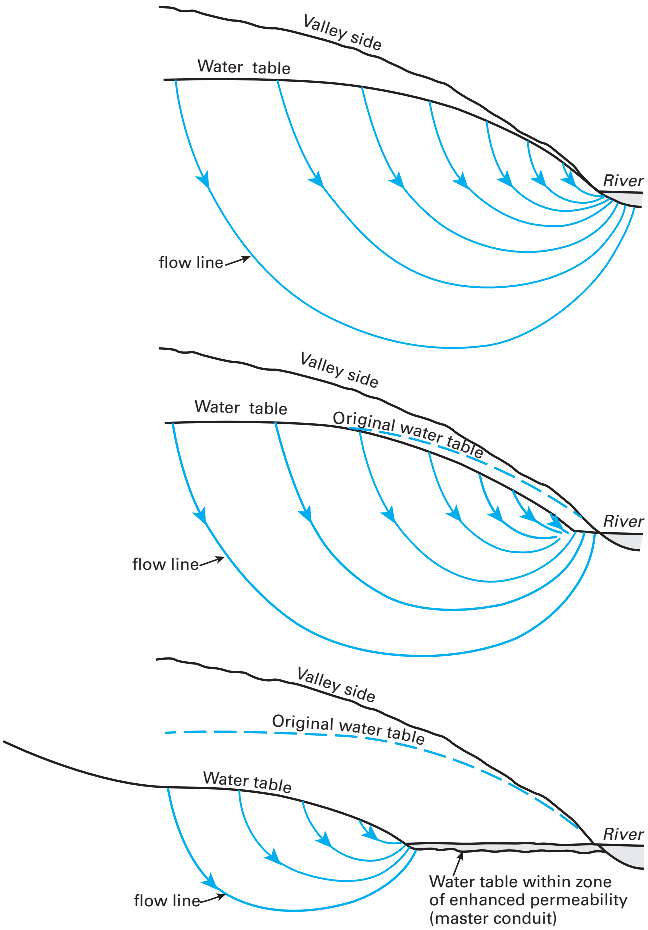


Figure 3.3 Schematic diagram showing the development of transmissivity around discharge zones (after Price, 1987).

recharge, so water levels do not rise significantly. When the water level falls as a result of low recharge, the rate of water level decline diminishes when the base of the high transmissivity zone is encountered due to the lower permeability below this zone (Allen et al., 1997). Solution of the Chalk occurs preferentially along fractures, as flow is concentrated along these more conductive paths.

Glacial–interglacial cycles involve large changes in sea level and, therefore, in the hydrological base level, to which surface and groundwaters drain. Changes in base level are accompanied by changes in the elevations of the water table and groundwater discharge points. Elevations of past water table positions are often zones of high permeability. The low base levels that occurred during glacial and periglacial events are, however, thought to be less significant than the warm interglacial base levels. This is because permeability development by solution is believed to have been most active during interglacial climates when recharge and groundwater circulation would have been greatest, as discussed in Chapter 2. This would equate with base levels within ± 30 m of the present day sea level (University of Birmingham, 1985).

3.3.1.3 Lateral transmissivity variations

Transmissivity varies widely throughout the area, by over three orders of magnitude (Allen et al., 1997; Figure 3.4). Transmissivity values of the exploited areas of the Chalk in Lincolnshire, as estimated from pumping tests, tend to be of the order of 1000–5000 $m^2 d^{-1}$. The minimum value of transmissivity for the study area is 4 $m^2 d^{-1}$, which was recorded at Galley Hill Farm [TF 544050 379150], while the maximum value of 10 000 $m^2 d^{-1}$ was recorded at Barton Bore [TA 503800 421000] and at Barrow [TA 506050 420300] (Allen et al., 1997). A median value for the 45 sites in the study area (taking the mean value for sites where more than one estimate has been made) was 2000 $m^2 d^{-1}$.

However, the dataset is likely to be biased towards high yielding situations, such as valleys, as boreholes are more likely to be drilled in areas where good yields have been obtained. Transmissivity is also greatly dependent upon the water level and in consequence significant seasonal differences are apparent in the unconfined aquifer (discussed in the next section).

In the southern confined Chalk the distribution of transmissivity reflects to some extent the presence of sands and gravels which directly overlie the Chalk. Higher transmissivities generally occur where the permeable Quaternary deposits are thicker (University of Birmingham, 1982).

The transmissivity of the Chalk is often higher in dry valleys, due to the former concentration of flow and the associated solution effects, although this may not always be apparent because the current water table may be below the solution-developed features. However, no correlation between estimated transmissivity and the pattern of surface drainage during the Quaternary in Lincolnshire was observed; this was attributed to erosion and the removal of higher transmissivity horizons (University of Birmingham, 1978). Higher transmissivity is also associated with the blow wells and springs due to the convergence of flow at these sites (Lloyd, 1980).

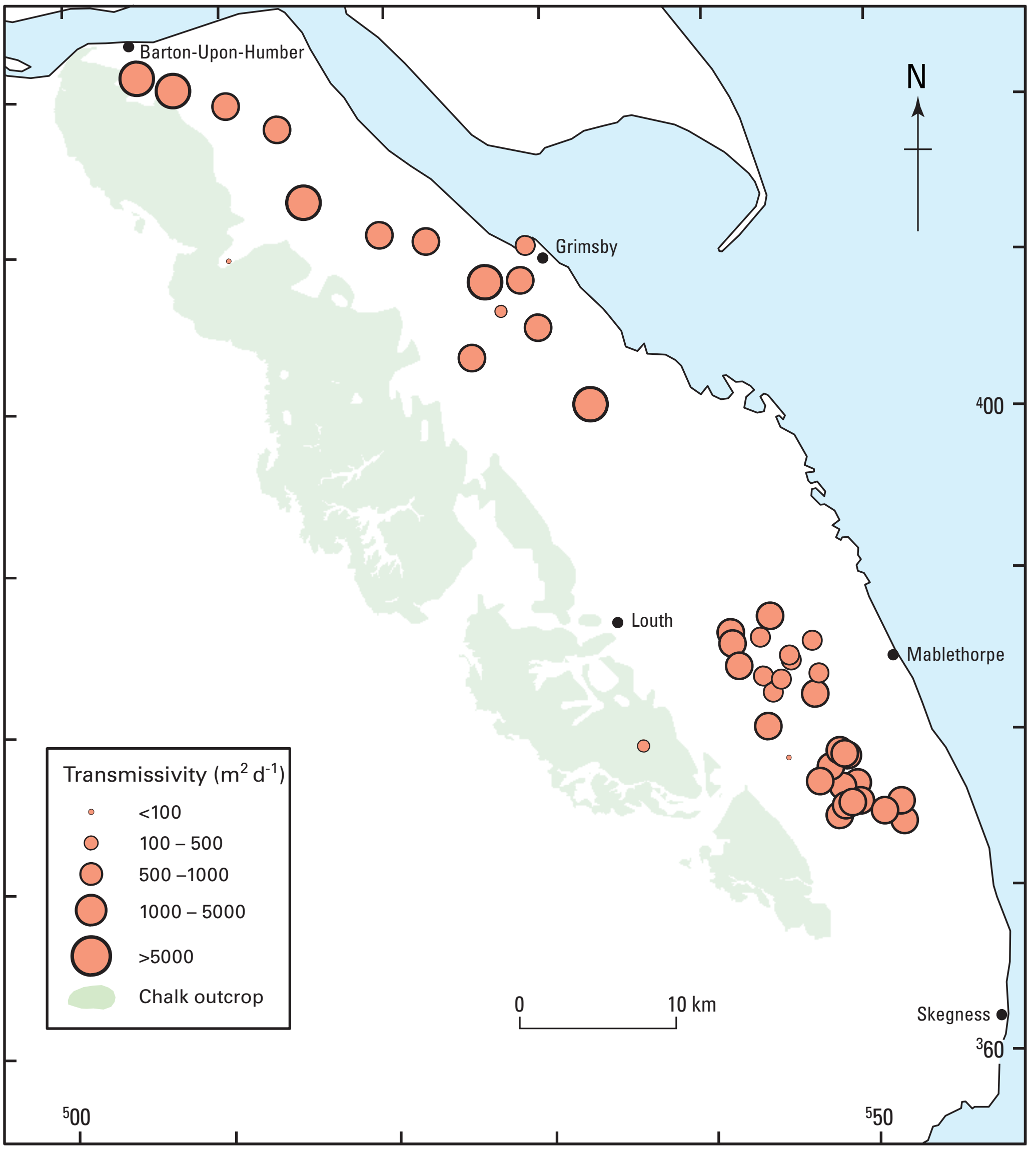
3.3.1.4 Permeability variations with depth

As discussed above, the permeability of the Chalk varies significantly with depth, especially as many of the solution enhanced fractures occur within ± 30 m of present sea level. In addition, fractures commonly close with depth due to overburden pressure (University of Birmingham, 1982).

Evidence for the importance of permeability differences with depth is provided by geophysical borehole logging which indicates that flow occurs almost entirely in the upper few tens of metres of the Lincolnshire Chalk, where fractures are most developed. For example, at one site (Ciba Geigy Borehole Number 1 [TA 2467 1156]), temperature and conductivity logs show that solution-enhanced fractures are concentrated between 30 and 40 m depth, with far fewer at greater depths (University of Birmingham, 1978). Flow metering has shown that most flow occurs within approximately 30 m of sea level (University of Birmingham, 1978). At North Killingholme, the main flow horizon is above flint bands within about 50 m of the ground surface (Figure 3.2).

This evidence is supported by hydrochemical data which suggests a thin aquifer, with tritiated (modern recharge) water occurring only at shallow depths (up to 30 m deep), with non-tritiated waters underneath (University of Birmingham, 1978). Similar vertical stratification of water types is observed in the southern Chalk aquifer where, for example, oxidised water overlies older reducing waters (University of Birmingham, 1982). Such stratification almost certainly reflects changing permeability with depth. This observation is supported by evidence from fluid logging during pumping which suggests that 90% of the flow into Chalk boreholes is derived from the Chalk Bearings (and associated sands and gravels) and the upper few metres of the Chalk (University of Birmingham, 1982).

Figure 3.4
Distribution of transmissivity in the Lincolnshire Chalk (data from Allen et al., 1997).



Three major zones of solution development have been recognised in the unconfined Chalk of Lincolnshire. The high permeability zones above and below the present day water table probably relate to palaeo-water table positions, from times during the Quaternary when the base level was different. The upper one lies 20 to 30 m above the present water table and has been ascribed to the Hoxnian stage (University of Birmingham, 1985); it has been removed by erosion in many of the dry valleys and is not of significance to present-day groundwater flow. As discussed in the preceding section, the present zone of water table fluctuation is also a solution-enhanced fracture zone. The third zone lies approximately 20 m below the present water table and frequently defines the base of the effective part of the aquifer.

The transmissivity of unconfined Chalk aquifers varies as the water table fluctuates. This is due in part to the dependence of transmissivity on saturated thickness, but more importantly to the variation in permeability with depth, as the water table falls below the zone where solution-enhanced fractures are most developed. This has several implications, for example, the yield and yield-drawdown characteristics of boreholes will vary seasonally, as will pumping interference effects. The seasonal fluctuation of the groundwater level in the Wolds can exceed 20 m (Hiscock and Lloyd, 1992).

3.3.2 Storage

The specific yield of the Chalk is small, typically in the range 0.005 to 0.025, since it is only the water within the fractures that drains. However where the Chalk is in continuity with overlying sands and gravels and the chalk bearings, the specific yield of the aquifer system can be significantly higher. Specific yield for sands and gravels can be 0.1 or more and where the sands and gravels are thick and unconfined, the storativity of the aquifer system can be considerably enhanced.

Specific yield is an important aquifer parameter because the change in the water stored within the aquifer is a major component of the water balance, and this value can be used to validate recharge estimates calculated by meteorological data.

Storativity for the confined Chalk aquifer is typically around 10^{-4}. In Lincolnshire, storativity has been estimated from pumping tests at 39 sites (Allen et al, 1997; Figure 3.5). These range from a minimum of 1×10^{-6} at Thurlby Test Bore [TF 550000 375900] to a maximum of 6×10^{-2} at Goxhill Station 1 and 2 [TA 509310 419350]. The median value for all 39 sites is 1×10^{-4}. Specific yield values as high as 0.06 clearly indicate a considerable contribution from the sands and gravels within the aquifer system. A test at Keelby (TA 158 111) designed to estimate the unconfined storage coefficient (specific yield) of the sands and gravels indicated a permeability of 22 ± 2 m d^{-1}, and a specific yield of 0.04 ± 0.02 (University of Birmingham, 1978). However as the abstraction phase of the test lasted only 30 minutes, the phenomenon of delayed yield could have significantly modified the specific yield estimated. Delayed yield is known to occur in gravels and, applying a correction based on the results from a long term pumping test in gravels (Rushton and Booth, 1976), an estimated specific yield of 0.06 ± 0.1 is possible.

In a study which attempted to quantify the total volume of water stored in the Chalk of England, it was shown that the long-term drainage from the aquifer exceeds that predicted using specific yields estimated from pumping tests (Lewis et al., 1993). The idea of delayed drainage from microfissures was proposed (Lewis et al., 1993; Jones, 1992). However, research by Price et al. (2000) found no evidence for macropores or interconnected microfracture network in samples of Chalk from quarries near Reading, Shoreham and Cambridge, and concluded that the storage was in the irregularities on the surfaces of the larger fractures.

Storativity varies not only spatially but also seasonally. Thus during periods of low groundwater levels the confined aquifer may become unconfined in places. Indeed, this happens seasonally as the unconfined-confined boundary moves eastwards in response to falling groundwater levels (Gaunt et al., 1992). This zone of movement of the unconfined-confined boundary is referred to as the transitional zone. When groundwater levels are low, and sands and gravels in the transitional zone change from being confined to unconfined, the higher storage in these deposits becomes operative (University of Birmingham, 1978). For example, along the buried cliff line in the Grimsby region, a glacial erosional hole filled with sand and gravel deposits exists beneath the till; this provides additional storage which results in lower summer drawdowns than are observed in adjacent Chalk abstraction boreholes (Lloyd, 1993).

3.4 THE SPILSBY SANDSTONE

3.4.1 Introduction

The Spilsby Sandstone outcrops to the west of the Wolds, from Grasby to the Wash (Figure 2.1). Abstraction from the Spilsby Sandstone has been an important source of water for public supply since the end of the 19th Century (Groundwater Development Consultants, 1989). Demand has been increasing in recent times, particularly for agricultural use, and also in response to the strong seasonal demand for water in coastal areas such as Skegness. Abstractions from confined Spilsby Sandstone are low in nitrate.

3.4.2 Physical description

The Spilsby Sandstone is mainly a medium to fine grained quartz sand, although the grain size is variable, and flow is predominantly intergranular. It is generally finer grained in the south. The Spilsby Sandstone is poorly cemented or unconsolidated, and loose sands have caused problems with borehole construction and sand pumping. Observations from boreholes indicate that fractures in the Spilsby Sandstone are sand-filled (Groundwater Development Consultants, 1989). The Spilsby Sandstone has high porosity (Jones et al., 2000).

3.4.3 Aquifer properties

A recent review of aquifer properties data for the Spilsby Sandstone was undertaken by Jones et al. (2000). They found that transmissivity values range from 6 to 1000 m^2 d^{-1}, with an interquartile range of 90 to 250 m^2 d^{-1},and a geometric mean of 141 m^2 d^{-1}. The data, calculated from 77 pumping test records, were distributed approximately log-normally. The absence of transmissivity data for the southern end of the sandstone, where it subcrops beneath superficial deposits, suggests it is little used in this area. The highest values of transmissivity (>1000 m^2 d^{-1}) were obtained from pumping tests conducted in boreholes north of the Caistor Monocline, however as this is close to the northern limit of the Spilsby Sandstone, where it thins out, they are assumed to be anomalous, probably representing boreholes in the Carstone which are in hydraulic continuity with the Chalk.

Storage coefficients vary between 6×10^{-5} to 6.3×10^{-3}, with a geometric mean of 4×10^{-4} (Jones et al., 2000).

The calculated specific capacity values range from 2.4 to 237 m^3 d^{-1} m^{-1}, with an interquartile range of 28 to 179 m^3 d^{-1} m^{-1}, and a geometric mean of 69 m^3 d^{-1} m^{-1} (Jones et al., 2000).

Jones et al. (2000) found no systematic areal variation in aquifer properties, although Groundwater Development Consultants (1989) found that the transmissivity was greatest in the central area, around Raithby and Hubbards Hills, where the sandstone is thickest.

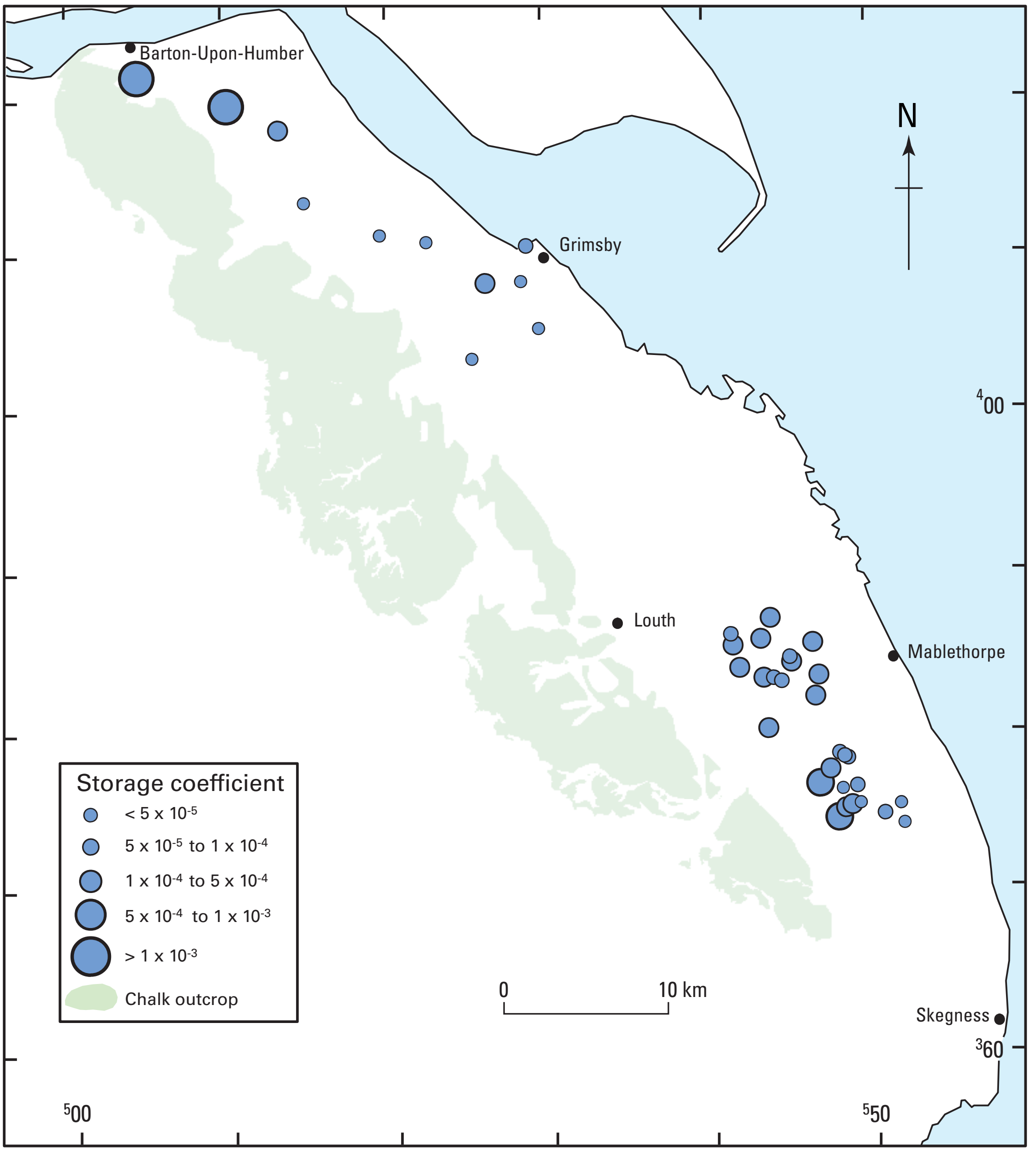
3.5 THE AQUIFER IN THE WATER CYCLE

3.5.1 Recharge

The bulk of recharge normally occurs as a result of effective rainfall (total rainfall minus actual evapotranspiration) falling on the outcrop of the aquifer. This recharge is normally greatest where soils are thin and permeable. The presence of low permeability superficial cover can reduce recharge; even thin layers of till can be influential. The Chalk aquifer is unconfined in the Wolds, where soil and superficial cover are thin or absent, and confined by glacial tills in the east and south. The unconfined-confined boundary coincides generally with the position of the buried coastline, east of which the thickness of till covering the aquifer is considerable (usually in excess of 20 m). The position of the boundary moves with the seasonal variation in groundwater head.

Recharge is a major component of the water balance, however, estimating it, especially in fractured aquifers, is not straightforward. Rushton and Ward (1979) reviewed methods of estimating groundwater recharge in temperate climates, using the Lincolnshire Chalk as a case study. They suggested that the conventional method of Penman and Grindley tends to underestimate the amount of recharge. The Penman-Grindley approach assumes that no recharge occurs when a soil moisture deficit (SMD) exists; the work of Rushton and Ward (1979) questions this idea. Indeed, they suggested that recharge can occur when an SMD exists. Two forms of evidence for this 'additional' recharge were cited (University of Birmingham, 1987): firstly, the total inflow calculated by the traditional method was less than the known outflows; and secondly, well hydrographs showed recovery (indicating recharge) occurring during the summer months when a SMD existed. Possible mechanisms by which recharge can occur even when there is a SMD include infiltration through cracks in the soil and runoff collecting

Figure 3.5
Distribution of storage coefficient in the Lincolnshire Chalk (data from Allen et al., 1997).



in ditches and stream channels which directly feed the aquifer.

The recharge calculation in the numerical model of the Lincolnshire Chalk aquifer produced by the University of Birmingham (1987) allowed for an empirical estimation of direct recharge of 10% of effective precipitation plus 10% of actual precipitation in excess of 6 mm. In modelling trials this was found to be the most appropriate direct recharge formula (University of Birmingham, 1987). Significant recharge was thought to occur only in the unconfined aquifer north of Louth, as recharge occurring on the southern Wolds does not reach the confined aquifer system to the east, as the buried Louth Window inhibits flow eastwards.

Much of the direct recharge to the Spilsby Sandstone at outcrop is discharged as spring flow (Groundwater Development Consultants, 1989). However, in addition to direct recharge, the Spilsby Sandstone is believed to receive recharge from the Chalk in the Wolds area, while upward leakage from the Spilsby Sandstone is thought to occur in the coastal area (see Section 3.5.9, below). Some additional recharge may also occur where runoff from the low permeability strata, which separate the Spilsby Sandstone from the Chalk, flows onto the sandstone outcrop.

3.5.2 Unsaturated zone flow

Limited data are available for the unsaturated zone in Lincolnshire, as all the major abstractions are from the confined aquifer unit, and few observation boreholes exist on the outcrop. In Lincolnshire the depth to the water table can exceed 40 m, although in the valleys the unsaturated zone is much thinner.

Because the Chalk pores are small, the matrix is largely saturated above the water table. Under normal recharge conditions, despite its relatively low permeability, the matrix can transmit the bulk of infiltration. Due to the high porosity of the Chalk matrix, travel time through the unsaturated zone can be very considerable (years to decades), although the water table will respond to rainfall more rapidly (piston flow effect). However, under extreme hydraulic loading, infiltration will also occur through fractures: this is known as ‘bypass flow’.

The Lincolnshire Chalk includes a number of hardgrounds, which have low matrix porosity and permeability. The influence of these on unsaturated zone water movement is uncertain but may produce temporary perched water tables. In these circumstances, lateral flow via bedding plane fractures at the contact with the hardgrounds may be possible.

3.5.3 Water-table fluctuations

The Environment Agency provided water level records representative of various areas of the Lincolnshire Chalk aquifer system spanning the interval 1978 to 2002, which are plotted in Figures 3.6 to 3.9. Figures 3.6 and 3.7 show the hydrographs of sites in the unconfined and confined Chalk of North Lincolnshire respectively. These hydrographs are very similar, with a typical seasonal fluctuation of water level of about 7 m. These hydrographs include two periods of low water level (1988 to 1993 and 1995 to 1997), which correspond to periods of lower than average rainfall.

The confined Chalk of South Lincolnshire (Figure 3.8) shows less annual variation in water level (about 1 to 1.5 m), and the effect of the low rainfall periods which are so clearly observed in North Lincolnshire is considerably dampened in the South.

Figure 3.9 shows the hydrograph for a site in the confined Spilsby Sandstone, in which a seasonal fluctuation of water levels of about 1 to 1.5 m can also be discerned. There is a gradual decline in water level of about 6 m from 1986 to 2001.

3.5.4 Flow in the saturated zone

In contrast to the unsaturated zone, groundwater flow in the saturated zone of the Chalk is concentrated along fractures that have been enlarged by solution, rather than through the Chalk matrix. Evidence from pumping test, flow logging and hydrochemical data indicated that over 90% of the flow into Lincolnshire Chalk boreholes during pumping is from the chalk bearings and the upper few metres of the Chalk (University of Birmingham, 1982).

Groundwater movement on a regional scale tends to follow the dip of the Chalk; flow is away from a major groundwater divide that closely parallels the Chalk escarpment, generally trending north-west. The hydraulic gradient is very shallow in the confined aquifer but is steeper in the Wolds, where it mimics the topography. However, the saturated zone of the unconfined aquifer can be very thin, especially south of the Caistor Monocline (University of Birmingham, 1978). A plot of potentiometric levels in the Lincolnshire Chalk is shown in Figure 3.10. The distribution of groundwater levels for the unconfined aquifer is not well defined as data are sparse. Groundwater levels in the confined aquifer are influenced by abstraction.

The Chalk aquifer is divided into two: one aquifer system north of Louth and the other south of Louth. In the northern Lincolnshire Chalk, groundwater flows primarily in a north-easterly direction from the unconfined aquifer to the confined aquifer. However, groundwater flow directions can be significantly different on a local scale for various reasons. For example, in the far north of Lincolnshire, groundwater is believed to move in a northerly direction away from the Chalk outcrop area and discharge as springs in the bed of the River Humber near Barton. This is probably due to major abstractions such as at Barrow and Barton, as well as the karstic nature of the Chalk in this area and the development of strong directional permeability. Elsewhere, groundwater flow directions may be modified by major abstraction sites such as Littlecoates Pumping Station in Grimsby. Although the Kirmington Channel is filled with low permeability deposits, which act as a barrier to groundwater flow, its influence on groundwater flow is probably not pronounced as it is parallel to the regional flow direction.

South of Louth the Chalk is completely eroded along the line of the buried Ipswichian coastline. This restricts groundwater flow from west to east, and is thought to prevent most of the recharge to the Wolds from reaching the confined Chalk. There is hydrochemical evidence to support this theory: low tritium counts indicate that the waters to the east of the Louth Window, in the confined part of the southern aquifer, have received little recent recharge. Indeed, these waters may, in part, be much older as they have low concentrations of ions such as chloride, sulphate and nitrate, which could reflect a glacial meltwater origin. Furthermore, a long residence time in the aquifer is indicated by high alkalinity and low hardness, characteristics which are attributed to ion exchange. The contrast between these waters and the recent waters found in the unconfined areas to the west of the Louth Window is striking and clearly demonstrates the lack of significant flow across the gap in the Chalk. Nevertheless, it is thought that some west–east flow of water occurs across the Louth Window via the sands and gravels and Lower Cretaceous strata (see following section). It has also been suggested that this southern area of confined Chalk receives limited recharge by flow from the northern confined Chalk, based on the shape of the potentiometric surface (University of Birmingham, 1982).

3.5.5 Outflows

The main components of outflow from the Lincolnshire Chalk are abstraction, discharge to streams and blow wells, and outflow to sea. Abstraction is currently the largest outflow and has a significant impact upon the natural outflows. The total abstraction from the Lincolnshire Chalk is about 110 to 130 Ml d^{-1}, which is mainly taken from the confined region of the aquifer north of Louth (Chapter 1).

There is a spring line on the western Wolds escarpment, with the springs appearing from horizons within the Lower Cretaceous Roach and Carstone formations. These springs receive recharge from the area of outcrop along the scarp face that is west of the groundwater divide. This groundwater divide is almost coincident with the surface water divide.

In the northern Lincolnshire Chalk, seasonal springs emerge at the edge of the till, representing the overflow from the Chalk where groundwater is flowing from the unconfined aquifer in the west to the confined zone in the east. Within the confined aquifer, blow wells occur where the till is thin or permeable and the aquifer is artesian. Most of the blow wells that existed in the past have now dried up as a result of groundwater abstraction, which has lowered the potentiometric surface. However, several perennial blow wells still exist, such as those at Tetney [TA 31 01]. Some diffuse outflow through permeable Quaternary deposits has also been suggested in an area between Mablethorpe, Alford and Louth (University of Birmingham, 1987).

The groundwater flow system in the Chalk south of Louth is very different because the Louth Window prevents flow directly to the confined aquifer. Instead, groundwater discharges to springs, which rise along the buried cliff line, that feed the headwaters of the River Lud and Great Eau.

3.5.6 Interaction between the Chalk and other components of the aquifer system

The Chalk aquifer of Lincolnshire does not function solely as an independent unit. For example, the overlying sands and gravels can significantly add to the storage capacity of the aquifer system where they are in hydraulic continuity with the Chalk. Groundwater flow between the Chalk and underlying strata is thought to occur, although the quantity and spatial extent of such flows, is not known.

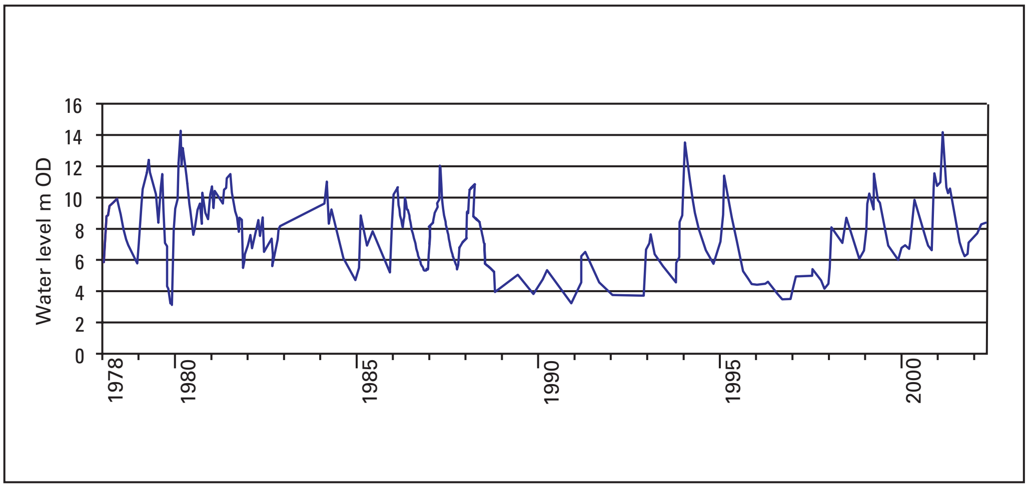


Figure 3.6
Hydrograph for a site in unconfined Chalk of north Lincolnshire.

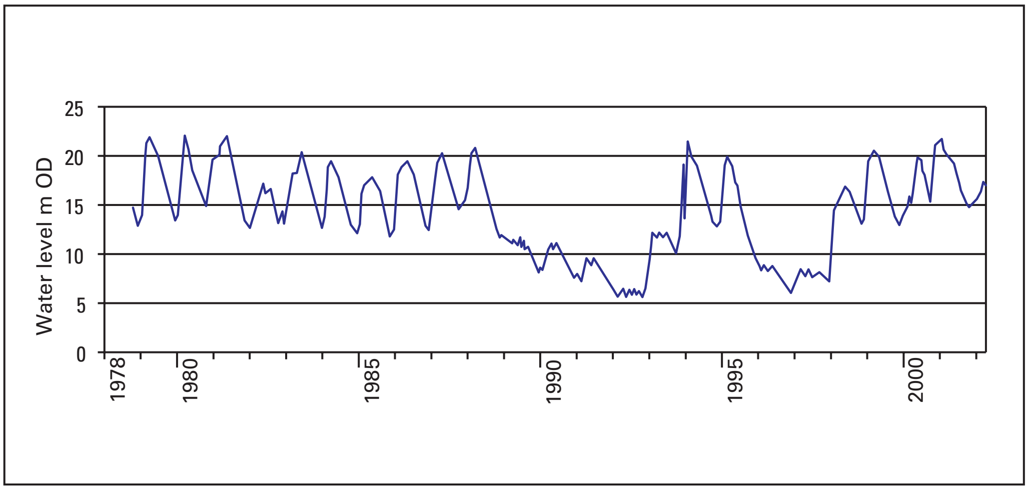


Figure 3.7
Hydrograph for a site in confined Chalk of north Lincolnshire.

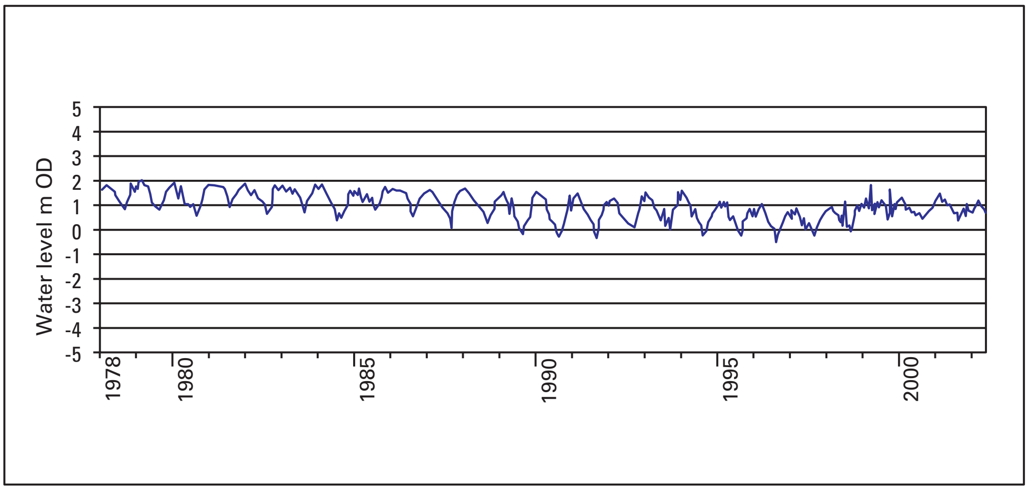


Figure 3.8
Hydrograph for a site in confined Chalk of south Lincolnshire.

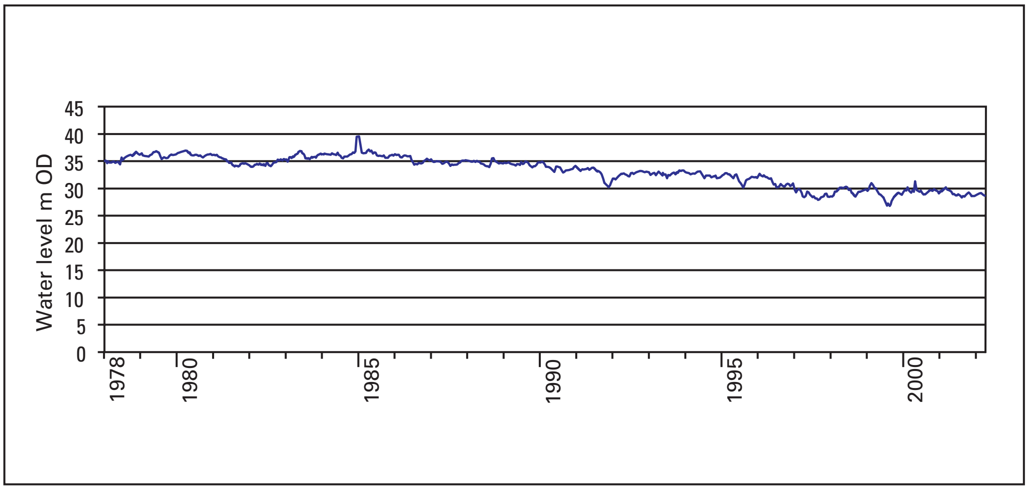


Figure 3.9
Hydrograph for a site in confined Spilsby Sandstone.

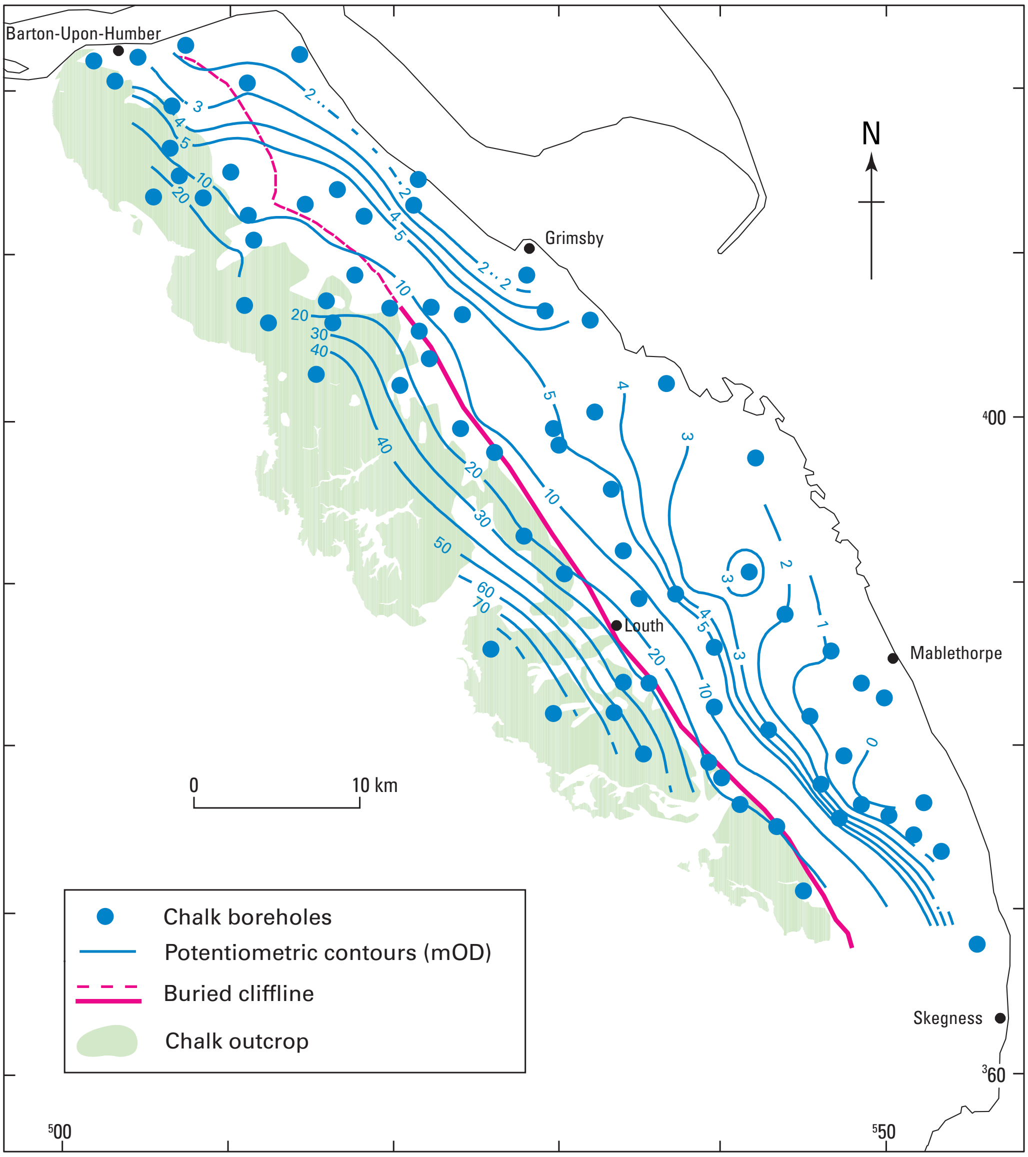


Figure 3.10
Potentiometric contour map of the Chalk.

South of Louth, where the Louth Window prevents direct flow between the Chalk of the unconfined and confined aquifer, the role of the other permeable members of the aquifer system becomes more important. It has been suggested that minor west-to-east flow occurs in the aquifer system either through permeable sands and gravels banked up against the Chalk at the base of the buried cliff (i.e. in the Louth Window) or via the underlying Carstone and Roach Formations (Price, 1957).

Groundwater hydrographs from adjacent Chalk and Carstone Formation boreholes at Belleau [TF 401 779] and Burwell [TF 351 795] show that there is a head difference between these formations, providing the potential for vertical flows (Figure 3.11). At Burwell, the more westerly of the two sites, downward leakage is thought to occur from the Chalk to the Carstone Formation, while to the east, at Belleau, the gradient is reversed. Similar conditions occur between the Chalk, and the Carstone and Roach formations, and the Spilsby Sandstone to the east of the Louth Window.

While the Elsham Sandstone is only present in a limited area of Lincolnshire, around Worlaby [TA 01 13] and South Killingholme [TA 14 17], there appears to be some leakage between this formation and the Chalk. Some groundwater flow is also believed to occur between the Chalk and the Spilsby Sandstone in the area immediately north of the Caistor Monocline (University of Birmingham, 1978). Due to overstepping (Chapter 2; Figure 2.2) this is the only area of Lincolnshire where the Spilsby Sandstone is in direct contact with the Chalk. The University of Birmingham (1978) do not consider the Elsham or Spilsby Sandstones to be part of the Lincolnshire Chalk aquifer system.

Groundwater flow in the Spilsby Sandstone is from the outcrop to the east (Figure 3.12). Groundwater levels have declined below sea level in the southern part of the area as a result of abstraction.

It has also been postulated that 35 Ml d^{-1} of downward leakage occurs from the unconfined southern Chalk aquifer to the Spilsby Sandstone (Environment Agency, 1998c). However, a long-term decline in water levels in the confined area of Spilsby Sandstone as a result of abstraction in the south of Lincolnshire has been observed, which appears to question whether downward leakage is so significant (Hutchinson, 1999, 2000). Recent analysis and comparison of heads in the Chalk and Spilsby Sandstone show that certain long term trends are not repeated in both aquifers. While this does not preclude leakage between them it emphasises the limited hydraulic connection. The relationship will be examined further by the Environment Agency's regional modelling strategy.

Although the Chalk and the Lower Cretaceous formations are considered as part of the same aquifer system, nevertheless, it is important to recognise that the

Chalk and the underlying Lower Cretaceous formations are not in hydraulic continuity throughout the whole of the area. This is because the Chalk oversteps these formations, as described in Chapter 2, causing the thickness of intervening low permeability strata to vary. This makes for a complex aquifer system and one in which it is difficult to quantify flow between different members of the system.

3.5.7 Surface water — groundwater interaction

Baseflow from the Chalk aquifer system feeds a number of streams and rivers in Lincolnshire, and outflows also support wetland areas (Chapter 5). However, it is not thought that surface water bodies contribute significantly to the recharge of the aquifer system; there are few rivers on the Wolds (the main recharge zone of the aquifer system) and those that do exist flow mainly on low permeability Lower Cretaceous clays. However, stretches of the Waithe Beck are reportedly influent under low flow conditions; the Environment Agency has a monitoring regime in place to further define this.

3.5.8 Anthropogenic impacts on groundwater systems

The flow system in the Lincolnshire Chalk has changed significantly as a result of pumping. The groundwater head in the Chalk has declined historically due to abstraction, and boreholes that were once artesian now require pumping. This fall in head has induced saline intrusion from the Humber Estuary, and springs that occur along the buried coastline have reduced in size and as a consequence stream flows are now less.

Human activity other than abstraction, particularly agriculture and industry, has also affected the quality of the groundwater. These issues, and the measures in place to control anthropogenic impacts on the groundwater resource, are discussed in Chapter 5.

3.5.9 A water balance

There is no traditional water balance for the Lincolnshire Chalk aquifer system, as not all components of the water balance have been measured. The flows between the Chalk and the Spilsby Sandstone are particularly poorly understood.

The Environment Agency (EA) approach to the water balance utilises what information is available to produce groundwater balances which are fundamental to the management of the aquifer system. The average annual recharge, which the EA term the *gross resource*, is obtained from the recharge estimate from the relevant modelling study of the area (University of Birmingham, 1978 and 1982 and Groundwater Development Consultants, 1989). To allow for uncertainty in these values and the fact that not all of the recharged water is accessible for abstraction, an aquifer-dependent availability factor is applied to the *gross resource* to determine the *available resource*. The *licensed demands* and *effluent returns* are then accounted for, by summing the various licensed abstraction quantities and subtracting the volume of water which is returned to the system by effluent returns. The third component of the EA water balance is the *in-situ resource requirements*, which accounts for the water required to maintain river and spring flows fed by discharges from the part of the aquifer system in question, and in some cases allows for the prevention of saline water inflows. The *resource surplus to licensed demands* and *in-situ needs* is then calculated by subtracting the *licensed demands* and *in-situ resource requirements* from the *available resource*.

A review by the EA in 1998 produced water balances for the northern Chalk (including the southern confined Chalk), the unconfined southern Chalk, and the Spilsby Sandstone. The components of the water balance for each of these areas are tabulated in Table 3.2.

3.5.9.1 Northern Chalk and southern confined Chalk

The average annual rainfall recharge to the northern Chalk and southern confined Chalk (the gross resource) was based on the University of Birmingham (1978) model output of 231 Ml d^{-1}. Upward leakage of 14 Ml d^{-1} from the Spilsby Sandstone is also included in the Gross Resource, which totals 245 Ml d^{-1}. The available resource is calculated as 0.8 of the gross resource, which equals 196 Ml d^{-1}. The major component of outflow is abstraction, and in 1998 the total licensed quantity was 180.8 Ml d^{-1}. Another component of outflow is the water needed to prevent saline incursion and to maintain river and springflows. These *in situ resource requirements* were estimated by the EA to be 26.6 Ml d^{-1}. The *net effluent return* (summer surface water abstraction for spray irrigation minus effluent return to surface water) is then subtracted from this value to give the *net in situ resource requirement* of 23 Ml d^{-1}.

The resource surplus, which is the available resource minus the licensed abstraction and the in situ requirement, is –25.6 Ml d^{-1}. This demonstrates that the aquifer is over-committed. However, in normal rainfall years actual abstraction is less than the licensed amount and the resource surplus is approximately in balance. In low rainfall years, it is necessary to restrict abstraction to maintain a resource surplus balance as discussed in Chapter 5.

3.5.9.2 Unconfined southern Chalk

The recharge to the unconfined southern Chalk is taken from the University of Birmingham (1982) modelling study, which reports an average value of 105 Ml d^{-1}. The availability factor of 0.6 for the southern Chalk is then applied, giving a value of 63 Ml d^{-1}. In the Groundwater Development Consultants (1989) investigation, modelling studies indicated that the Southern Chalk contributed 35 Ml d^{-1} leakage to the Spilsby Sandstone, so this is subtracted from the previous value to give a final gross resource of 28 Ml d^{-1}.

As described for the northern Chalk, the other components of the water balance are subtracted to give a final account of resource surplus to licensed demands and in situ needs, which in this case are -11.8 Ml d^{-1}, i.e. this part of the Lincolnshire Chalk aquifer system is also overcommitted.

3.5.9.3 Spilsby Sandstone

The average annual rainfall recharge to the Spilsby Sandstone was calculated by Groundwater Development Consultants (1989) to be 47 Ml d^{-1}. The availability factor applied to the Spilsby Sandstone is 1.0, and thus the gross resource is equal to 47 Ml d^{-1} plus 35 Ml d^{-1} leakage received from thesouthern unconfined Chalk minus 14 Ml d^{-1} leakage to the southern confined Chalk, which equals 68 Ml d^{-1}.

The surplus resources in the Spilsby Sandstone are estimated to equal –7.4 Ml d^{-1}.

The Environment Agency’s 1998 groundwater balance indicated that all areas of the Lincolnshire Chalk aquifer system and the Spilsby Sandstone were overcommitted at that time. However, as previously described, not all licences are fully utilised and thus the balance between abstraction and the other demands for water can be made.

It has been observed that there may be some discrepancies in the above groundwater balance. These were first observed when attempts were made to back-calculate average annual recharge in mm d^{-1} from the gross

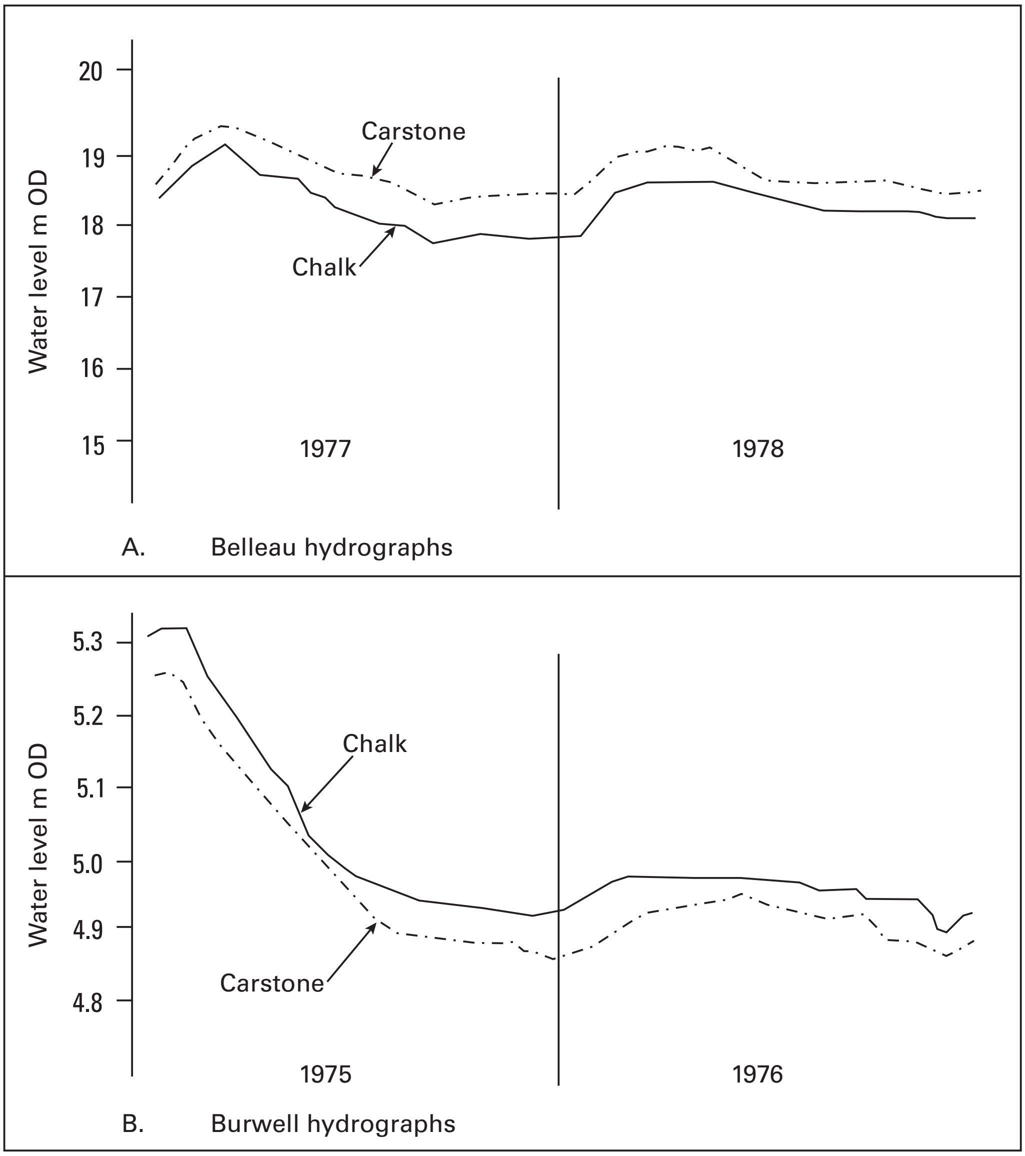


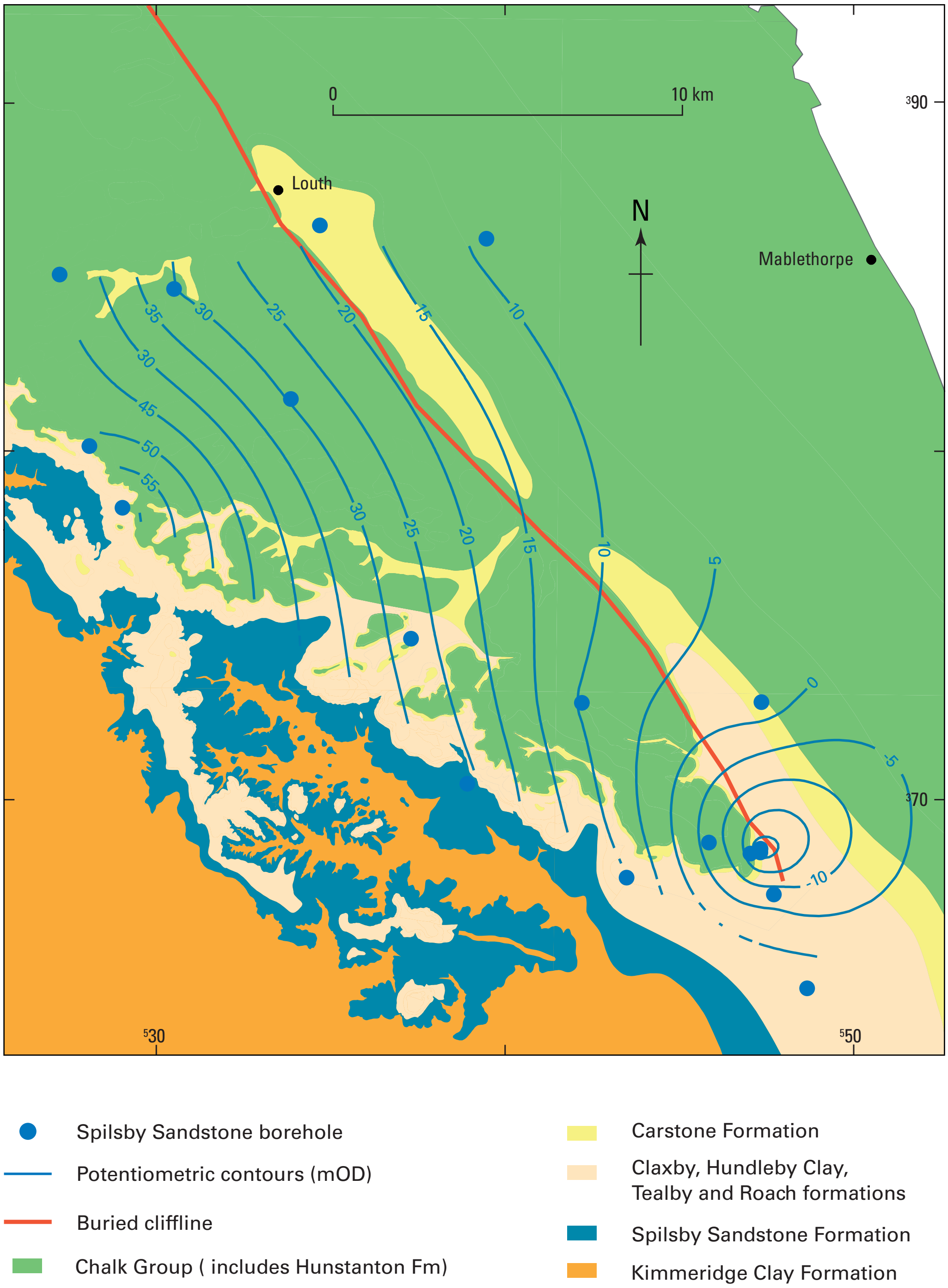
Figure 3.11 Chalk and Carstone hydrographs from Belleau and Burwell (University of Birmingham, 1982).

resource and recharge area values given in Table 3.2. These calculations gave reasonable rainfall recharge values for the northern Chalk and Spilsby Sandstone areas (248 and 245 mm per annum respectively), but an unrealistically high value for the southern unconfined Chalk (392 mm per annum). It was realised that the gross resource values for the Chalk areas were taken from the University of Birmingham reports of 1978 and 1982, however it seems that the fact that the areas of these studies overlapped significantly may have been overlooked. The southern Chalk Hydrogeological Investigation (University of Birmingham, 1982) study area extended to the north of Louth and included a total recharge area of 170.2 km^2. This is significantly greater than the recharge area of 97.8 km^2 which the Environment Agency gives for the southern unconfined Chalk. The gross resource value for the southern unconfined Chalk thus includes some part of the recharge to the northern Chalk, and is apparently higher than it should be. If rainfall recharge to the southern unconfined Chalk is set to 225 mm per annum (as calculated from the University of Birmingham (1978) values), then direct recharge over the recharge area of 97.8 km^2 (the Environment Agency figure) would be equivalent to 60.3 Ml d^{-1}, rather than the current value of 105 Ml d^{-1}. The South Humberside Salinity Research Project (University of Birmingham, 1978) area also extends into the southern Chalk as the agency defines it. In other words, it appears that some 'double accounting' has taken place for both the southern unconfined Chalk and the northern and southern confined Chalk.

If this inference is correct, it has implications for other parts of the groundwater balance. If the rainfall recharge to the southern unconfined Chalk is 60.3 Ml d^{-1}, then either the resource is being continually depleted or there is an error in the other components of the water balance. There is no evidence of falling water levels in the Chalk and thus an error in the water balance would appear to be more likely. The postulated leakage to the Spilsby Sandstone is based on previous modelling studies with little apparent direct quantified evidence and so this component could be significantly in error. If leakage is much less than has been estimated then the resource surplus for the Spilsby Sandstone must be in error (i.e. it is actually more negative than currently thought) and this could explain at least in part the trend of falling water levels in the Spilsby Sandstone.

This is an area where further research is necessary to clarify the water balance components, particularly the presence of interactions between the Chalk and the Spilsby Sandstone. The Environment Agency will be reviewing the water balance as part of their ongoing regional modelling strategy.

Figure 3.12
Potentiometric contour map of the Spilsby Sandstone.



3.6 NUMERICAL AND CONCEPTUAL MODELS OF THE AQUIFER

3.6.1 History of model development

The University of Birmingham has completed a series of modelling studies of flow in the Chalk aquifer system of Lincolnshire since 1975. The purpose of these studies was to develop sufficient understanding to be able to produce conceptual models, and later to develop numerical models. The first study was the South Humberbank Salinity Research Project (SHSRP; University of Birmingham, 1978), which had a broad scope including geology, hydrochemistry, geophysics, hydrogeology and aquifer modelling. The main outcomes of the SHSRP were a conceptual flow model for the northern part of the Lincolnshire Chalk aquifer and the development of a numerical model for use in groundwater resource management. Later studies updated and furthered this work; the Southern Chalk Hydrogeological Investigation (SCHI; University of Birmingham, 1982) involved research into the less well-understood southern area of the Lincolnshire Chalk. The Northern and Southern Chalk Modelling Study (NSCMS; University of Birmingham, 1987) returned to the model produced by the SHSRP and extended it to the entire Lincolnshire Chalk aquifer. This involved incorporating the results of the SCHI, utilising new data and advancing the model's capability to simulate groundwater flow in the Lincolnshire Chalk aquifer. This regional flow model was adopted by the Environment Agency and is used to manage the groundwater resource (Spink and Watling, 1995; Chapter 5). A contaminant transport model was developed in 1993 as part of the Northern and Southern Chalk Saline Intrusion Study (University of Birmingham, 1993) to enable the study of modern saline intrusion around Grimsby

Table 3.2 Groundwater balance calculations for the Chalk and Spilsby Sandstone in 1998 (Environment Agency, 1998c). All values are in megalitres per day (Ml d^{-1}), and are annual averages. GA = groundwater abstraction; SWA = surface water abstraction; SWER = surface water effluent returns.

Groundwater unit	**Northern Chalk and Confined Southern Chalk**			**Unconfined Southern Chalk**			**Spilsby Sandstone**		
Area (km^2)	906.5			180.0			1075.7		
Recharge area (km^2)	340.0			97.8			71.4		
Gross resource	245.0			105.0			68.0		
Availability factor	0.8			0.6			1.0		
Available resource	196.0			28.0			68.0		
LICENSED DEMANDS AND EFFLUENT RETURNS:									
	GA	SWA	SWER	GA	SWA	SWER	GA	SWA	SWER
Public water supply	144.9		0.5	0.0		0.0	31.1		0.2
Private water undertaking	3.4		2.5	0.0		0.0	0.5		0.4
General industry	31.1		0.0	0.1		0.0	3.4		0.0
Industry – mineral & cooling	0.1		0.1	0.0		0.0	0.0		0.0
General agriculture			0.7	0.8		0.7	0.3		0.3
Spray irrigation	0.3	0.4	0.0	0.1	0.2	0.0	1.4	0.6	0.0
Miscellaneous	0.2		0.2	0.0		0.0	0.0		0.0
Total	180.8	0.4	4.0	1.0	0.2	0.8	36.7	0.6	0.9
Net abstraction (-)	-180.8			-1.0			-36.7		
Net return (+)	3.6			0.6			0.3		
IN SITU RESOURCE REQUIREMENTS:									
River allocation (= gross 95 % ile flow)	11.9			35.2			35.9		
To prevent saline incursion and intrusion and to maintain springflow	14.7			4.2			3.1		
Net in situ requirement[1]	23.0			38.8			38.7		
Surplus resources[2]	**-7.8**			**-11.8**			**-7.4**		

1. Net in situ requirement = in situ resource requirements - net return
2. Surplus resources = available resource - net abstraction - net in situ requirement

(Farahmand-Razavi and Spink, 1993). The use of the models has so far been successful in helping to avert any further saline intrusion (Spink and Watling, 1995). Details about the numerical modelling of the aquifer are given below, while the application of modelling to management is discussed in more detail in Chapter 5.

3.6.2 Descriptions of models at regional or catchment scale

3.6.2.1 Flow models

The first numerical model to simulate flow throughout the whole of the Lincolnshire Chalk was produced during the Northern and Southern Chalk Modelling Study (NSCMS; University of Birmingham, 1987). The NSCMS model was developed by combining previous models of the northern and southern parts of the aquifer and modifying the code to improve the simulation. Transmissivity was made a function of saturated depth, reflecting the variation with change in water level. This provided a basis for springflow calculations, which determine natural outflows during the simulation, allowing for depth-related changes in permeability. The representation of the unconfined part of the aquifer was also improved in the 1987 study. The NSCMS model can be used to simulate both long and short periods, which enables the user to appraise management options on different time-scales.

The flow equation is solved with the finite difference approach, using a backward difference time approximation. Over most of the aquifer the mesh spacing is such that each nodal point represents an area of 2 km^2, but the spacing is greater offshore. The mesh is inclined at 45° to the National Grid so that it is congruent with the main groundwater flow direction. Aquifer properties such as transmissivity, storage coefficient and inflow are defined for each nodal point; the values of transmissivity and storage coefficient used by the University of Birmingham are shown in Figures 3.13 and 3.14 respectively.

The western edge of the model is defined as a 'groundwater divide that, in general, coincides with the highest land elevation above the scarp slope' (University of Birmingham, 1978). The northern boundary is mostly a no flow zone, defined by the very low transmissivity observed, apart from two constant head nodes that represent localised areas where the aquifer is in hydraulic contact with the Humber Estuary. The southern boundary is offshore, south of Skegness which is also represented by a no flow boundary, as is the eastern edge of the model. The eastern boundary is placed 31 km out to sea as, although the Chalk aquifer may extend far beyond this, the model simulates conditions adequately with this condition. Leakage nodes represent inflow of modern saline water in the Grimsby–Immingham area. The amount of flow across the buried cliff that divides the confined and unconfined southern Chalk was thought to be negligible (Chapter 3).

Recharge calculations were modified to take account of additional recharge when soil moisture deficits occur, since the estimation of recharge using the Penman and Grindley method was less than the sum of the known outflows from the system. The recharge calculation used allowed direct recharge of 10% of effective precipitation plus 10% of actual precipitation in excess of 6 mm. Mean monthly values of recharge are input to the model. Significant abstractions, from wells pumping over 1 Ml d^{-1}, were represented by an outflow at the nearest nodal point.

There were several challenging requirements for the model. Generally, little is known about the distribution of transmissivity and storage coefficient. Data coverage is

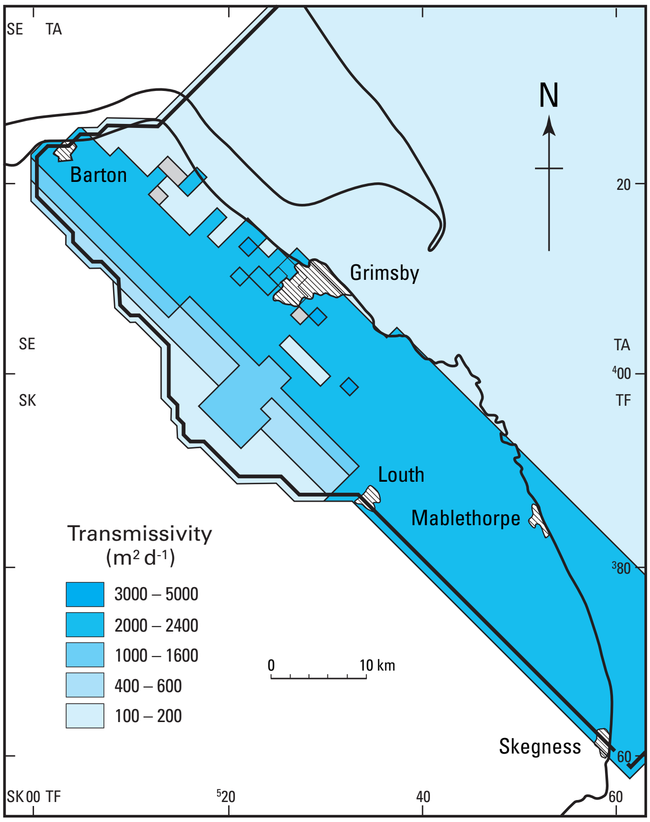


Figure 3.13 Modelled distribution of transmissivity in the Lincolnshire Chalk (after University of Birmingham, 1987).

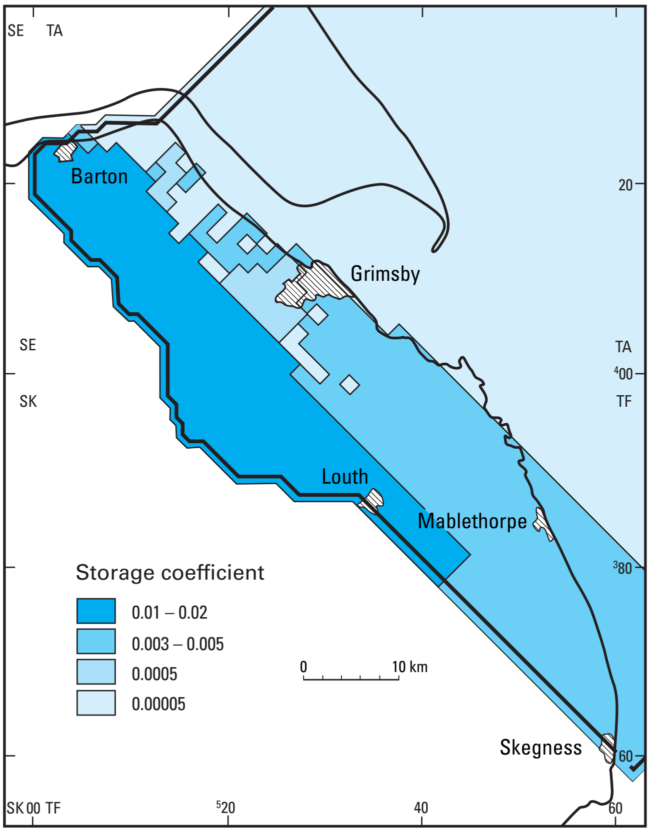


Figure 3.14 Modelled distribution of storage coefficient in the Lincolnshire Chalk (after University of Birmingham, 1987).

particularly low where little demand has so far been placed on the aquifer. There were four particular areas where uncertainty existed due to data scarcity, namely:

- the Humber estuary in the Barton area, where saline water enters the aquifer
- the Skegness–Mablethorpe area, where there are bodies of ancient saline water
- the area south-east of Louth
- in the vicinity of natural outflows

However, the model is thought to simulate these areas adequately.

The NSCMS regional groundwater flow model is periodically updated with observed field data to ensure that the calibration remains adequate; over the period 1988 to 1992/3 this was being done about 3 or 4 times per year and since then it is generally performed about twice a year.

A model of groundwater flow in the Spilsby Sandstone aquifer was developed by Groundwater Development Consultants Ltd (Mott MacDonald) over the period 1987–89. This model is not related to the regional Chalk aquifer model, but hydraulic connection between the Spilsby Sandstone and the Chalk was represented.

The Environment Agency is currently reviewing the numerical models in use in the Anglian Region, and has already produced draft reports on the Lincolnshire Chalk Model (Morgan-Jones and Power, 1999a) and the Spilsby Sandstone Model (Morgan-Jones and Power, 1999b). While recognising their value with regard to managing the aquifers, the authors found deficiencies in both models. For example, there were some problems with the Chalk model code, and 'significant water balance error' (Morgan-Jones and Power, 1999a). Furthermore, the models do not adequately represent groundwater-surface water interaction. Morgan-Jones and Power also felt that the use of constant head nodes to represent vertical leakage from the Chalk in the Spilsby Sandstone model was unrealistic. However, the main criticism was that the models of the Chalk and Spilsby Sandstone aquifers were not compatible: Morgan-Jones and Power (1999a) recommended that 'the conceptual model should be reviewed and a new multilayer model [incorporating all the aquifers in the system] should be constructed'. The new model should be better suited to evaluating the impacts of abstraction on spring discharges and river flows.

3.6.2.2 Contaminant transport modelling

Further modelling of the Lincolnshire Chalk aquifer system has been undertaken: an investigation of saline intrusion from the Humber Estuary was completed in 1993 and a contaminant transport model was developed (University of Birmingham, 1993). The mesh spacing of the flow model was reduced to approximately 350 m around Grimsby to generate a more accurate simulation of flow velocity in this area of modern saline intrusion (Farahmand-Razavi and Spink, 1993). Saline inflow is represented in the transport model by a leakage mechanism. The transport model, which is two-dimensional, uses an advection-dispersion equation for a conservative pollutant (chloride ions) in a homogeneous, isotropic aquifer. The transport of chloride ions is simulated by a random walk particle tracking method.

3.6.2.3 Limitations to numerical models

The University of Birmingham (1978) point out that 'the flow mechanism through the aquifers is complex and, therefore, the use of a mathematical model introduces many simplifying assumptions'. For example, that 'vertical components of flow are sufficiently small to be neglected' (University of Birmingham, 1978). However, in a review of the model, Morgan-Jones and Power (1999a) state that the hydraulic continuity between the Chalk and other strata, particularly the Spilsby Sandstone, should be represented.

3.6.3 A conceptual model of the aquifer

The Chalk groundwater system comprises the Chalk Group, the underlying permeable Lower Cretaceous formations and the overlying permeable Quaternary deposits. The Chalk Group possesses high transmissivity as a result of the solution enhanced fractures but only low storage. The latter characteristic is a consequence of the small pore neck size in the matrix which precludes drainage of the pores so that only fractures contribute to the storage capacity of the Chalk. However, the Quaternary sands and gravels do provide a valuable additional storage to the groundwater system.

The transmissivity of the Chalk is variable both spatially and, perhaps more importantly, with depth; the bulk of the permeability development being in the upper 30 m or so of the Chalk Group.

There are two distinct Chalk groundwater systems in Lincolnshire. One occurs to the north of Louth, here groundwater is recharged beneath the higher ground of the Wolds, where the Chalk is unconfined, and groundwater flows eastwards and north-eastwards where it becomes confined by till. Groundwater is discharged from the confined aquifer by pumping from abstraction boreholes, by flow out to sea and, to a lesser degree, by upwards leakage to blow wells where the confining layers are more permeable.

South of Louth the Chalk groundwater flow is very different, here the Chalk has been removed by erosion along a previous coastline (the Louth Window) so that the unconfined Chalk beneath the Wolds is in effect disconnected from the confined Chalk to the east. Recharge to the southern unconfined Chalk beneath the Wolds is largely discharged by springs. Some groundwater may be transferred from the southern unconfined Chalk to the confined Chalk either through the underlying Lower Cretaceous formations or through the overlying permeable Quaternary deposits although the quantities are believed to be small.

Groundwaters in the southern confined Chalk are very different to those in the north and evidence for only limited transfer of water from the unconfined Chalk is provided by the longer residence times of the confined groundwater (based on geochemical residence time indicators). Abstraction from the southern confined Chalk is very small in contrast to that in the northern confined aquifer.

Leakage between the Lower Cretaceous and Chalk formations undoubtedly does occur although the quantities remain uncertain. This is mainly because the area where the more permeable Lower Cretaceous formation are in hydraulic continuity with the Chalk is difficult to define accurately due to the overstepping of the Lower Cretaceous formations by the Chalk and due to variability in lithology and thickness of the Lower Cretaceous formations.

The continued decline in groundwater levels of the Spilsby Sandstone in the south eastern part of the area suggests that downward leakage from the Chalk may be less than had previously been anticipated.

In the 1970s and 1980s the University of Birmingham developed a series of regional numerical models which have been used to help manage the aquifer successfully and control the inland movement of saline water.

4 Groundwater chemistry

4.1 INTRODUCTION

The quality of groundwater is extremely important in terms of suitability for public supply and other uses. Hydrochemical studies also aid the understanding of groundwater systems, including the provenance of the water, flow paths and relative flow rates. This chapter commences with a discussion of the distribution and variability of water quality in the Chalk aquifer system. For the purposes of discussing the regional hydrogeochemistry, the Chalk aquifer system is subdivided into three areas: outcrop Chalk (both north and south Lincolnshire); confined Chalk of north Lincolnshire; and confined Chalk of south Lincolnshire. In this report we define the boundary between north and south Lincolnshire as a flow line which separates the Chalk east of the Louth Window in the south from the Chalk to the north where the Chalk is continuous from outcrop to the confined zone (Figure 2.9). Later sections discuss the origin of the waters and processes controlling these water types. Finally groundwater contamination problems are reviewed.

The data used to compile this chapter have come from a number of studies spanning half a century. The quality of groundwater in the Grimsby area was surveyed several times by the Institute of Geological Sciences during the 1950s and 60s (Gray et al., 1955, 1956, 1964). The University of Birmingham's studies (1978, 1982) of the Lincolnshire Chalk aquifer system included a large programme of water sampling and analysis, producing a valuable dataset and providing a good understanding of the flow system and the origin of the different water types. More recently, a report on the natural (baseline) quality of the groundwater of the Lincolnshire Chalk was published by the BGS in 1998; this incorporated data from the Environment Agency and from groundwater sampling and analysis by the British Geological Survey (Smedley and Brewerton, 1998). The Environment Agency have provided some data relating to pesticide contamination, and Anglian Water have made nitrate data available.

4.2 REGIONAL HYDROCHEMISTRY

4.2.1 Introduction

The Lincolnshire Chalk aquifer system contains water of various compositions, from fresh to saline. A statistical summary of the data from the BGS survey of the hydrochemistry of the Lincolnshire Chalk (Smedley and Brewerton, 1998) is presented in Table 4.1.

The maximum admissible concentrations of parameters for drinking water given in the Water Supply (Water Quality) Regulations 1989, SI 1989/1147, are included in Table 4.1 for comparative purposes. The quality of the fresh groundwater is generally good, especially in the confined aquifer. The dominant ions in most of the groundwaters are calcium (Ca^{2+}) and bicarbonate (HCO_3^-), although sodium and chloride become increasingly important towards the coastal zone where saline waters are present.

4.2.2 Concentrations and distribution of major and minor ions

Major ions are those ionic components of groundwater which are normally present at concentrations of greater than 1 mg l^{-1}, including sodium, potassium, calcium, magnesium, sulphate, chloride, bicarbonate and sometimes nitrate.

4.2.2.1 Chloride

Chloride ion (Cl^-) concentrations in the Lincolnshire Chalk aquifer system vary by two orders of magnitude, from 11 mg l^{-1} to 1100 mg l^{-1}(Table 4.1). Median values are 35.4 mg l^{-1} in the unconfined Chalk and 46.3 mg l^{-1} in the confined part of the aquifer (Table 4.1). Chloride ion concentrations can be affected by interaction with the rock matrix, saline intrusion, and contamination. The distribution of Cl is shown in Figure 4.1.

Several episodes of saline intrusion have occurred in various coastal areas which currently form part of the confined aquifer. Seawater can enter the aquifer in the Barton area when groundwater levels are low. In recent times, seawater intrusion has occurred due to abstraction from industrial boreholes in the Grimsby–Immingham area. Downhole geophysical logs run in the Ciba Geigy borehole [TA 24 11] clearly show the freshwater-saline water interface at depth. The conductivity of the water was observed to increase from less than 1000 µmho cm^{-1} at about 34 m depth to over 6000 µmho cm^{-1} at about 38 m depth (University of Birmingham, 1978). All of the major abstractors participate with the Environment Agency to prevent further saline intrusion (Chapter 5).

Early research into saline intrusion in the Grimsby area was conducted by Gray (1964) who found that salinity varied significantly with depth (Figure 4.2).

The chloride concentrations of freshwaters have increased over time in the unconfined aquifer, and some confined areas (University of Birmingham, 1978). This increase has been spatially variable, with the greatest increases north of the Caistor Monocline, moderate rise around Grimsby and little change in the Tetney area.

Modern, high chloride fresh groundwaters had reached all major abstraction and discharge points by 1978, indicating that rapid flow paths are operating between the recharge zone and these localities.

In their 1978 report the University of Birmingham described a large zone of low chloride concentration (<20 mg l^{-1}) groundwater in the confined aquifer around Tetney and to the east of the Louth Channel. The chloride concentration changed little in this area between 1956–58 and 1978, although it increased around Covenham St Mary [TF 33 94]. The University of Birmingham (1978) believe that minor ion and isotope data indicate that this groundwater originated from the Wolds recharge area during the last postglacial recharge event, and that it has since been preserved by a lack of west–east groundwater flow in this area.

4.2.2.2 Sulphate

The concentration of sulphate (SO_4^{2-}) in the Chalk groundwaters ranges from below the 10 mg l^{-1} detection

Table 4.1 Statistical summary of groundwater composition in the Lincolnshire Chalk (Smedley and Brewerton, 1998).

Determinand		Units	Min	Max	Median (Unconfined aquifer)	Upper baseline	n	Min	Max	Median (Confined aquifer)	Upper Baseline	n	Drinking water maximum
Temp		°C	9.6	20.2	10.5	14.5	32	9.4	14.0	10.1	13.0	24	
pH (field)			9.86	7.5	7.23	7.47	34	7.08	7.82	7.32	7.63	22	10[a]
DO	dissolved oxygen	mg l^{-1}	<0.1	9.9	6.7	9.2	29	<0.1	3.2	<0.1	3.1	20	
Eh	redox potential	mV	204	466	403	450	28	0	290	148	209	20	
SEC	conductivity	µg cm^{-1}	514	961	692	888	41	456	4230	636	1743	52	2500[b]
Ca	calcium	mg l^{-1}	83	161	115	157	41	4	211	82	144	51	
Mg	magnesium	mg l^{-1}	2.1	17.7	5.8	16.4	41	2.1	42.3	15.2	34.4	51	
Na	sodium	mg l^{-1}	8.8	31.6	15.4	30.0	41	8.4	542	34.4	235	51	200[a]
K	potasium	mg l^{-1}	1.1	22	2.0	5.6	34	2.21	10.6	4.41	8.7	22	
Cl	chloride	mg l^{-1}	17.4	75.4	35.4	55.5	42	11.0	1100	46.3	479	59	250[b]
SO_4	sulphate	mg l^{-1}	7.3	157	50.9	130	41	<10	130	32.1	93.3	52	250[b]
HCO_3	bicarbonate	mg l^{-1}	152	374	252	326	41	104	425	304	348	52	
NO_3-N	nitrate	mg l^{-1}	1.5	23.8	9.1	18.2	34	<0.01	0.6	<0.01	0.4	22	11.3[a]
NO_2-N	nitrite	µg l^{-1}	<0.002	0.061	<0.003	0.006	34	<0.002	0.50	<0.002	0.03	22	0.2[a]
NH_4-N	ammonium	µg l^{-1}	<10	870	<30	10	41	<0.01	1650	0.3	776	52	0.4[b]
TOC	organic carbon	mg l^{-1}	<1	4.6	1.8	3.9	7	<1	2.6	0.2	2.6	29	
Al	aluminium	µg l^{-1}	<0.6	23	<40	3.7	34	<0.9	338	<40	77	22	200[a]
As	arsenic	µg l^{-1}	<2	10.7	<2	2.5	34	<2	62	16	35	22	10[a]
As(III)	arsenic (III)	µg l^{-1}	<2	<4	<4	<4	34	<2	42	9	32	22	1000[a]
B	boron	µg l^{-1}	14	63	23	51	34	46	171	92	159	22	
Ba	barium	µg l^{-1}	14	268	68	143	34	59	186	101	147	22	700[c]
Be	beryllium	µg l^{-1}	<0.02	0.04	<0.02	<0.02	34	<0.02	<0.02	<0.02	<0.02	22	
Br	bromine	µg l^{-1}	67	227	119	177	34	40	1320	135	593	22	
Cd	cadmium	µg l^{-1}	<0.03	0.4	<0.07	0.2	34	<0.04	0.06	<0.07	<0.06	22	5[a]
Co	cobalt	µg l^{-1}	0.11	0.69	0.17	0.5	34	<0.01	1.9	0.43	1.8	22	
Cr	chromium	µg l^{-1}	<0.07	0.32	<0.22	0.28	34	<0.07	0.52	<0.22	0.31	22	50[a]
Cs	caesium	µg l^{-1}	<0.02	<0.04	<0.04	<0.04	34	<0.02	0.06	<0.04	<0.06	22	
Cu	copper	µg l^{-1}	<0.9	38	1.1	13.6	34	<0.04	40	0.07	14.6	22	2000[a]
F	fluoride	µg l^{-1}	90	350	150	246	34	130	1110	230	390	22	1500[a]
Fe	iron	µg l^{-1}	<6	760	<6	143	34	11	6790	757	5837	22	200[a]
I	iodine	µg l^{-1}	2.3	25.9	4.9	8.5	34	3.2	61	13.4	54	22	
La	lanthanum	µg l^{-1}	<0.004	0.03	<0.04	0.02	34	<0.005	0.07	<0.04	0.01	22	
Li	lithium	µg l^{-1}	0.97	8.1	2.4	5.1	34	3.6	8.5	5.1	8.2	22	
Mn	manganese	µg l^{-1}	<0.03	234	0.09	48	34	4	367	141	355	22	50[a]
Mo	molybdenum	µg l^{-1}	<0.11	0.53	0.16	0.44	34	<0.1	3.9	0.6	1.7	22	70[c]
Ni	nickel	µg l^{-1}	1.5	5.2	2.9	4.8	34	0.7	4.3	2.0	3.3	22	20[a]
Pb	lead	µg l^{-1}	<0.03	1.4	0.23	1.2	34	<0.03	0.96	<0.31	0.90	22	25[a]
Rb	rubidium	µg l^{-1}	0.34	3.4	0.59	1.25	34	0.5	3.0	1.1	2.8	22	
Sb	antimony	µg l^{-1}	<0.08	0.22	<0.09	0.19	34	<0.05	<0.09	<0.09	<0.09	22	
Se	selenium	µg l^{-1}	2294	5535	3470	4336	34	4380	6880	5880	6784	22	10[a]
Si	silicon	µg l^{-1}	189	602	313	453	34	377	1140	570	889	22	
Sr	strontium	µg l^{-1}	0.11	0.88	0.26	0.65	34	<0.04	0.29	<0.04	0.16	22	
U	uranium	µg l^{-1}	<0.004	0.04	<0.010	0.01	34	<0.004	0.05	<0.010	0.02	22	15[c]
Zn	zinc	µg l^{-1}	<1	359	5.4	191	34	<2	140	4.5	61	22	
$\delta^{18}O$	oxygen-18	‰	-5.3	-8.0	-7.5	-6.5	15	-6.8	-7.7	-7.6	-7.0	9	
$\delta^{2}H$	deuterium	‰	-39	-55	-51	-46	15	-50	-54	-51	-51	12	

SEC: specific electrical conductance at 25°C. The upper baseline estimate is calculated on the basis of the 95 percentile.

a Maximum acceptable concentration or value (Water supply (water quality) regulations 2000, SI 2000 No.3184)
b Indicator parameter (Water supply (water quality) regulations 2000, SI 2000 No.3184)
c WHO guideline value (WHO Guidelines for Drinking-Water Quality, 3rd edition)

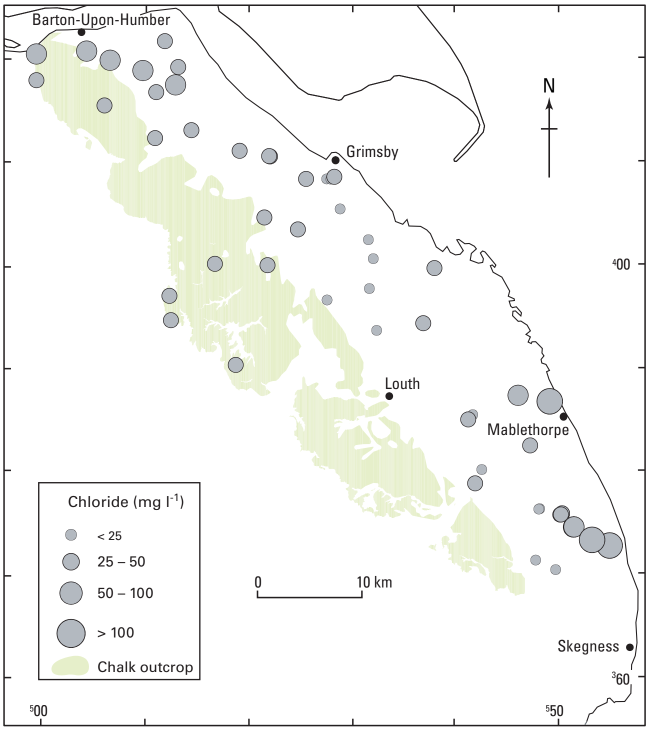


Figure 4.1 Chloride concentrations in Chalk groundwater (data from Smedley and Brewerton, 1998).

limit to over 150 mg l^{-1} (Table 4.1). Median concentrations of 50.9 mg l^{-1} and 32.1 mg l^{-1} were observed for the unconfined and confined aquifers respectively (Table 4.1). In recent years, sulphate concentrations in groundwaters have increased as a result of atmospheric deposition and of increased use of artificial fertilisers. Sulphate can also be derived from the oxidation of sulphide minerals in clay rich sediments, however, no enrichment in sulphate was observed in groundwaters from gravels in direct contact with the till at Laceby (University of Birmingham, 1978).

The distribution of sulphate (Figure 4.3) is similar to that of chloride, with higher concentrations found in modern waters, which occur in the unconfined aquifer and in the confined aquifer of north Lincolnshire (University of Birmingham, 1978). Some low SO_4^{2-} values are found in the northern confined aquifer, possibly due to upward leakage from the Elsham sandstone (University of Birmingham, 1978).

In the southern Chalk, SO_4^{2-} concentrations are low (<30 mg l^{-1}) around the buried Ipswichian coastline and the present coastal area (University of Birmingham, 1982). The low sulphate groundwaters coincide with a low chloride zone, possibly suggesting that concentrations of these ions were lower in the recharge waters at the time (University of Birmingham, 1982).

4.2.2.3 Bicarbonate

The concentration of the bicarbonate ion (HCO_3^-) ranges from 104 mg l^{-1} to 425 mg l^{-1}, with median values of 252 mg l^{-1} in the unconfined aquifer and 304 mg l^{-1} in the confined aquifer (Table 4.1). The distribution of the bicarbonate ion is shown in Figure 4.4. The carbonate ion is a negligible component of total alkalinity in Lincolnshire Chalk groundwaters as the pH is generally less than 8.6. Alkalinity (i.e. HCO_3) is lowest on the Chalk outcrop, where waters are relatively recently recharged and, therefore, undersaturated with respect to calcite, and increases down the hydraulic gradient as calcite saturation is approached.

4.2.2.4 Nitrate

Nitrate concentrations in groundwaters from the Lincolnshire Chalk outcrop are commonly close to or exceed the EC limit of 50 mg NO_3^{2-} l^{-1} (Smedley and Brewerton, 1998; Table 4.1). High nitrate concentrations are also present over large areas of the confined northern Chalk (Figure 4.5). However, nitrate concentrations are low in the southern confined Chalk. The origins of the high nitrate concentrations observed in Lincolnshire Chalk groundwaters are discussed later in this chapter.

4.2.2.5 Calcium and magnesium

Calcium and magnesium are the main ions contributing to hardness of the groundwaters in the study area. Calcium

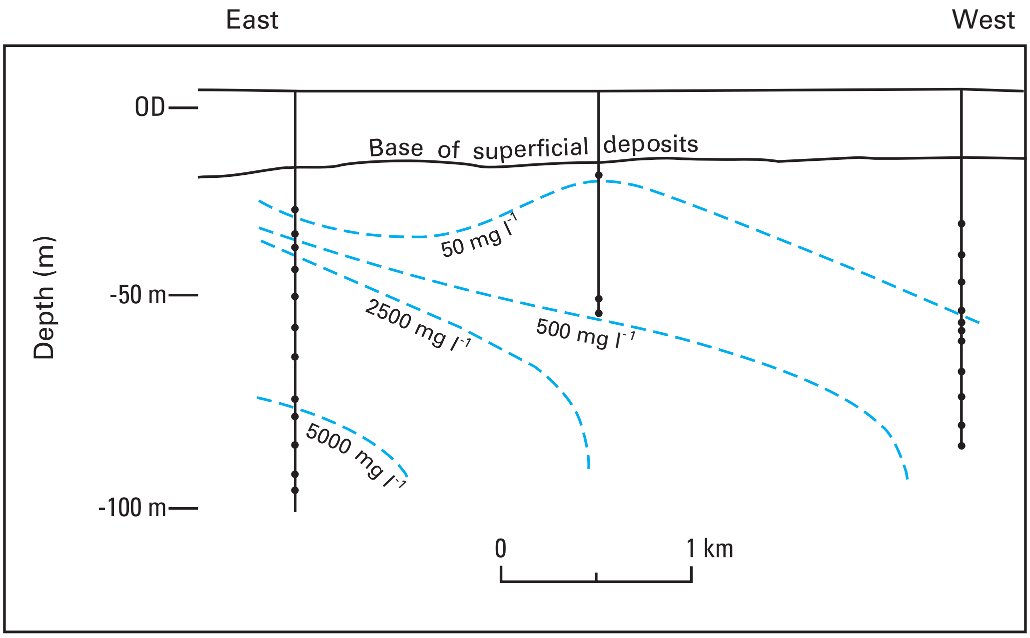


Figure 4.2 Cross-section illustrating vertical variations in chloride concentration in the Chalk of the Grimsby area in 1962 (Gray, 1964).

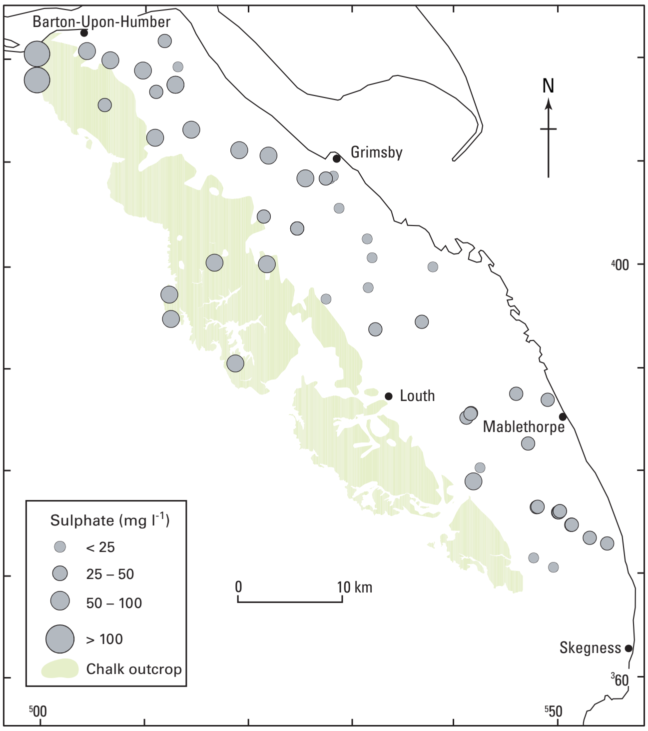


Figure 4.3 Sulphate concentrations in Chalk groundwater (data from Smedley and Brewerton, 1998).

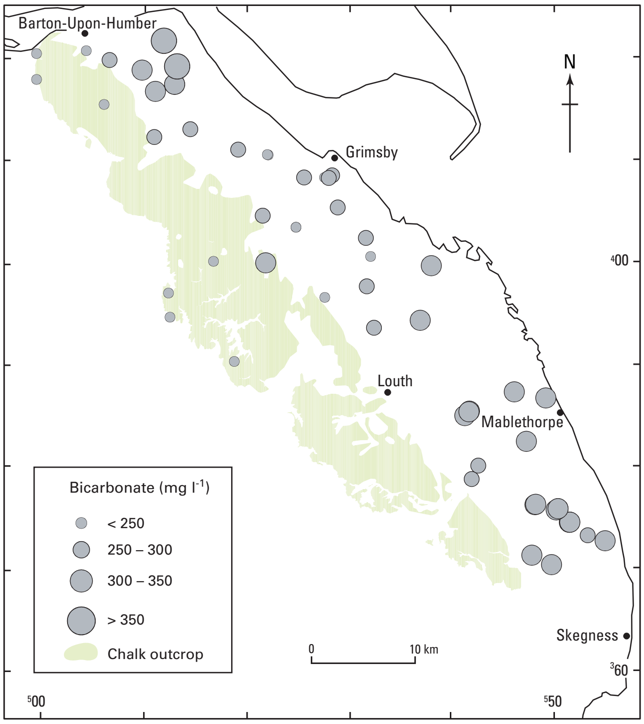


Figure 4.4 Bicarbonate ion concentrations in Chalk groundwater (data from Smedley and Brewerton, 1998).

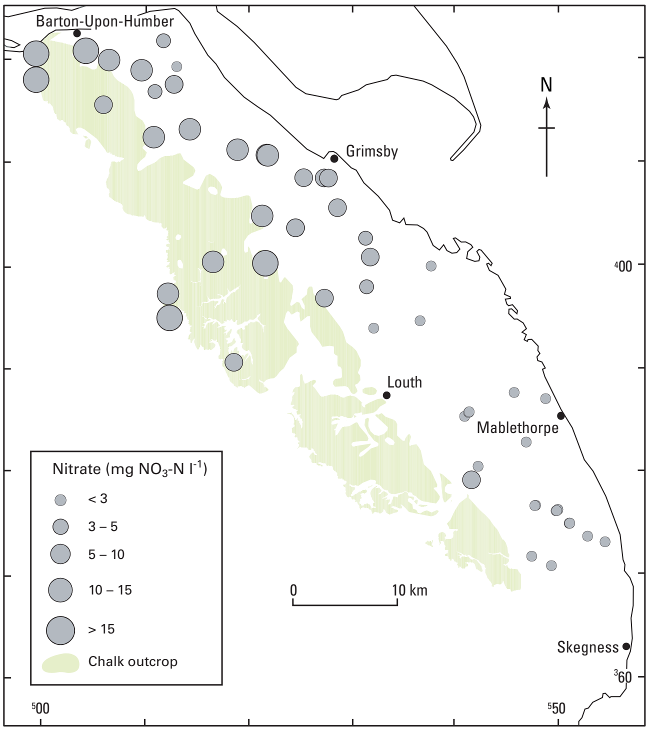


Figure 4.5 Nitrate concentrations in Chalk groundwater (data from Smedley and Brewerton, 1998).

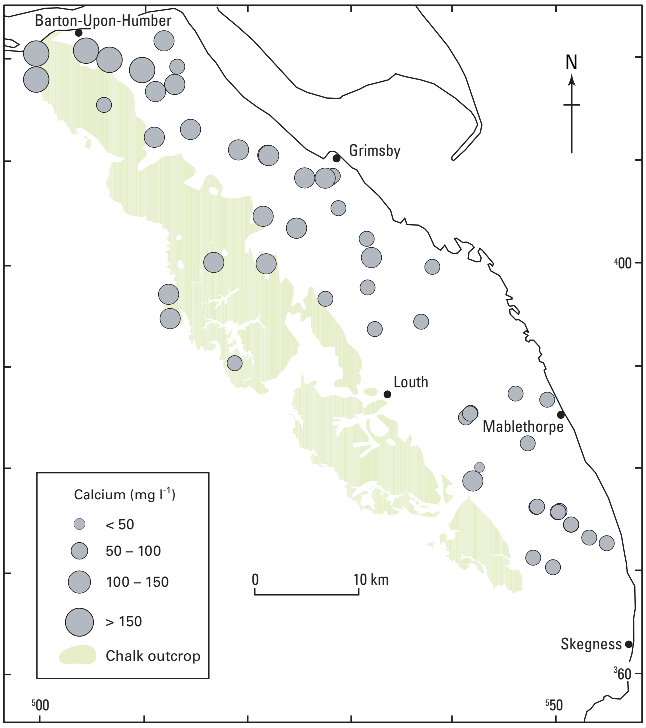


Figure 4.6 Calcium concentrations in Chalk groundwater (data from Smedley and Brewerton, 1998).

(Ca^{2+}) has been detected at concentrations ranging from 4 mg l^{-1} to 211 mg l^{-1}, with median values of 115 mg l^{-1} and 82 mg l^{-1} in the unconfined and confined aquifers respectively (Table 4.1). Magnesium (Mg^{2+}) concentrations range from 2.1 mg l^{-1} to 42.3 mg l^{-1}; median values are 5.8 mg l^{-1} (unconfined) and 15.2 mg l^{-1} (confined). The distributions of calcium and magnesium are shown in Figures 4.6 and 4.7.

The distribution of Ca^{2+} differs from that of magnesium. Recharged groundwaters are initially undersaturated with respect to calcite and so the concentration of Ca^{2+} generally increases as the waters flow down gradient and calcite is dissolved. Saturation with respect to calcite in Chalk porewaters is generally attained in the unconfined zone, soon after recharge (Edmunds et al., 1992), but this is not necessarily true of water flowing faster through fractures. Calcium ion concentrations are higher in modern recharge than in the past which partly explains why Ca^{2+} concentrations are higher in the unconfined zone. Softening resulting from ion-exchange (e.g. Na-Ca) can cause calcium concentrations to decrease with increased residence time. However, this is believed to have occurred only in the zone east of the Louth Window where groundwater residence time is very long due largely to lack of connection between the unconfined and confined Chalk aquifer (University of Birmingham, 1978). It has been suggested that the lower hardness values in this area may be due in part to upward leakage from the Carstone and Roach aquifers (University of Birmingham, 1982). The low values are not due to calcite precipitation as the groundwaters in this area are often undersaturated with respect to calcite.

Magnesium is typically not influenced by saturation controls, as Mg^{2+} concentrations are relatively low (University of Birmingham, 1978). The concentration of magnesium, and some minor ions such as strontium, should be a proxy indicator of residence time as the ions are derived from the Chalk matrix. The highest magnesium values are found north-east of Goxhill and east of the Louth Channel, which have been confirmed as old waters by isotope analyses (University of Birmingham, 1978). In contrast to calcium, Mg^{2+} concentrations have been less influenced by recent human activity (University of Birmingham, 1978).

4.2.2.6 Sodium

The concentration of sodium (Na^{+}) in groundwaters of the Lincolnshire Chalk aquifer system varies greatly from 8.4 mg l^{-1} to 542 mg l^{-1}, with median values of 15.4 mg l^{-1} (unconfined) and 34.4 mg l^{-1} (confined). The distribution of Na^{+} (Figure 4.8) is similar to Cl^{-} (Figure 4.1) as the source of both ions is commonly sodium chloride.

4.2.2.7 Potassium

Potassium ion (K^{+}) concentrations vary between 1.1 mg l^{-1} to 22 mg l^{-1} and median concentrations are 2.0 mg l^{-1} and 4.41 mg l^{-1} in the unconfined and confined areas respectively. The distribution of potassium (Figure 4.9) is similar to that of sodium.

4.2.3 Minor and trace ions

4.2.3.1 Strontium

Strontium (Sr^{+2}) in groundwater is derived from interaction with the matrix, so strontium enrichment is a proxy for groundwater residence time. 'Low strontium groundwaters (<0.2 mg l^{-1} Sr^{+2}) occupy large areas of the Chalk outcrop and extend down gradient to all major, past and present, abstraction and discharge sites' (University of Birmingham, 1978). High strontium concentrations are found in freshwaters classified by the University of Birmingham (1978) as Type III, which are relatively old. Most of the saline waters also have high strontium, a phenomenon that is partly explained by the high concentrations in seawater. However, strontium in most of these waters is enriched with respect to chloride, indicating that they have also been resident in the aquifer for a significant period (University of Birmingham, 1978). The exception is an area of shallow saline water in the Immingham–Pyewipe area, which is, therefore, considered to be younger, possibly resulting from modern seawater intrusion.

4.2.3.2 Iodide

The distribution of iodide (I^{-}), (shown in Figure 4.10) is closely related to that of chloride, as they are both halides and behave similarly in the subsurface. The University of Birmingham (1978) identified three areas of elevated iodide (I^{-}) concentrations that coincide with the saline groundwaters. They found iodide to be the most useful minor ion for interpreting the distribution and evolution of hydrochemical types; high iodide areas in the north and south of the northern Chalk study area were related to older, Type III groundwaters which have interacted with the matrix.

4.2.3.3 Trace metals

The majority of the groundwaters have low trace metal concentrations in the very recent recharge waters, which have elevated concentrations of many major ions (University of Birmingham, 1978).

4.2.3.4 Iron and manganese

Iron and manganese are more soluble in reducing waters so they are present at greater concentrations in the confined aquifer. Most of the groundwaters from the confined area of the aquifer in the south contain iron at concentrations in excess of the recommended limits for drinking water (0.2 mg Fe l^{-1}; SI 1989/1147) (University of Birmingham, 1982). Manganese concentrations exceed the drinking water standard (50 µg l^{-1}) in some samples from the unconfined aquifer, where the maximum concentration observed is above 200 µg l^{-1} (Table 4.1), and in many samples from the confined aquifer. The median concentration of Mn in the unconfined aquifer is 0.09 µg l^{-1} but is 141 µg l^{-1} in the confined aquifer (Table 4.1).

4.2.3.5 Arsenic

Smedley and Brewerton (1998) pointed out that some of the confined Chalk groundwaters have relatively high arsenic (As) concentrations, reaching up to 62 µg l^{-1} (median 16 µg l^{-1}). The precise mechanism for mobilisation of arsenic is unclear; it has been suggested that the As has desorbed from pyrite in the Chalk, although dissolution from iron oxides is also possible (Smedley and Brewerton, 1998). Until 2001,the EC drinking water limit was 50 µg l^{-1}, however this was reviewed and a new limit of 10 µg l^{-1} was introduced which water companies were required to comply with from the end of 2003. For most abstraction boreholes, arsenic concentrations in new water will be below 10 µg l^{-1}, however, where the new arsenic limit is exceeded, treatment is relatively easy.

4.2.4 Other exceedances of drinking water regulations

In the preceding sections it has been noted that the concentrations of nitrate, iron, manganese and arsenic can

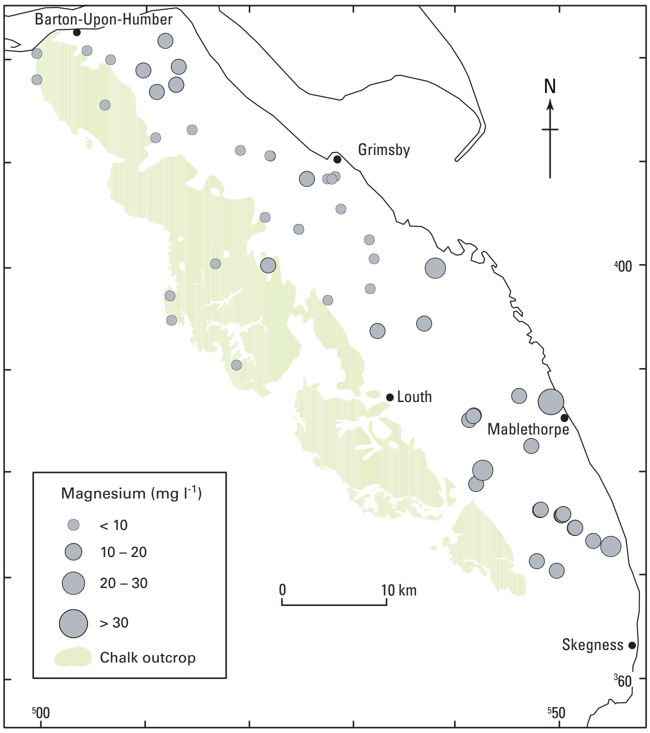


Figure 4.7 Magnesium concentrations in Chalk groundwater (data from Smedley and Brewerton, 1998).

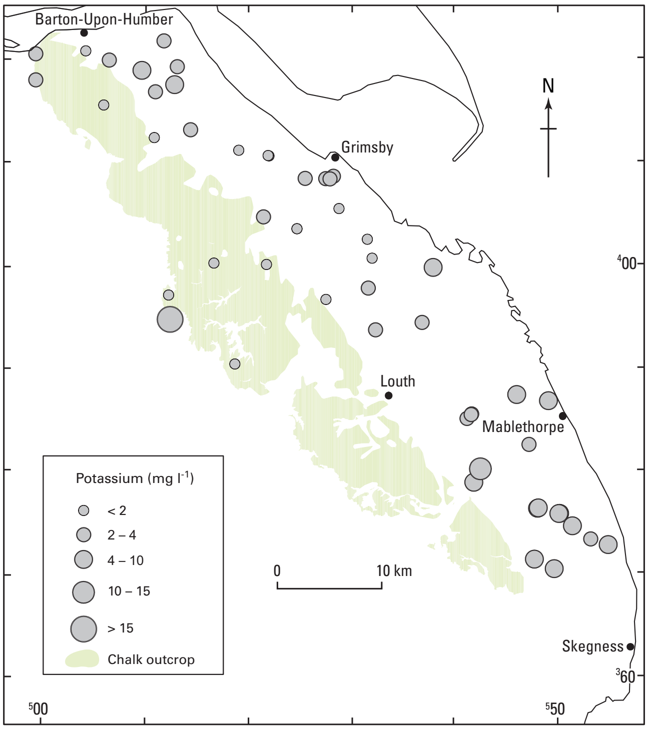


Figure 4.9 Potassium concentrations in Chalk groundwater (data from Smedley and Brewerton, 1998).

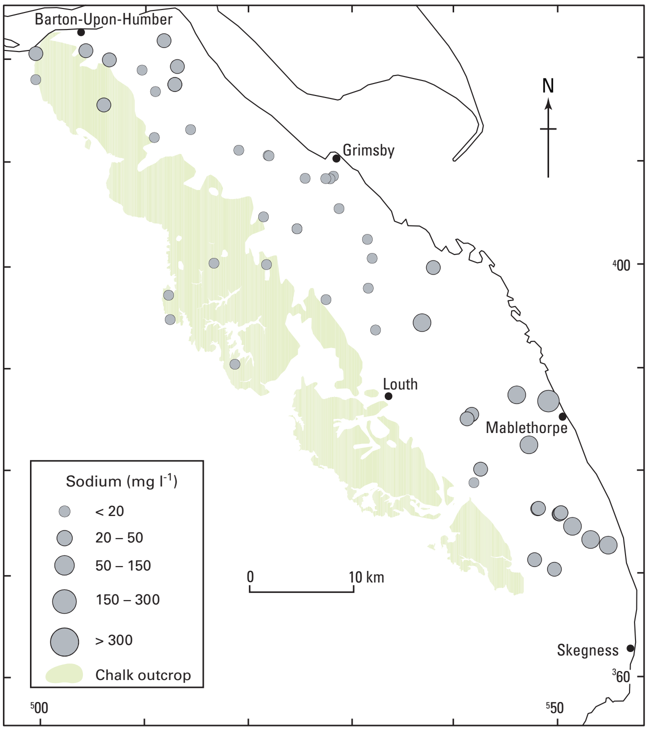


Figure 4.8 Sodium concentrations in Chalk groundwater (data from Smedley and Brewerton, 1998).

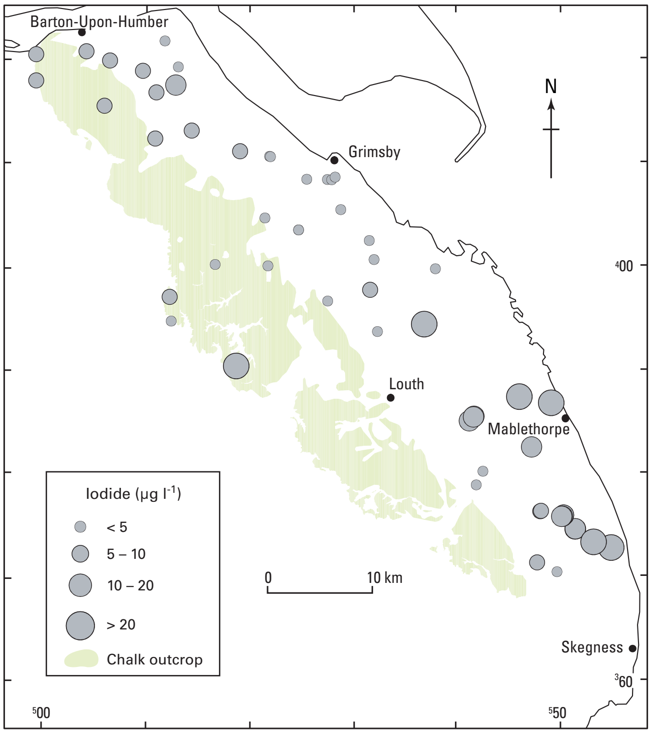


Figure 4.10 Iodide concentrations in Chalk groundwater (data from Smedley and Brewerton, 1998).

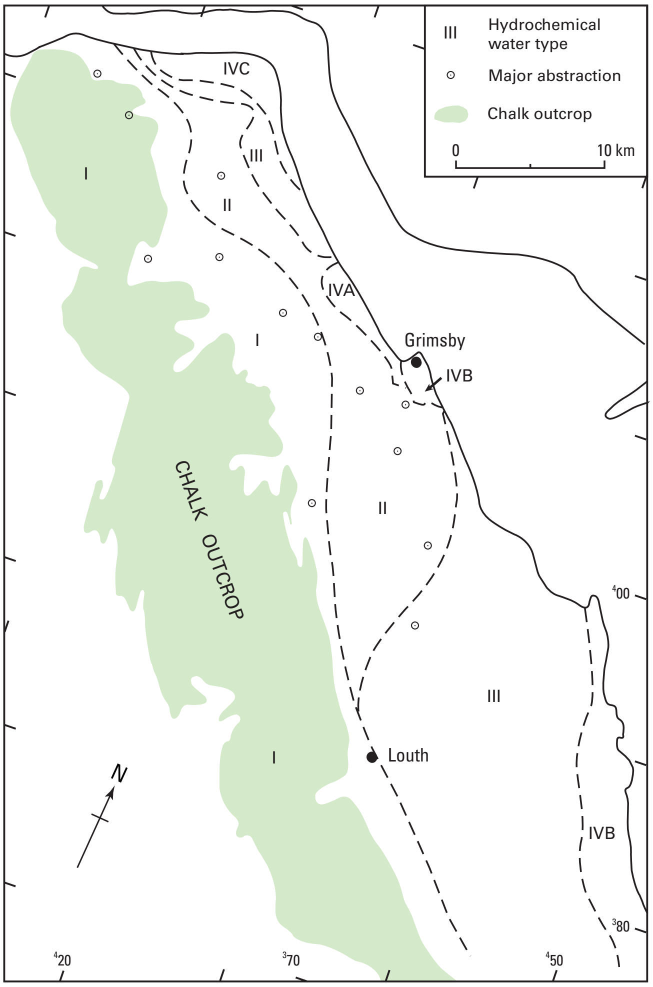


Figure 4.11 Distribution of hydrochemical water types in the northern Lincolnshire Chalk (University of Birmingham, 1978).

exceed the concentrations prescribed in the drinking water regulations. The conductivity and sodium and chloride ion concentration of groundwaters in the Lincolnshire Chalk can also exceed the maximum values allowed in drinking water, but these high values relate to the saline water that is not used for public supply. However, is it apparent from Table 4.1 that unacceptably high values of potassium, ammonium, and aluminium are also found in some Lincolnshire Chalk groundwaters.

4.2.5 Discussion of distribution of major and minor ions

The chemistry of the groundwater will be largely controlled by the physical characteristics of the chalk and by the groundwater flow system. Movement of groundwater in an aquifer system can only occur where there is an outlet for water. In the Chalk of north Lincolnshire, groundwater moves east within the confined aquifer in response to pumping and to discharge to the sea. In the Chalk aquifer rapid flow through fissures is known to occur and so rapid migration of modern water eastwards might be anticipated. While some component of rapid flow undoubtedly does occur, diffusion exchange between fissure and pore waters will retard the movement of the front of modern water significantly. This is important because the volume of porewater to fissure water can exceed 30:1. Modern waters, as indicated by elevated nitrate, have been observed 5 km east of the outcrop. The age and composition of the groundwater also varies with depth.

The confined Chalk aquifer of south Lincolnshire is different; the waters are older and represent trapped groundwater from a previous flow system.

4.2.6 Groundwater dating

Radiocarbon and tritium isotope data can be used to estimate the age, or relative age, of groundwaters and can provide valuable evidence regarding their provenance. Higher tritium activities in rainfall associated with aerial nuclear testing during the 1950s and 1960s characterise modern recharge, i.e. post-1950 water. On the other hand, radiocarbon (^{14}C) dating of groundwater is useful to indicate groundwaters that are older than 1000 years. However, such isotope data must be carefully interpreted as factors such as mixing of groundwaters of different age can change the apparent age. This can occur naturally in the subsurface or within boreholes where pumping can destroy any age-related stratification, producing a sample with a mixed age. Another problem of interpreting ^{14}C data in carbonate aquifers is that solution-precipitation processes cause the ^{14}C of the recharged groundwater to be diluted as there is no ^{14}C in the carbonate minerals in the rock (Darling et al., 1997). The University of Birmingham used the Wigley (1976) method to correct for the dilution of ^{14}C by interaction with the rock matrix. They estimated that the errors associated with the corrected ^{14}C ages of their samples range from about ± 1000 years for the younger waters to about ± 5000 years for ages above 20 000 years.

Groundwater dating again shows a clear difference between the northern and southern confined zones of the Lincolnshire Chalk. Throughout a large part of the northern confined zone modern groundwaters are indicated by the presence of tritium, although some of the saline groundwaters give old carbon-14 ages (see below). In the southern confined zone all of the groundwaters appear to be relatively older, based on absence of tritium and on radiocarbon ages of 1300 to >21 000 years.

Modern tritiated groundwaters had reached a major abstraction site in the area of Grimsby by 1967 (University of Birmingham, 1978), indicating that the front of modern groundwater had migrated eastwards fairly rapidly in response to abstraction. However, depth sampling at Goxhill Hallands (TA 086 202) showed a vertical stratification with modern high tritium waters overlying waters that had a lower tritium concentration (University of Birmingham, 1978). This supports the hypothesis that the Lincolnshire Chalk has an upper, higher permeability, saturated layer of about 20 m through which active flow occurs, and a lower layer which contains groundwater that moves at lower velocities.

In the north-east coastal zone groundwaters have both elevated tritium and apparent ^{14}C ages of several thousand years, and thus represent a mix of modern and older waters. It was observed that tritium activities decreased in these groundwaters between 1967 and 1973–4 (University of Birmingham, 1978), coinciding with a decline in water levels. This was attributed to increased abstraction in the Grimsby–Immingham area, which may have resulted in the removal of the uppermost (youngest) layer of water from a vertically stratified groundwater system.

Towards the south of the north Lincolnshire Chalk, groundwater appears to become older, based on both tritium and radiocarbon data. The area around Tetney is a transitional zone between younger waters in the north and older waters in the south.

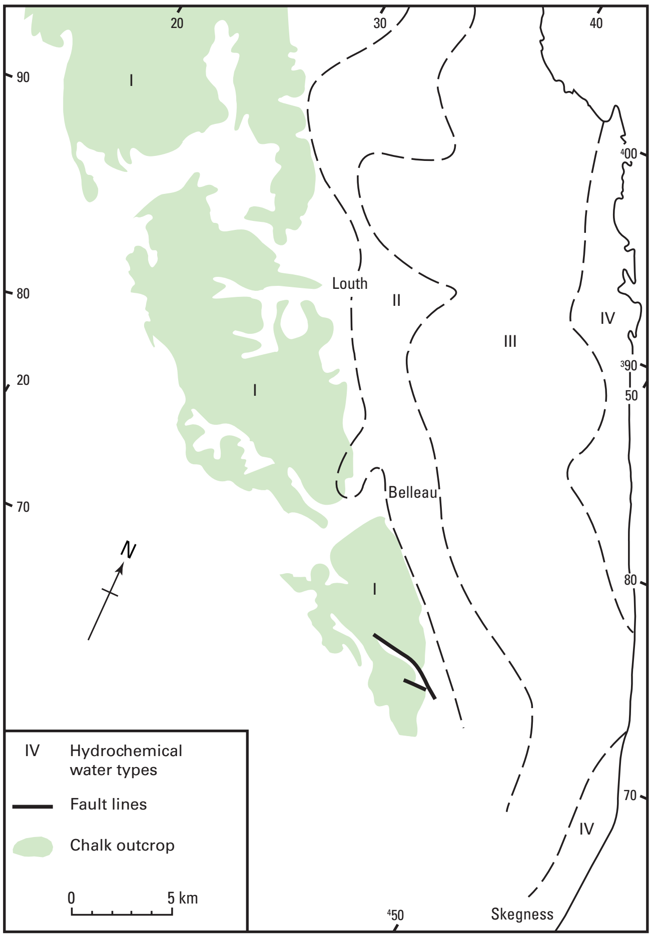


Figure 4.12 Distribution of hydrochemical water types in the southern Lincolnshire Chalk (University of Birmingham, 1982).

In the confined aquifer of south Lincolnshire, east of the Louth Window, the groundwaters are old: tritium is generally absent and ^{14}C ages are typically greater than 1000 years and can exceed 10 000. This suggests that there is little if any modern groundwater movement eastwards from the unconfined aquifer.

The carbon isotope (^{14}C) data show that a wide range of groundwater ages exists in the Lincolnshire Chalk aquifer system, from modern waters to those more than 21 000 years old. The oldest are saline waters that are believed to have entered the aquifer during the Ipswichian interglacial.

4.2.7 Distribution and evolution of hydrochemical types

The University of Birmingham (1978, 1982, 1987) classified the groundwaters of the Lincolnshire Chalk aquifer system into four hydrochemical types based on major ion composition and according to the chemical changes and processes occurring. Such a broad classification is useful for identifying flow paths and barriers to flow, and enables the production of distribution maps that incorporate multiple determinands. While there are drawbacks to this approach that must be considered during interpretation, the 'water type' approach taken by the University of Birmingham (1978, 1982, 1987) assisted in understanding the groundwater flow system in Lincolnshire Chalk. The distribution of water types is shown in Figures 4.11 and 4.12.

Type I waters

These are Ca-HCO_3 type waters which contain tritium, and are, therefore, of modern (post-1950s) origin. These groundwaters have high concentrations of nitrate, chloride and sulphate as a result of human activity. Type I waters are found over the whole of the Chalk outcrop, and also extend for several kilometres to the east of the buried Ipswichian coastline in north Lincolnshire. Type I waters are absent to the east of the Louth Window, where the Chalk is completely eroded along the Ipswichian coastline (Figure 4.12). This indicates that most or all of the water recharged in the Chalk outcrop area in south Lincolnshire is prevented from flowing into the confined part of the aquifer and instead discharges as springs.

Type II waters

The Type II waters are also Ca-HCO_3 type waters, but show increasing sodium content as a result of ion exchange. Concentrations of nitrate and sulphate are generally lower than in Type I; these ions are derived, at least in part, from anthropogenic sources. Type II waters occupy a zone around 1 to 6 km wide, east of the buried cliff region, in the north Lincolnshire Chalk, but in the south it is difficult to distinguish between Type II and Type III waters and the former might well be absent. Type II waters are thought to represent slightly older meteoric waters than Type I.

Most public supply boreholes abstract Type I and Type II waters.

Type III waters

Type III waters occupy a wide zone in the confined area of the southern Lincolnshire Chalk (Figures 4.11 and 4.12). Their major ion concentrations are characteristic of mixing between recharge waters and brackish water. The cation chemistry varies from calcium dominant to a mixed calcium-sodium type water, whilst bicarbonate is the dominant anion. The calcium-bicarbonate Type III waters are difficult to distinguish from Type II. The major ion data indicate that ion exchange and dissolution has occurred, which suggests slow groundwater circulation. Elevated concentrations of minor ions such as strontium also indicate that the water has been in the aquifer for a long time, allowing significant water-rock interaction to occur. Carbon isotope dating corroborates this interpretation, indicating recharge at the onset of the Flandrian, as the Devensian ice melted. Type III waters are thought to be derived from Type II waters by hydrochemical modification, i.e. they are meteoric waters which have had longer residence times and have undergone more change via processes such as water-rock interaction and in the north the boundary between these two water types is gradational. In the southern area of the aquifer, Type III waters are typically oxidising in the west and become reducing to the east (University of Birmingham, 1982). These waters may have evolved from Type II waters that were trapped following the Ipswichian interglacial.

Type IV waters

These are saline waters (mainly sodium chloride type) with total dissolved solids in the range of 1000 to 35 000 mg l^{-1} that occur in coastal areas. The University of Birmingham (1978) has delineated three saline zones in Lincolnshire, which they term the 'north-eastern saline zone' (from Barrow to Killingholme), the 'Grimsby saline zone' and the 'saline zone east of Louth'. Historical data indicate that these zones were stable in 1978 (University of Birmingham,

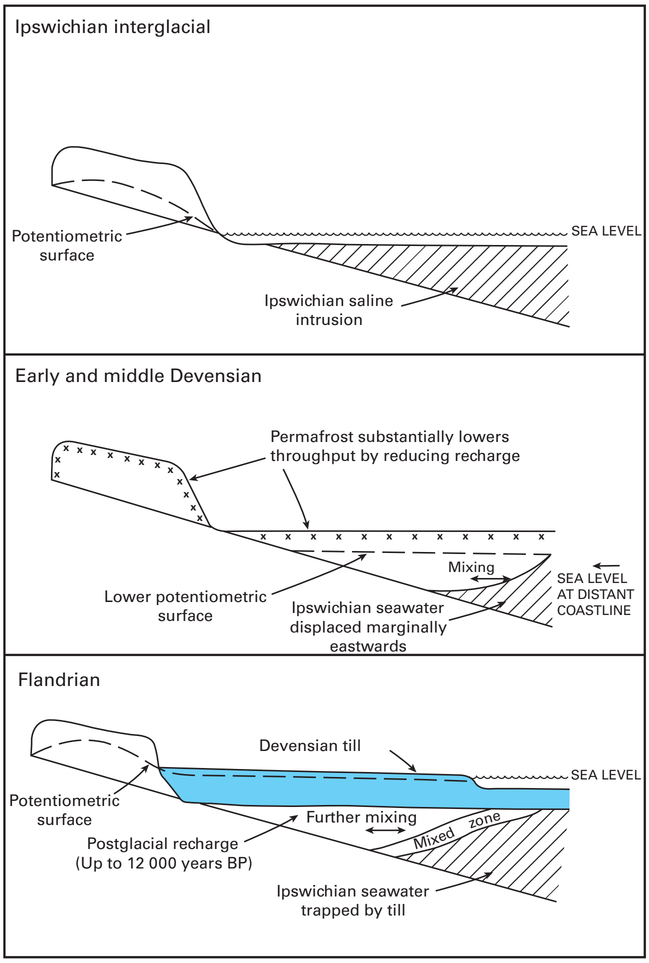


Figure 4.13 Schematic representation of saline intrusion in the saline zone east of Louth: Type IVB (University of Birmingham, 1978).

1978). The saline waters have been divided into three sub-types on the basis of major ions, minor ions (particularly iodide), and ^{14}C age data. Howard and Lloyd (1983) looked at dilution diagrams, which corroborated previous interpretations of origins of different types of saline waters.

Type IVA groundwaters are characterised by only limited iodide enrichment and have I^-/Cl^- ratios close to that of Humber Estuary water. The shallower waters in the Grimsby saline zone are of this type, which indicates that modern seawater leakage is occurring locally from the Humber Estuary (University of Birmingham, 1978). Historical variations of groundwater salinity in the Grimsby zone show a progressive increase in chloride ion concentration until the early 1970s, since when concentrations have stabilised. This stabilisation is due to groundwater management policies that restrict pumping in the area (Chapter 5).

Type IVB groundwaters are found in the saline zone east of Louth and the deeper waters of the Grimsby saline zone. They have extreme iodide enrichment and ^{14}C ages greater than 21 000 years. It is thought that they intruded the Chalk during the higher sea level of the Ipswichian interglacial. This interpretation is consistent with their location beneath Devensian tills, which presumably trapped the saline waters in the aquifer (University of Birmingham, 1978). This mechanism is illustrated in Figure 4.13. The Type IVB groundwaters east of Louth, which are present at depth beneath fresh waters, form the most extensive zone of saline groundwaters.

The waters of the north-eastern saline zone occur as an individual groundwater type, Type IVC. These waters also have strong iodide enrichment, but radiocarbon data shows that they are not older than 8000 years and they are therefore considered different in origin to the Type IVB waters. When sea levels rose during the Flandrian stage (which followed the Devensian glacial period), till was eroded locally, allowing leakage of seawater into the aquifer. The eroded areas were subsequently covered with low permeability deposits that trapped the saline waters (Figure 4.14).

An examination of hydrochemical data by Howard (1985) led to the conclusion that the water types defined above did not originate by simple chemical evolution of groundwater as seen in other aquifers and described by Chebotarev (1955). Howard (1985) showed that the hydrochemistry of the groundwaters in the Lincolnshire Chalk is inexorably linked to the geological history of the aquifer as well as being influenced by the processes which have occurred during residence in the aquifer.

Type II waters are not evolved from Type I as although they are both meteoric in origin and are successive in age, they have different compositions that reflect changes in solute inputs due to anthropogenic influences. Extensive pumping has caused Type 1 waters to migrate eastwards into the confined northern Chalk. Type IV groundwaters are also distinct, having a seawater rather than meteoric origin. However, chemical evolution has occurred between Types II and Types III during flow through the aquifer, as made apparent by the chemical signatures of progressive water-rock interaction and of processes such as ion exchange (Smedley and Brewerton, 1998).

4.3 GROUNDWATER CONTAMINATION

4.3.1 Introduction

As discussed in preceding sections, there are some elements (for example As, Fe and Mn) that occur naturally in the groundwater of Lincolnshire which are present in some boreholes at concentrations greater than drinking water guidelines. However, elevated concentrations of these elements are normally associated with reducing groundwaters and are more frequently encountered in the confined Chalk of south Lincolnshire, which are less used for public supply. Furthermore, these elements can be readily removed by water treatment.

The greatest concerns regarding water quality usually relate to contamination resulting from human activities such as waste disposal or chemical use. Anthropogenic groundwater pollution can occur from diffuse sources (e.g. use of agricultural chemicals such as fertilisers and pesticides applied over large areas) or point sources (e.g. a hydrocarbon spill from a storage tank).

The measures in place to prevent groundwater contamination occurring, and to mitigate existing contamination, are discussed in Chapter 5.

4.3.2 Nitrate

The issue of rising nitrate concentrations became a concern in the late 1970s and 1980s throughout the UK, and a great deal of investigation was undertaken during this time. This work showed that ploughing up of grass pasture and increased use of nitrate fertilisers during the 1950s and 1960s was largely responsible for the rise in groundwater nitrate concentrations. Most leaching of nitrate to groundwater occurs during the

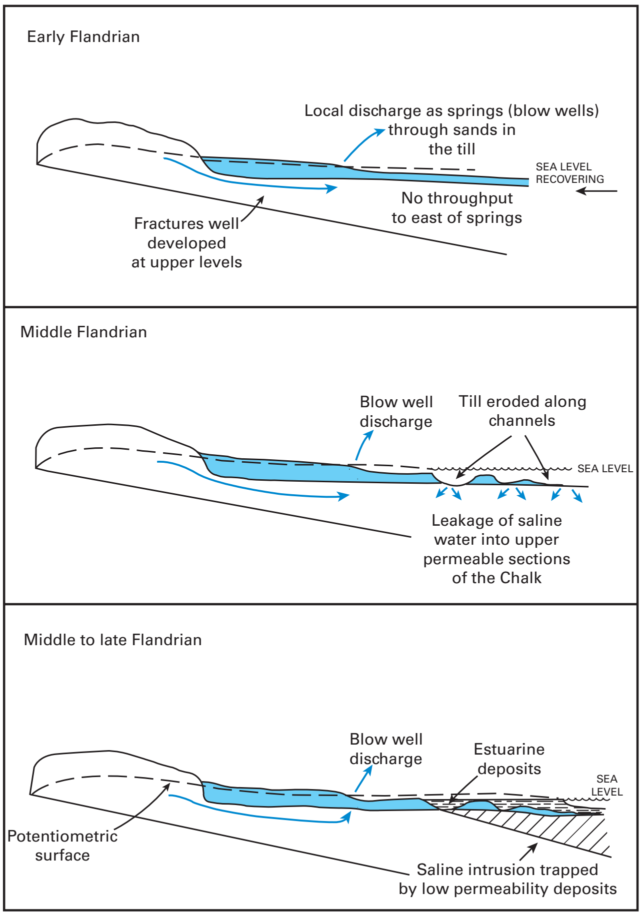


Figure 4.14 Schematic representation of saline intrusion in the north-eastern saline zone: Type IVC (University of Birmingham, 1978).

autumn and winter months when the soil reaches field capacity and recharge is taking place. At this time, nitrate which has accumulated in the soil prior to the onset of the recharge event is transported through the unsaturated zone by the recharging water. Careful management of the land at this time is important to reduce the amount of nitrate which is available to be leached (Jones and Robins, 1999).

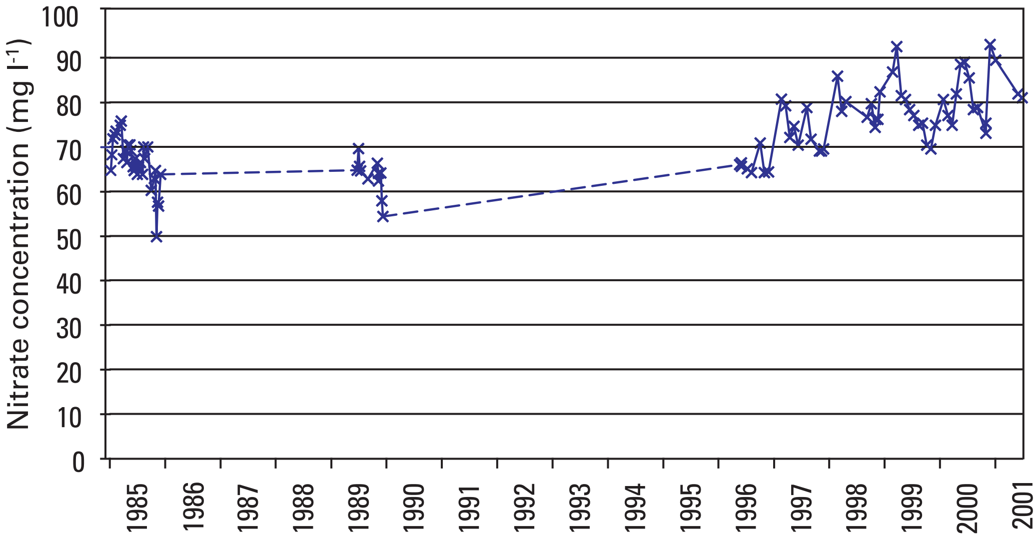
In 1980 the EC set the current maximum limit for nitrate concentrations in drinking water at 50 mg l^{-1} NO_3 (Directive 80/778/EEC). In 1991, EU legislation was brought in to protect surface and groundwaters from high nitrate concentrations resulting from agricultural practices (the Nitrate Directive, 91/676/EEC). The directive empowers regulators to assign Nitrate Vulnerable Zones (NVZs) to the recharge zones of areas where waters exceed or are at risk of exceeding the 50 mg l^{-1} limit. Within NVZs farmers are required to modify farming practices in order to reduce nitrate leaching (see Chapter 5). Almost the whole of the outcrop area of the Lincolnshire Chalk is designated as an NVZ as it forms the catchment for public water supply sources which have high nitrate concentrations.

The Chalk Wolds have a long tradition of agriculture and during the 1960s and 1970s the application of nitrogen fertilisers to arable land increased considerably. Nitrate concentrations in the unconfined aquifer increased significantly as a consequence. Modern high nitrate groundwater has penetrated the confined aquifer and raw water from public supply boreholes frequently exceeds the drinking water guidelines. Figure 4.15 shows the long-term trend of increasing nitrate concentrations at one borehole in the unconfined Chalk of north Lincolnshire. The observed increase of about 20 mg NO_3 l^{-1} rise in about 20 years is typical for this area. Treatment works have been installed at many AWS groundwater sources; these are effective in reducing nitrate concentrations but are costly. The nitrate problem is accentuated in Lincolnshire as the county has a relatively low average annual rainfall, so less recharge is available to dilute the nitrate.

4.3.3 Inorganic contaminants

Seawater intrusion has been seen for many years as the most serious long-term threat to the Northern Chalk aquifer (Spink and Watling, 1995). This concern provided the impetus for developing an aquifer management model to help maintain groundwater levels in the Chalk aquifer and thus prevent saline intrusion. The concentration of industrial centres around the coast has resulted in significant abstractions being centred in coastal areas, which has aggravated the problem of saline intrusion. While the saline water has never encroached far enough inland to threaten public water supply sources (M Cook, personal communication, 2000) this was a possibility had the saline intrusion continued to move inland. Data from the groundwater quality monitoring network showed that

Figure 4.15 Rise in nitrate concentrations in a borehole in the unconfined Chalk of north Lincolnshire.



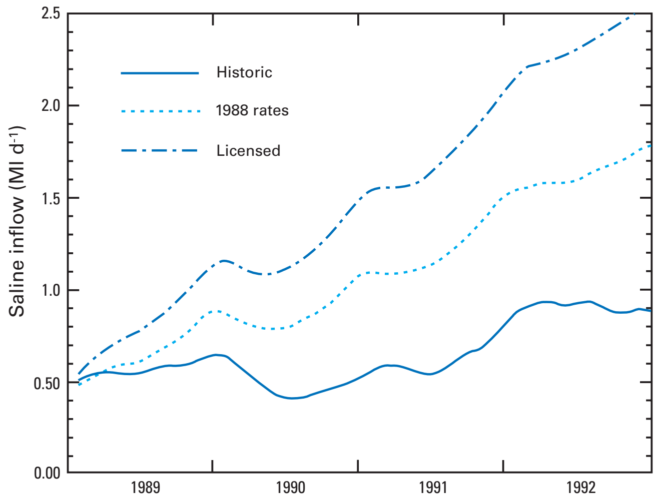


Figure 4.16 Modelled saline inflow under various abstraction regimes (after Spink and Watling, 1995).

chloride ion concentrations increased significantly in the 1970s in certain areas in response to pumping. However, rainfall was generally higher in the 1980s, and the increased recharge pushed back the saline interface; this demonstrated that the 1970s situation was recoverable.

An important aim of the Environment Agency is to manage the aquifer sustainably, maintaining saline intrusion to historical (early 1970s) levels. The management strategy is described in Chapter 5, however the policy has been successful as during the period 1988 to 1995 there had been no significant increase in chloride concentrations at key monitoring boreholes in the coastal area (Spink and Watling, 1995). Figure 4.16 shows modelled saline inflow under various abstraction regimes, which demonstrates that abstracting at licensed levels, or continuing at 1988 abstraction rates, would have significantly worsened the saline intrusion problem. The actual levels of abstraction, controlled by agreements, have not caused excessive saline inflow (Figure 4.16).

The aquifer system also contains some old saline waters, however, these zones are distant from the main abstraction centres (Spink and Watling, 1995).

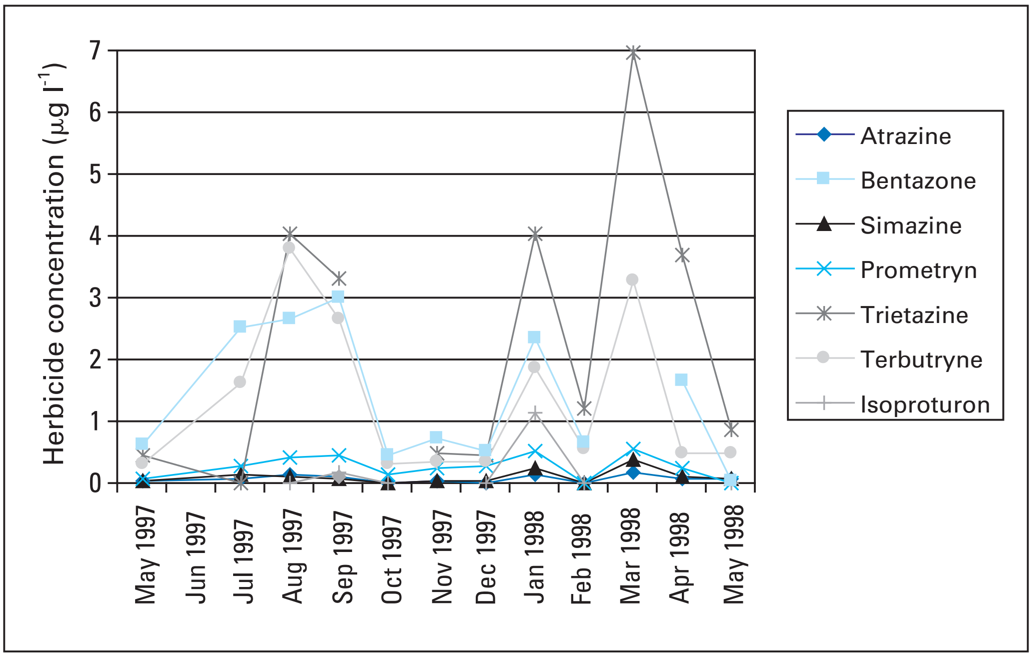
4.3.4 Organic contaminants

In recent years groundwaters worldwide are facing a growing threat of pollution from an increasingly wide range of synthetic organic chemicals. Many such compounds have very low acceptable concentrations in drinking water, often below 50 μg l^{-1} and in some cases below 1 μg l^{-1}. There are two very different potential sources of organic contaminants: a) the leaching of pesticides applied to agricultural land under normal farming practices; and b) the casual ground disposal, accidental leakage or spillages of organic compounds, particularly hydrocarbons and chlorinated solvents.

The Chalk of Lincolnshire is no exception and faces the threat of both diffuse pollution by agricultural practices and more localised point source pollution following spillages and improper disposal. A survey of the concentrations of List 1 and List 2 substances (as defined by the EC Directive on the protection of groundwater against certain dangerous substances, 80/68/EEC) in Lincolnshire groundwaters was conducted by the Environment Agency in 2000 in response to the Groundwater Directive. The results showed that most organic compounds were below the detection limit, but that some samples contained detectable concentrations of pesticides. It is not known whether these pesticides originate from a diffuse or point source, however, recent research suggests that following agricultural applications of pesticides, the parent compounds do not normally reach the water table in the Chalk aquifer (Chilton et al., 2001).

Significant concentrations of herbicides, exceeding EC Drinking Water Standards, have occurred in boreholes in the Goxhill area (Figure 4.17). This contamination has caused the closure of a public water supply abstraction. An investigation was carried out by the Environment Agency with support from AWS and the evidence suggested that the pollution may have occurred as a result of the disposal of pesticide containers in a chalk pit.

Figure 4.17 Time series of herbicide concentrations in a borehole in the Goxhill area (data from Hutchinson, 1998).



Pesticide contamination has also resulted in a requirement for treatment at other public water supply sources; this is achieved by either blending or by treatment using granular activated carbon (oral communication from Mike Cook, 2000). AWS also has treatment plants which remove pesticides from water by passing it through granular activated carbon (GAC). The pesticides, which are organic chemicals, become sorbed to the GAC, which is replaced when it becomes saturated with pesticides.

4.3.5 Other point source pollution

Another major threat to water quality is anthropogenic contamination, which may be caused by practices such as waste disposal (e.g. old landfill sites) or accidental spillages. Contaminant plumes can migrate considerable distances in the Chalk aquifer with its high transmissivity and low storage capacity. The capacity of the aquifer to attenuate contaminants by degradation will depend on the type and volume of contaminant. However, even where natural attenuation occurs, rapid transport in the Chalk aquifer may result in the contaminant plume spreading over a considerable distance. As it is such a vulnerable hydrogeological environment, where remediation may be particularly difficult and expensive to successfully implement, the Chalk aquifer requires strong protection measures: these are described in Chapter 5.

Some groundwater pollution incidents are referred to in the LEAP document for the Grimsby–Ancholme catchment (Environment Agency, 1999), including the pesticide contamination at Goxhill. The LEAP also points out the potential for pollution problems from the 30 active landfill sites and other closed landfill sites in the Grimsby–Ancholme plan area.

The threat to the aquifer was considered to be of significance when plans for development above an old landfill site (Macauley Lane) were being proposed. The intention was to construct a building, which, due to the nature of the underlying glacial till, required that piling was undertaken through the waste and the clay into the underlying Chalk. Due to the sensitive location of the site with regard to nearby abstractions the Environment Agency argued that the piles could create a pathway from the waste to the underlying aquifer. Following detailed design consideration an alternative construction method was proposed.

4.4 SUMMARY

The quality of groundwaters in the Lincolnshire Chalk aquifer system is variable; the fresh waters are typically of good quality, but problems of high nitrate, arsenic and iron concentrations exist in some parts of the aquifer. Saline waters are present in some coastal areas of the aquifer. The chemistry of the groundwater is controlled both by natural processes, such as water-rock interaction, and by human influences, primarily abstraction, agriculture and industrial activities.

The waters have been categorised into four broad types, of which Types I to III are bicarbonate (fresh) waters, and Type IV are saline. Type I are modern waters, meteoric, with anthropogenic inputs; Type II are slightly older meteoric waters, which were also recharged in modern times; Type III are considerably older fresh waters, believed to have entered the aquifer system during the Flandrian; and Type IV are saline waters. The Type IV waters can be further subdivided on the basis of their age and composition. This analysis of the hydrochemistry has revealed much about the present and historical flow systems in the aquifer.

The groundwater in the outcrop zone is all modern. This modern water has also penetrated the confined Chalk of north Lincolnshire, as demonstrated by the high nitrate concentrations observed in this area. The groundwater in the confined Chalk of south Lincolnshire is old due to lack of flow across the buried cliff, which eroded completely through the Chalk in this area. Saline waters exist in some parts of the coastal zone.

5 Management of the Lincolnshire Chalk aquifer system

5.1 OVERVIEW

There is a long history of abstraction from the Lincolnshire Chalk aquifer system: the National Well Record Archive (held at BGS Wallingford) contains records of wells dating back to 1848. Significant development of the Chalk aquifer began in the mid 1800s with the construction of boreholes for both public water supply (PWS) and industry. The availability of groundwater attracted industries to the Grimsby area in the 1950s and demand for water in North Lincolnshire rose rapidly in the 1960s, particularly due to industrial expansion along the south Humber bank. The locations of major present day abstractions are shown in Figure 5.1.

Where readily available, groundwater is normally less expensive to use than surface water as it generally needs less treatment: groundwater is, therefore, in great demand (Spink and Watling, 1995). However, abstraction of groundwater can reduce baseflow to rivers, with consequent impacts on ecology and amenity value. Over-abstraction can lead to derogation of the resource and cause problems such as reduced well yields and movement of saline water into the aquifer. Saline intrusion has been a major problem and concern in Lincolnshire for a number of years as many boreholes are located close to the Humber Estuary and are, therefore, vulnerable to seawater intrusion. Management of the aquifer system is essential to achieve a satisfactory balance between the competing water requirements and to safeguard the environment and the resource.

Significant changes to the management of the aquifer system have occurred since the 1950s in response to greater awareness of the impact of increasing abstraction on a finite water resource and increased appreciation of the inter-relationship between groundwater and surface water. This progression has also resulted from changes in the distribution of responsibility for water supply and management of the water resource between various organisations over the years. Management of groundwater in the UK began when the 1945 Water Act brought in the first abstraction licences. Further abstraction licences, Licences of Right, were introduced following the Water Resources Act of 1963. The 1973 Water Act set up Regional Water Authorities in England and Wales, with Anglian Water Authority covering this study area. These authorities had a dual role as both water suppliers and regulators/enforcers. Privatisation of the water industry in 1989 led to the establishment of the water companies, responsible for the supply of water and sewerage services, and the National Rivers Authority (NRA), which was given responsibility for regulation and enforcement. The water company in the area of this study is Anglian Water Services (AWS). The Environment Act of 1995 merged the NRA, Her Majesty's Inspectorate of Pollution and the Waste Regulatory Authorities, forming the Environment Agency. The Environment Agency is responsible for the sustainable management and protection of the water resources of England and Wales.

Management strategies to control abstraction from the Chalk aquifer commenced with abstraction licensing in 1963. In the 1960s and early 1970s management policies were based on the use of surface water and groundwater as a single resource, to encourage more efficient use of water resources. Water transfer schemes were initiated in this period. Later in the 1970s, chloride concentrations in the aquifer reached record levels along parts of the coast. The Anglian Water Authority responded by commissioning the University of Birmingham to undertake a series of investigations of the aquifer system, which improved the conceptual understanding of the system and led to the development of groundwater flow models. These models have formed the basis of a pioneering management strategy which has operated in Lincolnshire since the late 1980s. The model is regularly used to predict saline intrusion based on the winter rainfall pattern and groundwater levels and thus indicate acceptable abstraction regimes.

The University of Birmingham groundwater investigations demonstrated that the total licensed quantity exceeded the available sustainable resource of the aquifer (i.e. the average annual recharge). The aquifer was, therefore, considered 'over-committed'. This position has primarily resulted from the practice of granting Licenses of Right to abstractors in the 1960s prior to understanding the available resource. Fortunately, actual rates of abstraction have been less than the licensed amount and during the 1990s the Environment Agency has negotiated with abstractors to agree reductions in the abstracted quantities during drought periods.

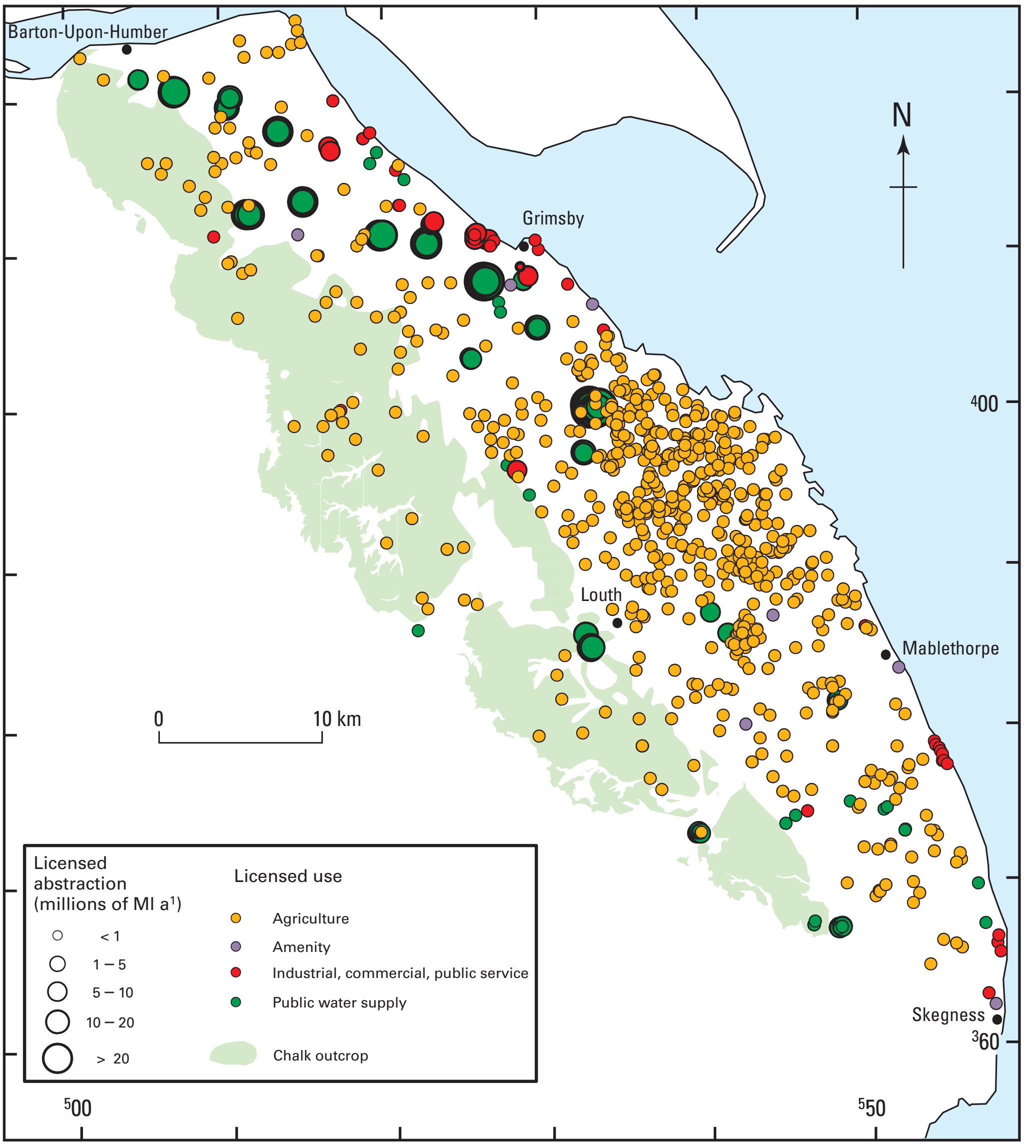
Apart from areas affected by saline intrusion, groundwater quality in the Lincolnshire Chalk aquifer system is generally very good, although the intensification of agriculture in the second half of the 20th century has produced changes in quality, as discussed in Chapter 4. Nitrate and pesticide concentrations are of particular concern and have required costly treatment at some public water supply sources. Groundwater quality is protected under European and UK legislation and through local policy; the regulatory framework is described later in this chapter. The Water Framework Directive, which was introduced in 2000, has major implications for how groundwater is managed. However, much of the detail regarding implementation is still under discussion and so the impact on operational management is difficult to fully assess and as a consequence this report does not discuss the directive in detail. The likely impact of climate change and predicted long-term trends in water demand are considered in Chapter 6.

5.2 THE NEED FOR MANAGEMENT

5.2.1 The main issue

The main resource management issue with regard to the Lincolnshire Chalk aquifer system is maintaining a balance between groundwater abstraction and aquifer recharge to ensure that groundwater levels do not fall below critical limits. Groundwater levels have to be maintained for environmental reasons (e.g. to protect rivers and wetlands), to prevent saline intrusion, and to ensure that the groundwater resource is available for abstraction in the long term, particularly during drought periods.

Figure 5.1 The locations of major present-day abstraction boreholes (2000).



The occurrence of saline intrusion, induced by abstraction, first brought recognition that management of the aquifer system was necessary and led to measures to reduce abstraction when required. As saline intrusion is now controlled, the management remit has broadened to include other issues, particularly environmental concerns.

5.2.2 A complex aquifer system

While the majority of abstraction boreholes penetrate the Chalk, which is the main aquifer, other formations contribute to flow and storage in some areas of the aquifer system, notably the Quaternary sands and gravels, Carstone, Roach and Spilsby Sandstone.

The Chalk itself is a highly transmissive aquifer but can store relatively little groundwater as the majority of flow and storage is attributable to fractures. These characteristics mean that it is susceptible to drought, with rapid flow and discharge occurring after winter recharge (i.e. most recharge passes rapidly through the aquifer system). Significant contributions to the storage capacity of the aquifer system are made by the overlying sands and gravels, the distribution of which is not well known (as they are in turn overlain by more recent deposits). As water moves less rapidly through the sands and gravels, their storage capacity buffers the aquifer system in times of lower recharge.

The distribution of transmissivity with depth within the Chalk is uncertain, although it is understood that much of the transmissivity relates to horizons of present and past water table fluctuation and occurs within ± 30 m of the present water table. The discharge from the springs and blow wells in the study area is highly sensitive to changes in water level. This corroborates the observation that a large proportion of the transmissivity is attributable to discrete horizons, such as the zone of present day water-table fluctuation. Hence a relatively small fall of the water-table in this critical zone could lead to the cessation of spring flows, which in turn could cause the streams fed by the springs to dry up. A seemingly small change in water-table elevation could, therefore, have a relatively large environmental impact.

The flow system in the confined aquifer system of southern Lincolnshire is particularly poorly understood, especially with regard to recharge mechanisms to the Spilsby Sandstone. Groundwater levels in the Spilsby Sandstone have not fully recovered since the drought periods of the early and mid 1990s; the reason for this poor recovery of water levels is unclear. While the effects of the droughts can be seen in most Spilsby Sandstone boreholes, abstraction effects in certain areas seem to be more significant in contributing to low or declining heads. Some locations show heads falling over a 20 year period, not just during 1988–92 or 1995–97. Drought effects in both the Spilsby Sandstone and the Chalk are generally less clear around the major abstraction points. The south-easterly part of the confined southern Chalk, in which four public water supply groundwater sources have been developed, shows a slight long term fall in levels, with small drought effects superimposed. The magnitude of this fall is less than that observed in the Spilsby Sandstone, though its statistical significance has not been assessed.

The complexity of the aquifer system and the uncertainties inherent in any natural system, make the task of managing the aquifer system a difficult one. However, these difficulties make it even more important to monitor and manage the aquifer system to ensure proper protection of the resource and dependent environment.

5.2.3 Sustainable abstraction

The demand for water for public supply increased from the 1950s, probably peaking in the 1970s, as industrial, agricultural and per capita demand rose. Since then demand has fallen due to improved water use efficiency and a decline in heavy industry. Even so, it would not be feasible to return to pre-1950s levels of groundwater abstraction. While abstractors must be protected from drought, it is also important to minimise the impact of abstraction on the environment. The term 'sustainable abstraction' is used in this report to mean a balanced approach to water use. Such an approach allows groundwater to be exploited for public water supply, industrial and agricultural uses, while avoiding unacceptable derogation of surface water sources, groundwater quality and the environment, so that following generations continue to have access to these resources. As described in Chapter 3, the Environment Agency calculate the available resource for a groundwater unit, and the in situ resource requirements which take into account environmental needs for water. The difference can be considered the volume of water which can be abstracted without adversely affecting river flows or groundwater quality.

The Environment Agency has responsibility for monitoring groundwater levels, groundwater quality and spring discharges and has a management strategy in place to control abstraction. While the aquifer is over-licensed (the total volume of licences significantly exceeds the average recharge), it is only over-committed at certain times (e.g. during droughts) when total abstraction exceeds average recharge. Furthermore, actual abstraction is significantly less than the licensed quantities.

Sustainable development refers not only to groundwater quantity, but also to safeguarding water quality. Thus the Environment Agency uses its regulatory power where necessary both to prevent any deterioration in groundwater quality and to promote improvement in water quality. The legislation relating to the protection of water quality is described in more detail later in this chapter.

The Environment Agency also produces national and regional water resources strategies. *Water Resources for the Future — a strategy for England and Wales* was published in 2001 (Environment Agency, 2001a) which is reviewed annually (e.g. Environment Agency, 2002a). A detailed strategy for the Anglian region was published in 2001 (Environment Agency, 2001b).

5.2.4 Environmental concerns

The requirements of the Water Framework Directive dictate that more attention must be paid to the requirements of rivers and other water-dependent bodies. Chalk groundwater feeds many rivers in Lincolnshire, including sections of the Waithe, Laceby, Barrow, East Halton, Keelby and Skitter Becks, and the River Rase. Such 'Chalk rivers' are very important as 'the Chalk influence gives rise to a distinctive hydrochemistry and flow regime, creating characteristic assemblages of animals and plants' (Environment Agency, 1999). The UK Biodiversity Action Plan (www.ukbap.org.uk) lists Chalk streams as a 'high priority' habitat.

In addition to providing baseflow to rivers, groundwater feeds certain wetlands which are important habitats for wildlife, such as Tetney Blow Wells (TA 31 00). Protection of wetlands is of particular importance as the number of wetlands and wetland species of plants and animals diminishes globally. Internationally important wetlands are protected by the RAMSAR designation. There is evidence that a number of wetland sites may have been lost along the Lincolnshire coastal plain as a result of reduced flow from blow wells.

There are other designations such as Site of Special Scientific Interest (SSSI) and Special Protection Area (SPA) that are relevant to groundwater. OFWAT funding to water companies under the AMP4 investment programme includes improvement of SSSIs/SPAs. However, the area of Lincolnshire Chalk contains relatively few groundwater dependent SSSIs and SPAs compared to other parts of the Anglian region hence the degree of expenditure on investigation will be limited. The locations of water-dependent RAMSAR sites, SSSIs and SPAs are shown in Figure 5.2.

As well as providing habitats for plants and wildlife, rivers support fisheries and provide a location for recreational activities; hence there are economic, ecological and amenity interests to consider. The Environment Agency have the responsibility for setting targets for river flows in the first part of the 21st century, but, given the fact that the majority of rivers have been significantly altered by man, setting targets raises many economic, technical and environmental issues. Such issues include whether the aim is to protect the status quo or to improve the river environment and its associated benefits. Furthermore, while maintaining set minimum flows may provide benefits to river users and ecology, a significant decrease in groundwater abstraction could be required at certain times to achieve these. It is, therefore, essential to consider how to make the most effective use of any reduction in abstraction for the greatest environmental benefit and whether such environmental aims are effective in cost-benefit terms.

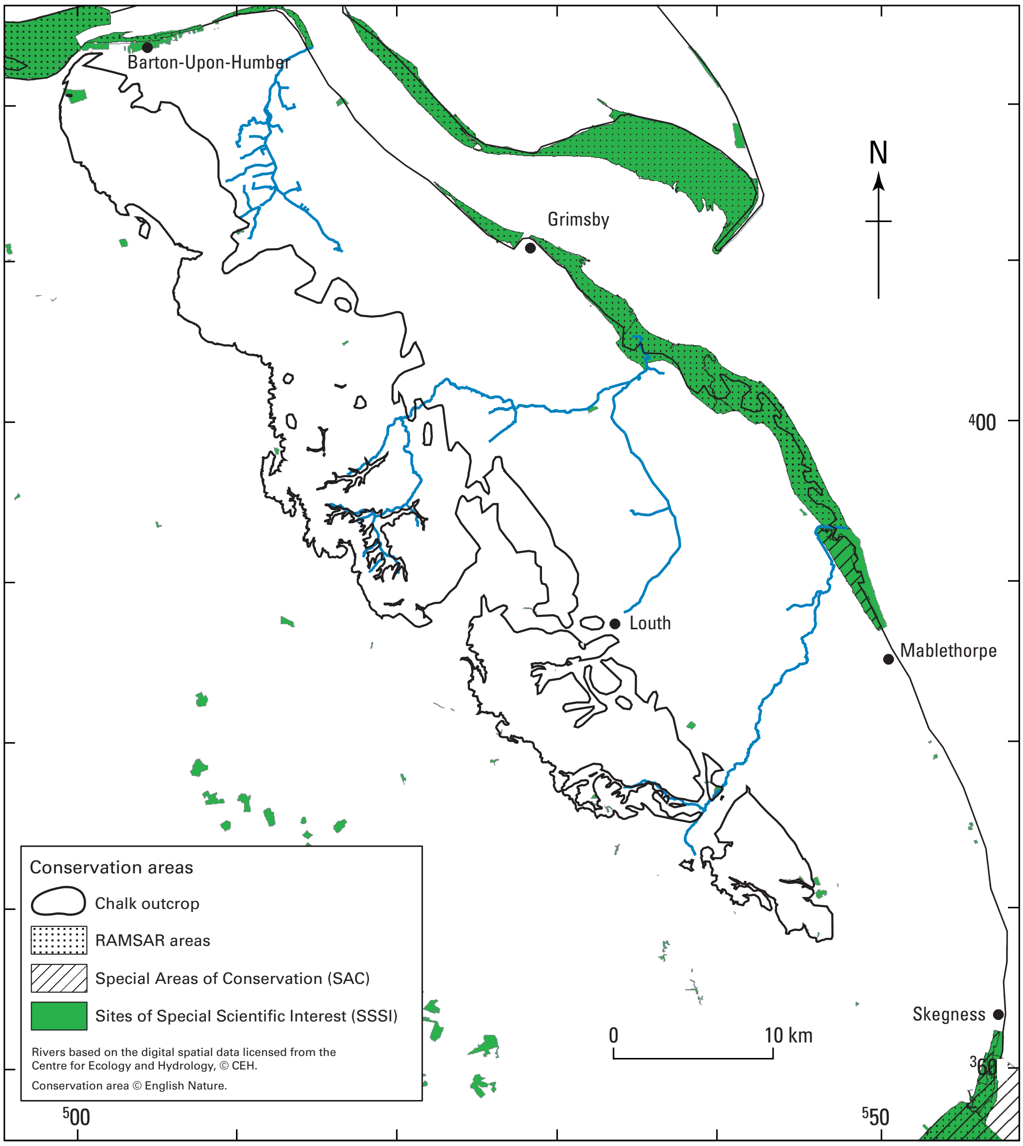
Judging the worth of environmental improvement schemes is a complex problem. In order for cost-benefit analyses of schemes to improve river flows to be performed, it is necessary to understand how flows affect the parameters of interest. The Lotic-invertebrate Index for Flow Evaluation (LIFE) technique, which links the populations of invertebrates in rivers (considered to be useful indicators of the 'health' of a river) to the river flow regime has been developed (Extence et al., 1999). A strong correlation has been observed between the LIFE index and mean summer flows for Chalk streams, including the Waithe Beck which rises from the Chalk of the Lincolnshire Wolds (Extence et al., 1999).

5.3 MANAGEMENT TOOLS

5.3.1 Abstraction licensing in the past, present and future

The first licences that were introduced throughout the UK were Licences of Right, which were given to pre-existing

Figure 5.2
Locations of water-dependent RAMSAR sites, SSSIs and SPAs.



abstractors in 1963. These early licences were given at a time when little was known about the extent of resources in the Lincolnshire Chalk aquifer system, and the majority gave the abstractor the right to use the full licensed quantity with very few, if any, restrictions. However, by the 1960s it was apparent that abstraction was too high and was inducing saline intrusion.

The Chalk aquifer system became severely stressed during the 1988–1992 drought; baseflow dependent watercourses dried up and saline intrusion increased along parts of the coast. This led the National Rivers Authority to appeal to large abstractors over the whole of the aquifer area to reduce abstraction. Both the water undertaking and industrial abstractors responded positively as they accepted that a problem existed and that reductions in abstraction were in their interests as well as that of the regulator. Another factor which helped ensure this success was that the major abstractors accepted the validity of the groundwater management model.

Reductions in abstraction were achieved over several years, allowing the abstractors time to make alternative arrangements. When necessary the water company were able to substitute surface water from Covenham Reservoir for groundwater, this reservoir being mainly used to supply industry along the Humber Bank. This episode led to greater awareness and improved efficiency in the industrial sector and abstractions have declined since this period as a result of better management (Dave Watling, personal communication 2000).

The success of these informal arrangements was followed up with a formal agreement between the Environment Agency (which replaced the NRA in 1995) and AWS. The first 'Section 20' northern Chalk agreement[2] (where Section 20 refers to that part of the Water Resources Act, 1991) was signed in 1995, for a five-year term, and a follow-up agreement was signed in 2000. The aim of the agreement is to manage the aquifer sustainably and in particular to prevent significant saline intrusion at times of low recharge. As discussed previously, the agreement utilises the groundwater management model, and during times of low recharge AWS have, in the past, been required to reduce their maximum annual average abstraction from 140 Ml d^{-1} to 110 Ml d^{-1}. Recent experience has been that in times of drought, actual abstraction falls to about 80–90 Ml d^{-1}, partly due to the nature of the supply network. Although there is no formal agreement with other licence holders, industrial abstractors along the

2 For the purposes of aquifer management the northern Chalk resource unit comprises the northern Chalk unconfined and confined areas plus the confined area of the southern Chalk. Note that this use is different to that of the University of Birmingham.

coast have voluntarily reduced abstraction upon the request of the Environment Agency during low rainfall periods.

Licensed abstraction from the Lincolnshire Chalk aquifer system totalled about 182 Ml d^{-1} in 1998. However, the actual abstraction was probably in the order of 110 Ml d^{-1} and includes some very large sources, e.g. Littlecoates PWS in Grimsby supplies 18–20 Ml d^{-1}, as does the PWS supply at Tetney. The majority of sources are smaller (Figure 5.1).

The amount of abstraction that the Environment Agency would normally license in an aquifer is termed the 'renewable resource', which is equal to the 95 percentile of mean annual average recharge (David Burgess, pers. comm. 2000). In the year 2000 the total licensed abstraction for the Lincolnshire Chalk aquifer exceeded this, and as a consequence the EA did not consider granting licences for any additional groundwater abstraction except for quantities less than 20 m^3 d^{-1} accompanied by full justification and an impact assessment by the EA. This resulted in a negligible amount of additional water being licensed during the 1990s. Abstractions for strictly non-commercial purposes are exempt from this licensing regime, providing they are for less than 20 m^3 d^{-1}.

A new approach to managing water abstractions in England and Wales is being introduced during the first decade of the 21st century (Department of the Environment, Transport and the Regions, 1999). Catchment abstraction management strategies (CAMS) are water resource management plans which will be developed on an area by area basis (Environment Agency, 2002b). The CAMS areas have been based mainly on surface water catchments, complementing the existing local environment action plans.

The CAMS will operate on a six-year review cycle, during which time the Environment Agency will undertake a detailed assessment of the resource, including total available resource, environmental requirements, licensed quantities, and actual abstracted quantities. The balance between the committed and available resources determines the 'resource availability status' for each water resource management unit within the area (see Table 5.1), i.e. whether further abstraction licences can be granted without derogating the environment or other users. 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 will also be open to the public, providing more open access information than was available in the past.

The development of the first 25 CAMS started in 2001. There are 126 CAMS areas covering England and Wales. The Lincolnshire Chalk area is covered by the Grimsby & Ancholme and Louth CAMS, and work started on developing these strategies in April 2003 and April 2004 respectively. The CAMS for all 126 areas will be completed by 2008, by which time the review and update phase will begin on those which were first produced.

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, with the Environment Agency 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 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 upon the concept of integrated river basin management: all waters will be managed within river basin districts, with groundwater assigned to groundwater bodies within these. 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. These plans will be reviewed every 6 years. The Environment Agency intends to use CAMS as the basis for river basin management plans.

5.3.2 Application of numerical models to groundwater management

The regional Chalk aquifer model, developed by the University of Birmingham (see Chapter 3), plays an important role in the management of water resources in Lincolnshire. The Lincolnshire Chalk regional groundwater flow model was developed partly as a tool to manage saline intrusion at the coast. This model is run to determine whether or not the expected quantity of abstraction is acceptable in terms of consequent saline intrusion and has been used to examine the effects of various management strategies.

The model is run to consider possible recharge and abstraction scenarios. In recent years runs have assessed average recharge, 50% of average recharge and 20% of average recharge. Abstraction scenarios have been adjusted according to AWS' prevailing operating patterns or planned changes. Such extremely low recharge events have a low incidence: even the serious 1975–1976 drought resulted from recharge falling to about 50% of the average, so 20% of average is a very conservative prediction. Nevertheless, these simulations give the regulators a good idea of what can be expected over the following period, and enable them to respond to any predicted problems.

The Environment Agency determine whether or not to reduce abstraction on the basis of a control rule, which was developed with the use of the contaminant transport model (University of Birmingham, 1993). The control rule states that the predicted level of abstraction is unacceptable if simulated saline inflow at a particular model node exceeds 1 Ml d^{-1}. This, along with consideration of the time of the year, preceding water levels and springflows and abstraction requirements is used to assess resource management options.

At times of below average recharge (precise timings being the result of ongoing liaison between the Agency and AWS and EA analysis through modelling), under the terms of the Northern Chalk Agreement, AWS are required to reduce abstraction from their northern Chalk groundwater sources

Table 5.1 Definition of the CAMS 'resource availability status' classifications.

Indicative resource availability status	Definition (relating to the availability of water for abstraction licences)
Water available	Water likely to be available at all flows including low flows. Restrictions may apply.
No water available	No water available for further licensing at low flows although water may be available at higher flows with appropriate restrictions.
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-abstracted	Existing abstraction is causing unacceptable environmental impact at low flows. Water may still be available at high flows with appropriate restrictions.

from their annual average aggregated licensed maximum of 140 Ml d^{-1} down to a maximum of 110 Ml d^{-1}. Partly because the Environment Agency and the abstractors have confidence in the ability of the model to provide reasonably accurate simulations, the regional Chalk aquifer model has played a fundamental role in the abstraction reduction agreements described in the previous section.

5.3.3 Use of alternative surface water supplies

AWS hold licences for a range of groundwater and surface water sources including surface water reservoirs. This enables them to use the resources conjunctively, for example, supplying industrial customers with water from reservoirs during times of drought when it would not be possible for them to abstract the usual quantity of groundwater because of impact on groundwater levels and consequent saline intrusion.

There is a network of surface water transfers that assist this pattern of use. Some of this water is imported from neighbouring catchments. The Environment Agency owns and operates the Trent-Witham-Ancholme River Transfer Scheme (TWAS), which involves transfers from the River Witham (at Short Ferry) to the River Ancholme and from the River Trent (at Torksey) to the River Witham. The scheme also includes a storage reservoir located at Toft Newton. The Trent-Witham-Ancholme Transfer Scheme supported over 100 abstraction licences in 1998. During the summer and periods of low rainfall the flow and level of water in the River Ancholme is supported by transfers from the River Witham. At times when the flow in the Witham is not sufficient to support the various abstractions, transfers are made from the River Trent to the Witham. This scheme has been in operation since the mid 1970s, and water is transferred from the Witham to the Ancholme every summer, usually starting in May/June and continuing until September. A series of drought years from the late 1980s and through the 1990s, combined with growth in spray irrigation in the lower Witham catchment, has led to an increase in use of the Trent–Witham transfer.

The other large scheme is the Great Eau Transfer Scheme at Cloves Bridge. In times of drought when Covenham Reservoir is heavily used, the water company can transfer water from the Great Eau (a river which drains the southern Chalk outcrop, and has a high baseflow) via the Louth Canal to the reservoir. In non-drought times, Covenham Reservoir is primarily a winter abstraction. Covenham Reservoir was built in the late 1960s. Although the Great Eau Transfer Scheme is fully owned by AWS, they have a 'Section 20' agreement with the Environment Agency which states that abstractions from the reservoir must not exceed the volume added to the reservoir as a result of the transfer scheme (Dave Watling, personal communication, 2000).

5.3.4 Local environment action plans (LEAPs)

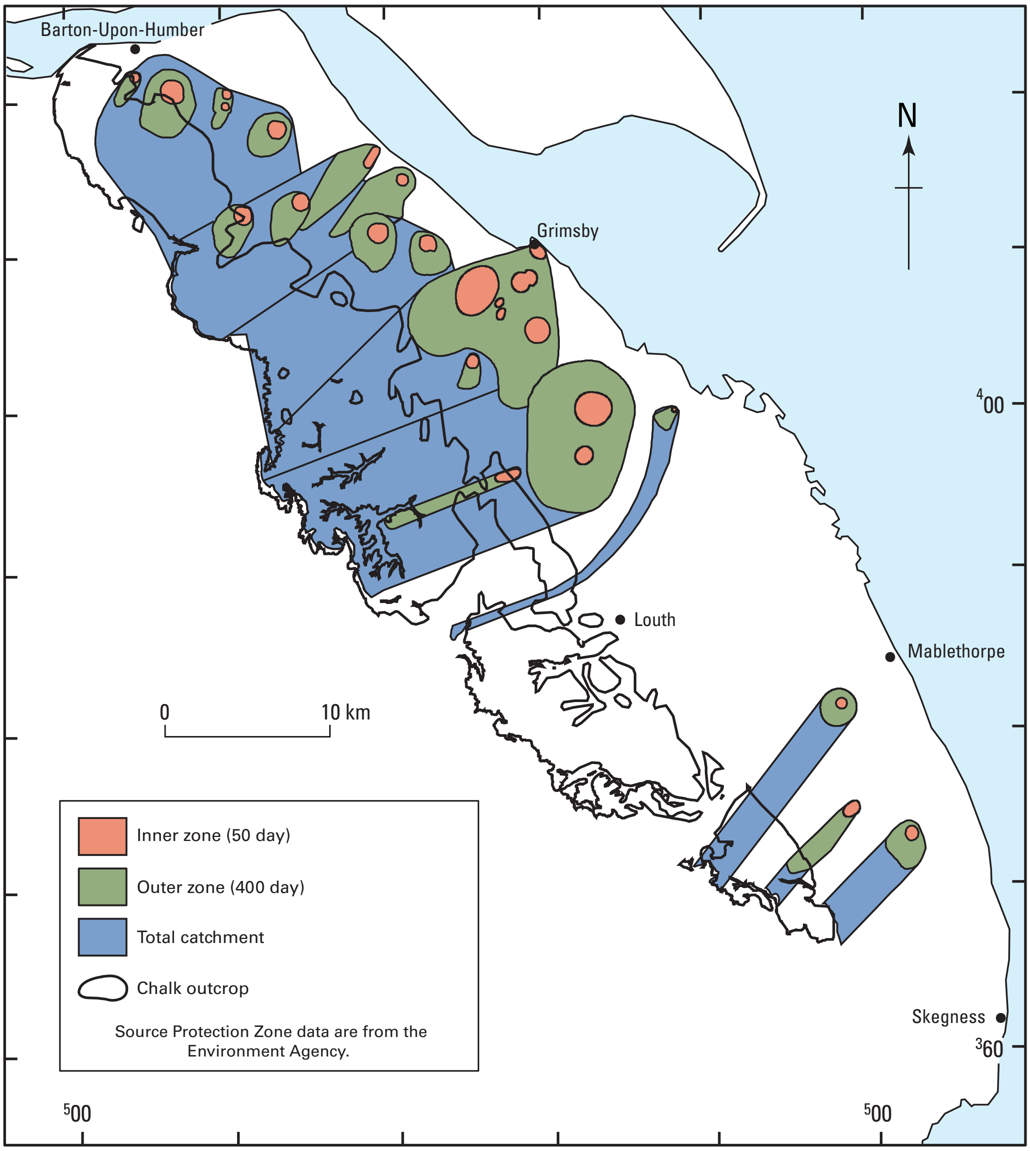
As of the year 2000, the Environment Agency produce a local environment action plan (LEAP) for each surface water catchment. The area in which the Lincolnshire Chalk aquifer system is present is covered by two catchments, Grimsby-Ancholme in the north and Louth Coastal in the south (Environment Agency, 1998a and 1999). The LEAPs are descriptions of the key environment issues in the plan areas, and of the state of the environment at the time of publication. They are plans which set out the work that the Environment Agency and others will do in the future to protect and enhance the environment of the plan area over the following five years. The process of local environment action planning is undertaken at a local level and although the LEAP is an Environment Agency document, other organisations such as local authorities, industry, conservation bodies, and other interested parties, are involved.

The key issues identified in the Grimsby-Ancholme and Louth Coastal LEAPs that are relevant to groundwater are low flows in baseflow-fed rivers and groundwater quality, with particular reference to contamination. The LEAPs also set out water resources management actions for the future, such as demand management.

5.3.5 River support schemes

Studies to determine how the negative impact of groundwater abstractions on surface water flow can be reduced have been carried out by the Environment Agency with co-operation from AWS. One approach is to use low flow alleviation boreholes, where groundwater is pumped and discharged into the stream to augment flow. The effectiveness of low flow alleviation boreholes can be assessed by measuring the net gain of the river support scheme. The net gain is a measure of the proportion of actual additional contribution to river flow. For example, if the augmentation boreholes are positioned too close to the river which they are intended to augment they will be intercepting water which would otherwise have flowed to the river naturally, and therefore will be of little benefit.

Figure 5.3 Source Protection Zones in the Lincolnshire Chalk area.



As of the year 2000, one river support borehole, on the Laceby Beck/River Freshney a few kilometres upstream of Grimsby, had been installed to augment flow when required. This work was funded by AWS to offset the impact of their abstractions on river flow.

River support boreholes have proved successful in other parts of Lincolnshire such as on the River Slea at Sleaford where water levels are maintained in the watercourse through pumping from the underlying Lincolnshire Limestone aquifer. The potential for other river support boreholes in the area, such as on the Waithe Beck, is being investigated.

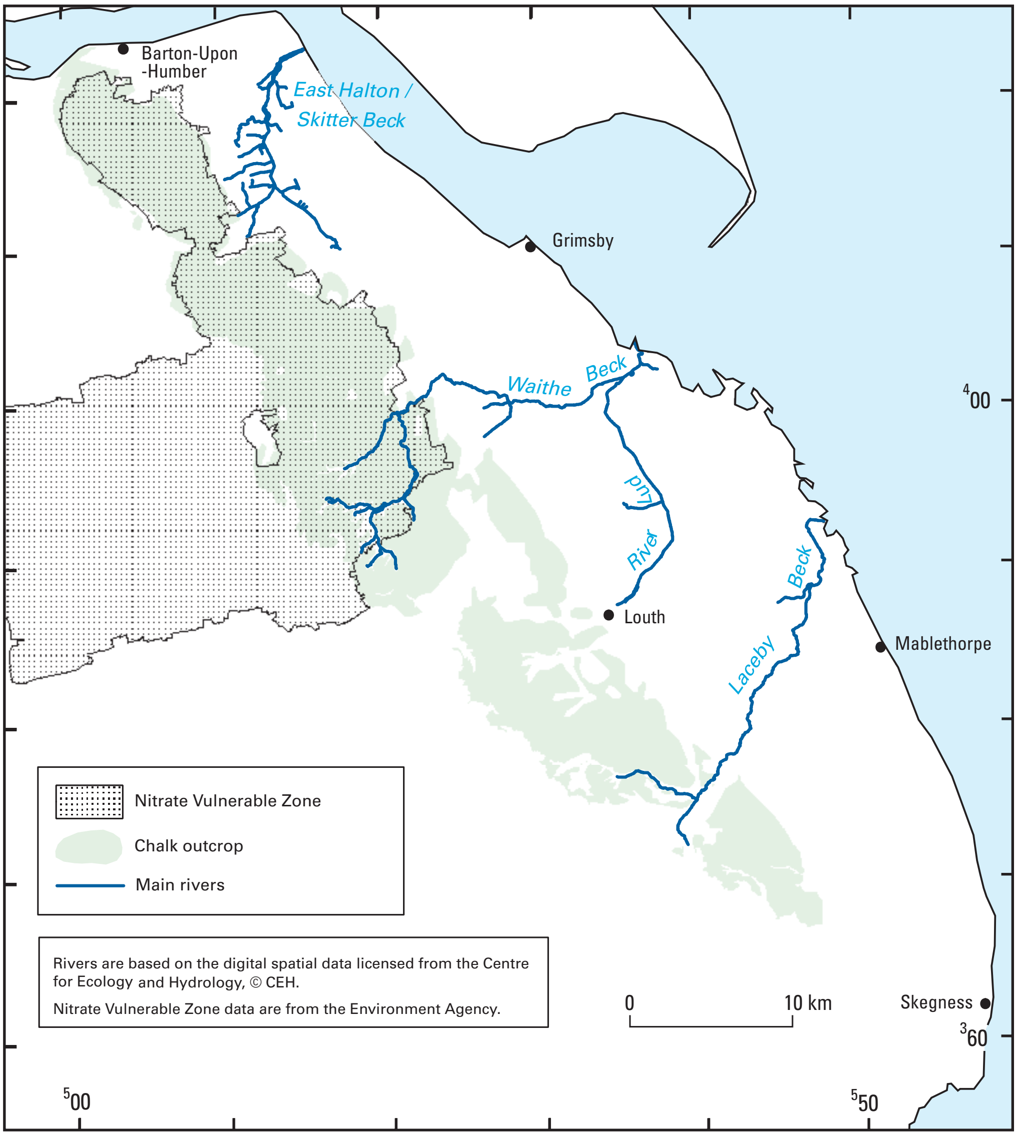
5.4 GROUNDWATER PROTECTION AND AQUIFER VULNERABILITY

5.4.1 Aquifer vulnerability, rapid flow and groundwater protection practices

An early project to map the vulnerability of the Lincolnshire Chalk aquifer to pollution was undertaken for the Anglian Water Authority by the Soil Survey and Land Research Centre (SSLRC) and the British Geological Survey in the 1980s. A series of maps entitled 'Soil and rock characteristics above groundwater' was produced to aid management of the nitrate problem. The maps identify 'groundwaters that are potentially sensitive to pollution by nitrate leaching from agricultural soils' (Palmer, 1988a). Land above aquifers was classified on the basis of the leaching characteristics and thickness of soil and drift cover, and given a rating of extreme, high, moderate or low. The classification 'indicates the relative rate at which percolating water and contained solutes can reach groundwater'. The Lincolnshire Chalk is covered by Map 1 North-west Lincolnshire (Palmer, 1988a) and Map 5 East Lincolnshire (Palmer, 1988b). The Wolds are generally classified as 'extreme' or 'high' vulnerability, due to the thin or absent drift cover, while the coastal plain, which is mostly covered by thick low permeability till, is predominantly classified as 'low'. This method does not consider depth to water table or local conditions such as soil structure, and the maps were therefore intended as a management tool rather than for use in field-scale studies.

In the 1990s, the National Rivers Authority (NRA) and the Environment Agency produced vulnerability maps covering the whole of England and Wales. The definition of vulnerability used by the Environment Agency and the method by which they classify aquifers is described in the 'Policy and Practice for the Protection of Groundwater' (Environment Agency, 1998b). Geological strata are

Figure 5.4 Nitrate Vulnerable Zones in the Lincolnshire Chalk area.



classified as major, minor or non-aquifers depending upon their permeability, the nature of the aquifer (e.g. whether it is fractured) and its productiveness. The vulnerability of major and minor aquifers to contamination is then classified by assessing the type and thickness of overlying soils. The Groundwater Vulnerability Maps Sheets 13 (Humber Estuary) and 19 (Lincolnshire), published by the NRA in 1994 and 1995 respectively, cover the Lincolnshire Chalk. The Chalk is classified as a major aquifer and as highly vulnerable across most of the Wolds and in near-coastal areas, while other areas have moderate to low vulnerability. However, these classifications do not take into account the thickness of low permeability drift which covers a significant part of the aquifer (although the presence of such drift is indicated on the vulnerability maps by stippling) and nor do they account for the thickness of the unsaturated zone. Such factors need to be considered when dealing with site specific issues.

The main European legislation intended to protect groundwater from contamination is the Groundwater Directive 80/68/EEC. This Directive is implemented in the UK mainly through the Water Resources Act 1991 and the Groundwater Regulations 1998. The Groundwater Regulations control the discharge of polluting matter to groundwater, particularly with regard to certain harmful substances. These substances, and groups or families of substances (e.g. organotin compounds) are classified under List I or List II; List I substances must be prevented from entering groundwater at any concentration (although exceptions can be made in some circumstances), while discharge of List II substances must be controlled so that, although some of the substance may enter the aquifer, pollution of the groundwater is avoided.

The nature of the aquifer determines what type of contamination it may be susceptible to. The confined zone of the Lincolnshire Chalk aquifer system is mostly protected from surface contamination by low permeability drift cover. The degree of protection depends on the nature and thickness of the overlying drift deposits, which can be variable; there are known permeable patches in the drift cover, such as around past and present blow wells. The outcrop zone is vulnerable as fractures give potential for rapid flow to the water table. However, where the unsaturated zone is thick, such as in the southern part of the aquifer, contaminants may take longer to reach the water table, in which case there is more time for attenuation to occur.

The Chalk has high transmissivities and flow is predominantly via fractures so there is potential for rapid flow between sources of contamination and abstraction points. The rapidity of the flow depends upon the distribution of the transmissivity. If the overall transmissivity is primarily due to the presence of a few very highly permeable pathways (often associated with present and past zones of water-table fluctuation), some of the flow will be extremely fast. If the transmissivity is made up from a very large number of smaller aperture fractures there will not be the potential for such high flow velocities. In reality, both scenarios are probably applicable to the Lincolnshire Chalk, as there are likely to be a spectrum of flow velocities, although little is known in detail about the distribution of transmissivity in the aquifer. One implication of rapid flow is that travel times between sources of pathogens and abstraction points may not be long enough for all pathogens to be removed from the water. Abstracted water is therefore routinely disinfected at all PWS sources to remove any potential pathogens. Some pathogens (notably *Cryptosporidium parvum*) are resistant to the normal methods of disinfection and recent legislation (The Water Supply (Water Quality) (Amendment) Regulations 1999) required a risk assessment to be carried out for each public water supply source in England and Wales. Any sources considered at significant risk of *Cryptosporidium* contamination have a more frequent raw water monitoring regime for *Cryptosporidium* in accordance with the regulations.

While it is important to protect all potentially exploitable or environmentally beneficial groundwater from contamination, it is also pragmatic to place a higher level of emphasis on protecting existing sources. Groundwater Source Protection Zones (SPZs) are defined by the Environment Agency for sources used for public supply, other private potable supply (including mineral and bottled water) and commercial food and drink production (Environment Agency, 1998b). Three zones are defined in the 'Policy and Practice for the Protection of Groundwater' (Environment Agency, 1998b). The zones are defined on the basis of travel times, i.e. how long it would take recharge reaching the water table to arrive at the source. Zone 1 is delineated by a travel time of 50 days, the time over which faecal indicator bacteria are reduced to very low or non-detectable concentrations by die off and dilution. Any recharge contaminated with pathogenic microbes occurring within this zone may therefore cause an unacceptable concentration of viable microbes at the groundwater source. It is, therefore, wise to minimise potentially polluting activities within this zone and thus activities like sewage sludge spreading or landfilling of waste are not permitted within Zone 1. Zone 2 is the 400 day travel time zone, while Zone 3 contains the entire catchment for the source.

The direction of groundwater flow and the properties of the surrounding strata determine the orientation, shape and size of SPZs. The zones are delineated by numerical modelling or semi-analytical techniques which assume uniform permeability and transmissivity to calculate travel times. Further information about this process is given by National Rivers Authority (1995) and Environment Agency (1996). However, in reality the Chalk aquifer has a spectrum of velocities associated with the varied aperture and distribution of the fractures. The manner in which the SPZs have been delineated in the Chalk aquifer is, therefore, simplified as a consequence of the lack of knowledge regarding the spectrum of velocities. This means that some recharge may be able to reach a borehole more quickly than predicted by the SPZs. The Environment Agency has recently undertaken a project to assess existing methods to develop a rigorous and defensible methodology for deriving SPZs in fractured/fissured aquifers (Robinson and Barker, 2000). The SPZs in the Lincolnshire Chalk area are shown in Figure 5.3.

In the late 1990s, two schemes were developed to protect groundwater through changes in farming practice to reduce the amount of excess nitrate leached from the soil, the Nitrate Vulnerable Zone (NVZ) and Nitrate Sensitive Area (NSA) schemes. Farmers volunteered to participate in the Nitrate Sensitive Area (NSA) scheme, for which compensation is offered. The catchment for three sources — Habrough, Healing and Little London — was a Nitrate Sensitive Area, however the NSA scheme ended in 2001 and this area is now designated solely as an NVZ. The Nitrate Vulnerable Zone (NVZ) designation is compulsory where groundwater quality is significantly threatened by nitrate from agricultural sources, as assessed by the Environment Agency (Figure 5.5). Farmers who are farming land within NVZs are required to comply with measures to control leaching of nitrate to rivers and groundwater.

Groundwater contamination can lead to sources being abandoned, or expensive treatment or blending schemes being installed. The costs of remediating a contaminated aquifer, treating water, or relocating sources can be considerable and are usually met by the consumer. Prevention of groundwater pollution is clearly the most cost effective policy, as emphasised by European and UK policy.

6 The present and the future

6.1 PRESENT-DAY SITUATION

The Lincolnshire Chalk aquifer system has been an important source of water for many years, providing water for public supply, industry and agriculture.

The Chalk aquifer is a dual-porosity aquifer with fractures that provide the transmissivity and the drainable porosity, while the water contained within the highly porous matrix is largely immobile due to the small size of the pore throats. The aquifer is thus characterised as a high transmissivity, low storage aquifer and is therefore susceptible to drought and vulnerable to contamination because of rapid travel times from the surface to the water table.

Due to the high transmissivity of the aquifer, borehole yields can be high: this, combined with the good quality of the water, led to the rapid growth of groundwater use. The increase in groundwater use together with the lack of control on abstraction resulted in problems of saline intrusion, as total abstraction approached and exceeded the safe yield of the aquifer during the late 1950s. This was exacerbated by major industrial abstractions in some coastal areas, such as Grimsby. The policy of those responsible for managing groundwater in the second half of the 20th century has been both to reduce abstraction where possible and to make use of surface water resources by utilising surface water transfer schemes.

The fact that the policy of abstraction reduction has been successful can be attributed to:

- the abstractors accepting that a serious problem of over-abstraction existed and that it was in the interest of all water users to reduce pumping
- the development of a groundwater model that has been used to manage water resources and control saline intrusion
- the acceptance by major water users that the groundwater model provides a reasonable representation of the groundwater system and that the reduction in abstraction that the Environment Agency requests to control saline inflow is both realistic and acceptable.

The use of groundwater models to manage the Lincolnshire Chalk aquifer was a pioneering development as this was the first area of the UK where numerical models were used routinely as management tools. This also provided a framework for a working agreement between the regulator and major abstractors to reduce abstractions.

While for much of the last part of the 20th century, management strategy has been focused on, and largely successful in, safeguarding the water resources and controlling saline intrusion, attention in the 1990s has moved to protecting wetlands and maintaining surface water flows for environmental and amenity value.

Another major issue facing the water industry has been rising nitrate concentrations, resulting from changing agricultural practices. National schemes to reduce leaching of nitrate from agricultural soils have been introduced in the Lincolnshire Chalk area. Even so, nitrate concentrations in some public supply boreholes continued to exceed the drinking water guideline level and treatment of such supplies is necessary. Other water quality issues that have been monitored and evaluated since the early 1990s include pesticides and microbiological parameters such as *Cryptosporidium*. While some efforts have been made to protect the aquifer from activities that might lead to contamination by pesticides and microorganisms (for example, providing farmers and other land users with codes of practice), these will never be entirely successful, particularly in an aquifer such as the Chalk where travel time from the surface to the water table can be very rapid. It is, therefore, practical to focus on protecting existing water sources through controlling land use within GPZs and, if necessary, treating the water before supply.

6.2 ISSUES THAT NEED TO BE ADDRESSED

6.2.1 Introduction

At the start of the 21st century the main driver for policy is the EC Water Framework Directive, which aims to

- protect, enhance and restore groundwater, surface water, environment and habitats
- ensure a good balance between abstraction and recharge
- to progressively reduce pollutant concentrations.

Particular emphasis will be placed on further reduction in groundwater abstraction where this is necessary to achieve the good status of associated waterways and terrestrial ecosystems. The Water Framework Directive required Member States to identify groundwater bodies (the Chalk will be subdivided on a catchment basis), characterise those bodies and report on their quantitative and qualitative status by December 2004.

Catchment Abstraction Management Strategies (CAMS) define environmental goals. Consultation with local people, water users and environmental groups is seen as an important stage in this process.

A major uncertainty for those attempting to manage future water resources is how climate change may affect the water cycle, in particular the volume and timing of rainfall.

6.2.2 Changing demand

The demand for water may be controlled by various factors including the cost of obtaining water, regulatory controls, technological advances and changes in land use. The Environment Agency, Anglian Region developed four demand scenarios incorporating potential changes in social values, systems of governance, the economy and technology (Environment Agency, 2001b). They found that overall future demand would rise in two of these scenarios (increase of up to 73% by 2025) but fall under the other two scenarios (decrease as much as 28% by 2025). For example, in the latter scenarios they predict a high or very high uptake of drought tolerant crops, reducing the irrigation demand. Demand for water is also predicted to fall with more widespread metering of household and industrial water use.

Industrial water consumption has fallen in the past as a result of the decline in heavy industry, and may change again in the future due to shifts in industrial practice, or through technological advances. AWS predict that demand for water will decline in the future due to better demand management.

6.2.3 Future management options

The main challenge in the future is to understand where sustainable abstraction fits with environmental concerns, particularly river flows and river ecology. Further research, such as that of Extence et al. (1999), will aid policy-making and help to achieve an acceptable balance. Greater understanding of the aquifer system will enable the Environment Agency and AWS to agree on optimum abstraction patterns and the most effective locations for river support boreholes. Similarly, improved knowledge of river ecology and the needs of fisheries will enable resources to be focussed on the most valuable stretches of river.

It is possible that, in the future, abstraction boreholes could be relocated to less environmentally sensitive locations. This has occurred in the Sleaford area of Lincolnshire, where the River Slea, predominantly baseflow fed by the Lincolnshire Limestone, suffers from low flow problems at times of low recharge. AWS's original abstraction boreholes are located close to springs feeding the river. In the early 1990s a new source was developed further east into the confined aquifer to reduce the impact of abstraction in the area on the river and also to benefit from lower nitrate water. In addition, the NRA installed a river augmentation borehole in the early 1990s as an additional measure to maintain flows through the town.

The conjunctive use schemes currently in place are aiding the environmentally responsible use of water resources in the area, with some water being imported from other catchments. The Environment Agency (1999) stated that 'with the introduction of water demand initiatives such as metering and leakage control, it is anticipated the combination of groundwater and surface water resources from outside the catchment will be sufficient to meet future forecast demand.'

The potential for Aquifer Storage and Recovery (ASR), where treated surface water is injected into aquifers at times of surplus, ready to be abstracted in dry periods, has been assessed by Jones et al. (1999). This technology has great potential to smooth out supply-demand imbalances, use small areas of land and have minimal environmental impact (Williams et al., 2001) and has frequently been used in aquifers containing poor quality groundwater. However, this technique is not ideally suited to dual-porosity aquifers such as the Chalk, as diffusive mixing occurs between the good quality injected water and poor quality matrix water, resulting in low recovery efficiency and hence a reduction in cost-effectiveness (Gale et al., 2002).

6.2.4 Climate change

The available evidence suggests that our climate is changing as a result of human activities, particularly emissions to the atmosphere. It is possible that resulting modifications to the pattern of rainfall and changes in temperature, and thus evapotranspiration, will affect UK groundwater resources in the future. Predicting the likely changes to our climate in the future is difficult, and translating these into possible effects upon water resources is even harder.

The Environment Agency undertook a study to assess the impacts of published climate change forecasts on the Lincolnshire Chalk groundwater system (Muten, 1997). Rainfall and potential evaporation (PE) values were generated for the different climate change scenarios by applying 'climate change factors' (percentages of historic values) to data for Lincolnshire for the period 1961–1997. The study then calculated recharge with the Lincolnshire Chalk recharge model (University of Birmingham, 1978), and input these values of recharge to the northern and southern Chalk Model (University of Birmingham, 1987). In the absence of forecasted values, the abstraction which actually occurred over the period 1961–1997 was used in this study. As expected, recharge varied substantially between the different climate change scenarios, as did the influence that these changes had on the groundwater resource. Further predictive modelling of this nature is likely to be undertaken as part of the Environment Agency's modelling strategy, which will include the development of a new integrated Chalk-Spilsby Sandstone model including better representation of groundwater-surface water interaction and streamflows.

As well as changes to the availability of groundwater and surface water, climate change may affect other water resource issues, such as the demand for water. If summers become hotter and drier as predicted by some, agricultural irrigation and garden watering demands are likely to rise. Cropping changes may occur in response to changing climate which could impact upon water demand and water quality (e.g. agrochemical usage).

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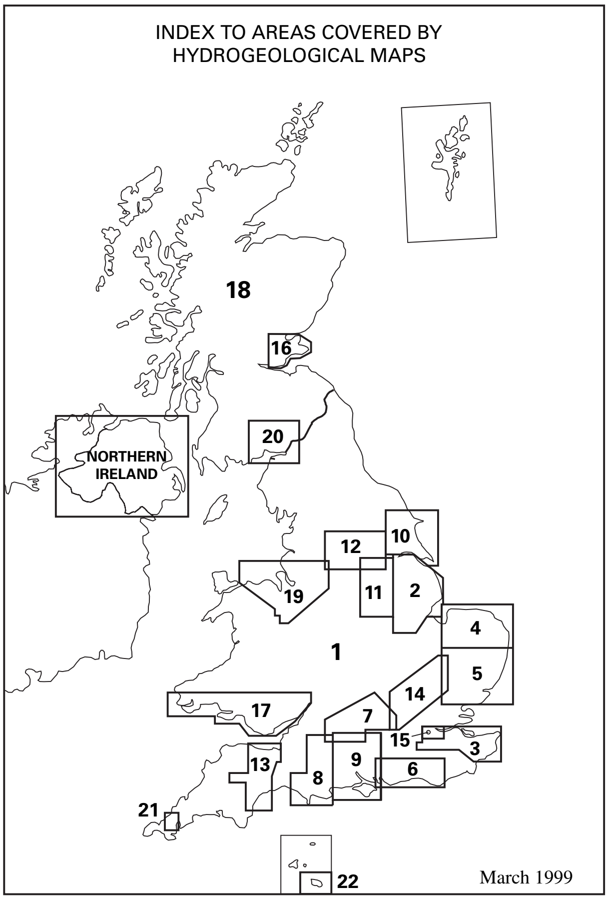

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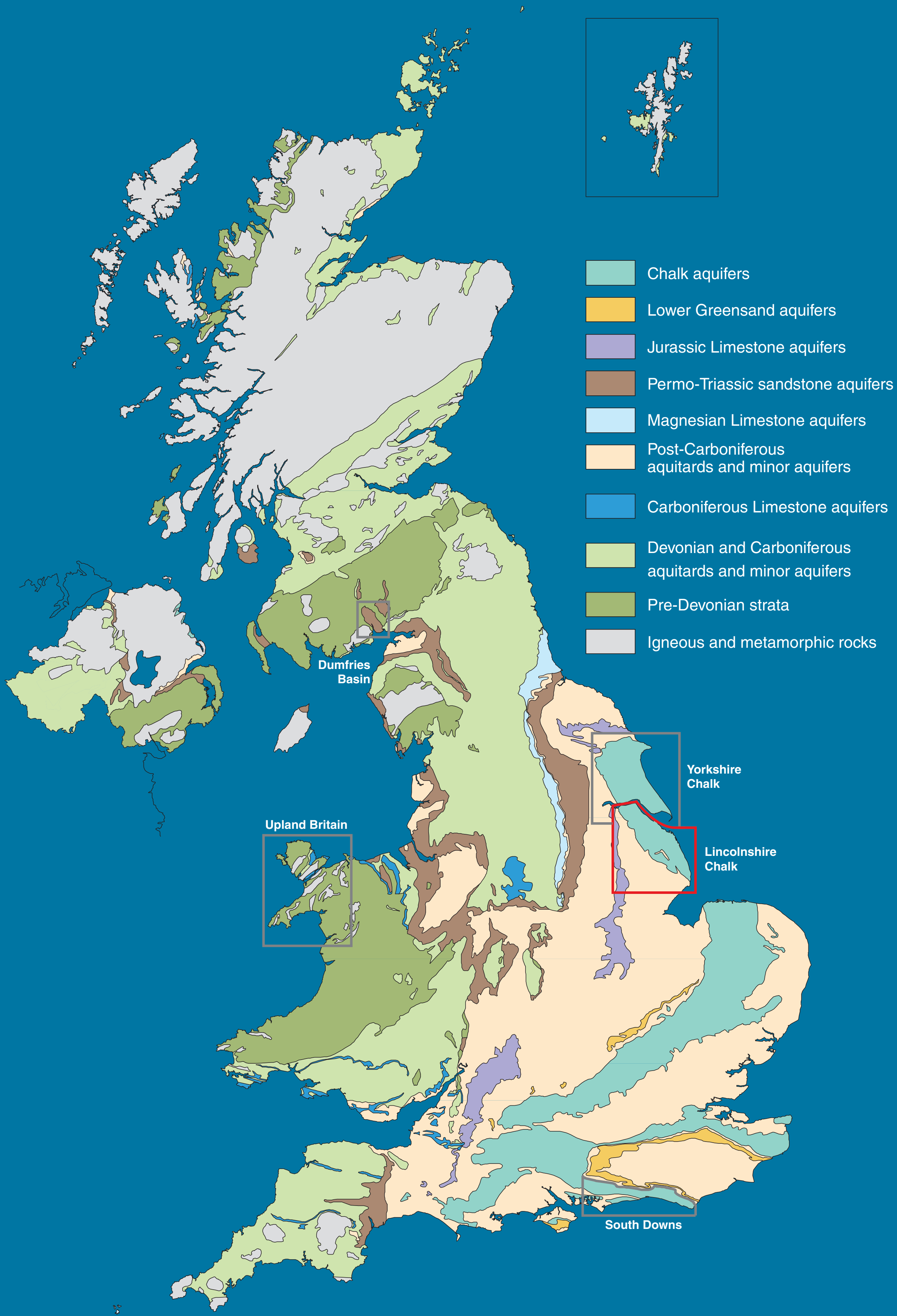

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