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The Chalk aquifer of Yorkshire

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The Chalk aquifer of Yorkshire

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Incised dry valley in the Chalk of the Yorkshire Wolds above Millington Spring.

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Preface

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

The study of the Chalk aquifer of Yorkshire was carried out in collaboration with the Environment Agency, Northeast Region, and Yorkshire Water plc. The report brings together information from published and unpublished sources and in addition includes new data collected from research undertaken by the BGS as part of the study in collaboration with Yorkshire Water and the Environment Agency. These additional studies included the drilling of an observation borehole at Carnaby Moor, in order to collect hydrogeological data, and a survey of the geochemistry of the groundwater in the area.

This report has been compiled from reports written by, and reviewed by hydrogeologists with extensive experience of development and management of the aquifer, from quantity, quality and protection perspectives. It, therefore, aims to summarise the current understanding of the hydrogeology of the Chalk aquifer in Yorkshire and provide a foundation on which further work can be based. To aid this objective a comprehensive bibliographic list of references forms part of the report.

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

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Of the many individuals who have contributed to the project and the production of this report, the authors would particularly like to thank the following: Dr J Aldrick, Dr D Chadha and colleagues at the Environment Agency, Northeast Region, for provision of data, reports and information as well as for supporting the collaborative studies at the Carnaby Moor Borehole, tracer tests at Kilham, and the regional survey of groundwater quality. Mr D Smith and Mr G Cachandt and colleagues at Yorkshire Water Services plc., for access to their archives of reports and data, and for commissioning the investigation into the nitrate concentrations in the Etton area. This was undertaken 17 years after the initial investigation and provided an invaluable set of comparative data that has enabled a better understanding of the processes controlling the movement of nitrate in the unsaturated zone.

Within the BGS, many colleagues have made contributions to fieldwork, core and water quality testing and analysis as well as report production for which the authors are grateful. Dr S S D Foster provided an excellent peer review based on his extensive experience in the area in the early 1970s.

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Executive summary

Groundwater from the Chalk aquifer in Yorkshire has been a major source of water supply in the development of the urban, industrial and agricultural infrastructure of East Yorkshire. At the beginning of the 21st century, the annual average abstraction is about 100 Ml d^{-1}; approximately one quarter of this being taken from the large adited sources around Kingston-upon-Hull. In the first half of the 20th century many industries in the area relied on groundwater from their own boreholes but the combined over-abstraction resulted in saline intrusion from the Humber. As boreholes began to produce brackish water, abstraction was reduced to a level to permit sufficient groundwater to flow to the Humber to maintain a static saline interface.

Development of the southern part of the aquifer has reduced artesian pressure and stopped springs flowing. However, in the northern part of the aquifer abstraction totals only about 7% of annual average recharge, the balance maintaining spring and river flows. Any further development of this resource would have to be balanced against the consequent impact on wetlands, spring and river flow in this very responsive groundwater/surface water interactive system. The southern half of the aquifer is more heavily developed to supply Hull, resulting in the cessation of spring flow in the area. For the whole aquifer the average annual recharge (1975–1992) is 719 Ml d^{-1}, 14% (105 Ml d^{-1}) being abstracted, largely for public supply, 31% (226 Ml d^{-1}) flowing to the North Sea and the Humber to balance saline intrusion, and about 55% (408 Ml d^{-1}) discharging to springs to maintain river flow.

The Cretaceous Chalk forms the Yorkshire Wolds rising to around 180 m and dipping to the south and south-east beneath a glacial cover reaching thicknesses of over 50 m in some parts of Holderness. The Wolds are characterised by dry valleys with springs in their lower reaches where covered by Devensian and Holocene deposits. The exception to this is the Gypsey Race which cuts through the Chalk in the north of the area to discharge at Bridlington on the coast. Flow in the Gypsey Race is intermittent and is dependent on groundwater levels rising to the ground surface.

The Chalk aquifer in Yorkshire is characterised by having a matrix porosity typically ranging from 20 to 35%. Lower porosities are associated with hardgrounds which reflect changes in sedimentation and burial diagenesis. Groundwater movement is determined by fracture porosity which may be less than 2%. Where enlarged through solution, fractures become highly productive, hence the practise of constructing horizontal adits from vertical shafts to intersect productive fractures. Solution enhanced fractures tend to occur in the upper 40 m of the saturated zone and can be controlled by bedding related horizons such as hardgrounds or current and former zones of water level fluctuation. Two major flow horizons have been identified in the Yorkshire Chalk, thought to be related to zones of water level fluctuation during the Holocene under a different hydrological and base (sea) level regime. The two horizons merge along the line of a buried Pleistocene coastline which can be traced along the edge of the Quaternary cover. This zone forms the edge of the confined part of the aquifer and is associated with springs discharging through thin, more permeable cover. There appears to be little groundwater movement beneath the Quaternary cover due to low hydraulic gradient and transmissivity (<50 m^2 d^{-1}) and. This is also demonstrated by the deterioration in groundwater quality beneath the Quaternary cover.

As with all carbonate aquifers where solution enhanced fractures dominate groundwater flow, the transmissivity of the Yorkshire Chalk is very variable both laterally and vertically. At Etton pumping station, pumping tests showed an increase in transmissivity from 1000 m^2 d^{-1} to 2200 m^2 d^{-1} when the groundwater level was 7 m higher and hence saturating a higher fractured horizon. The geometric mean of reliably measured transmissivity values in the Yorkshire Chalk aquifer is about 1250 m^2 d^{-1} but the range is from 1 to 10 000 m^2 d^{-1}, the higher values being found along the edge of the Quaternary cover and along dry valleys, although these values may be partly attributed to a breccia like deposit called chalk bearings. Yields from groundwater sources vary greatly from 4 to 7 Ml d^{-1} from large public supply boreholes to a potential licensed abstraction of 68.2 Ml d^{-1} from the adited source at Cottingham.

The complexity of the Quaternary deposits covering the Chalk aquifer in the east of the region and Holderness makes quantification of their impact on groundwater resources uncertain. Impermeable strata will inhibit recharge but will also protect the aquifer from pollution. To the east of the River Hull the Chalk aquifer is relatively inactive. However, within a kilometre or two of outcrop of the Chalk, springs discharge where the cover is thinnest or where sand and gravel deposits are present. Recharge in these artesian areas would not occur due to the upward movement of groundwater but where the gradient is reversed through pumping, recharge and pollution could occur. Within the Quaternary deposits, glacigenic sands and gravels form locally important aquifers, the use of which has declining due to the risk of pollution. These small groundwater bodies can significantly increase the available groundwater storage where in contact with the underlying Chalk aquifer.

The major towns on the Chalk aquifer, Kingston-upon-Hull and Bridlington, are located on the coast of the Humber and the North Sea respectively. Urban pollution of groundwater is therefore largely restricted to the coastal aquifer and, in the case of Hull, polluted by saline intrusion induced by over-abstraction. Apart from the inland towns of Beverley and Driffield located to the north of Hull, the area is largely rural and agriculture is largely arable. Thin permeable soils on the Wolds make the aquifer vulnerable to pollution from agricultural activities. Nitrate concentrations in groundwater in the unconfined Chalk aquifer have been rising steadily since the 1970s resulting in Millington Spring public supply source on the scarp slope having to be closed. Nitrate concentrations in dip slope sources, such as Etton, rose steadily during the 1970s but subsequently at a much lower rate of 0.05 mg l^{-1} NO_3–N per year. Pollution by pesticides and non-aqueous

phase liquids (NAPLs) are potential problems but, to date very few samples have had concentrations greater than EC guidelines. The majority of samples had concentrations below detection limits.

Implementation of aquifer protection policies and the designation of Nitrate Vulnerable Zones (NVZs) and Source Protection Zones (SPZs) have aimed to reduce the input at the ground surface, acknowledging that nitrate and other pollutants already in the aquifer, both the unsaturated and saturated zones, will take decades to pass through the system. Understanding the controls on the movement of nitrate and other pollutants from soil to borehole still warrants further research in order to optimise the management of the aquifer to meet water supply demands. This will include an understanding of the impacts of climate change on the water balance and hence groundwater flow as well as pollutant transport and degradation.

1 Introduction

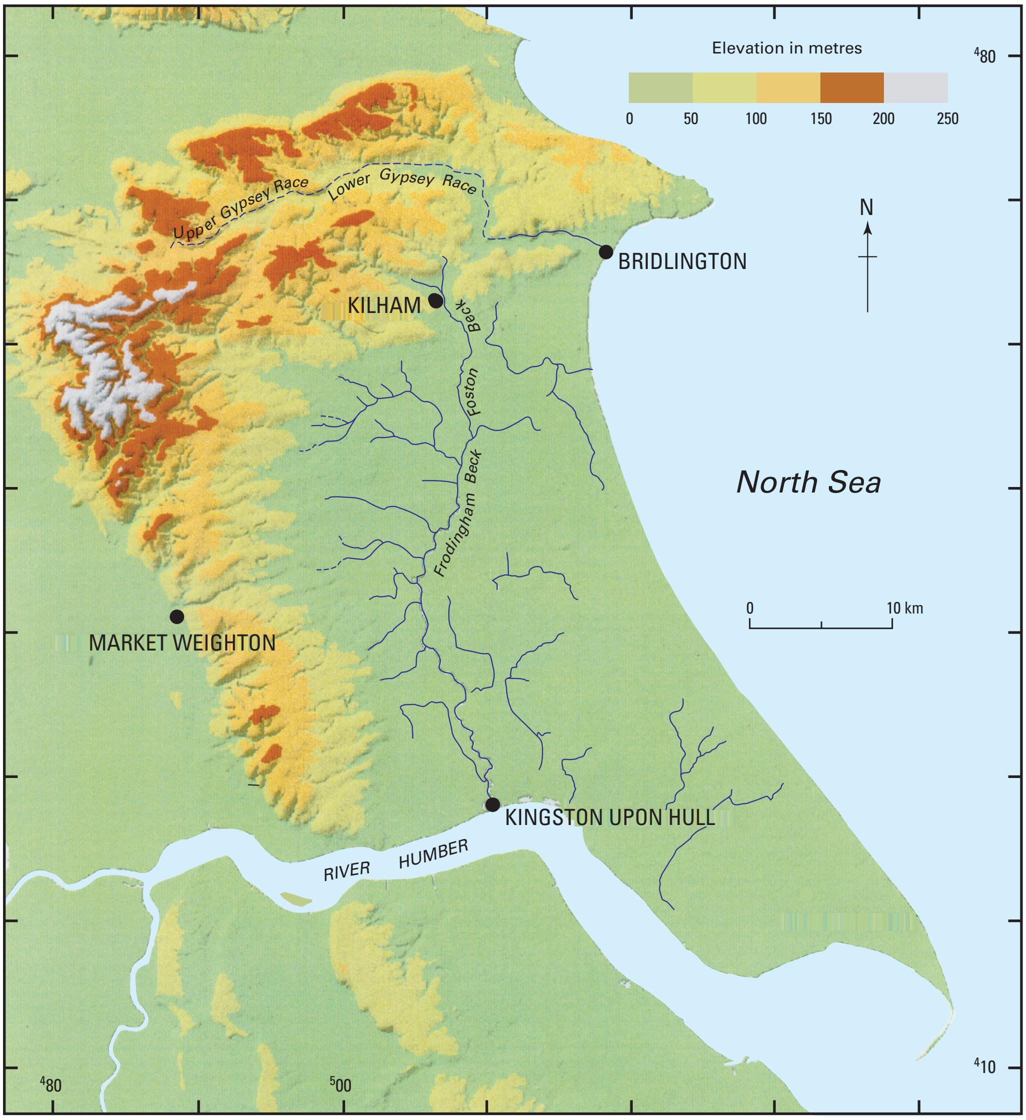
The Chalk outcrop in Yorkshire extends from Flamborough Head and arcs round to the River Humber, to the west of Kingston-upon-Hull. The outcrop forms the Yorkshire Wolds, which are typical Chalk downlands, consisting of a steep west- and north-facing escarpment, with a dip slope dipping gently south and eastward beneath Quaternary deposits, which thicken to the south-east. The upland areas reach elevations of around 180 m in the north-west, but are lower around the Humber Estuary. In the east, where thick Quaternary deposits cover the Chalk, the ground is a relatively flat, low-lying coastal plain, some of it with an elevation of only 1–2 m, draining towards the Humber Estuary and the North Sea. Figure 1.1 shows the major physiographic features of the region.

Precipitation is controlled orographically; the average ranging from below 600 mm per annum on the low-lying Holderness Plain to over 750 mm per annum over the highest parts of the Wolds (Figure 1.2). Average monthly rainfall ranges from 60 mm in the early summer to about 80 mm in the winter, the major recharge occurring in the first quarter of the year.

There is a network of dry valleys across the Wolds and there is little surface drainage on the outcrop, as the topography rarely intersects the water table; the only significant flow occurs in the Gypsey Race along the Great Wold Valley. During periods of high groundwater level the Gypsey Race runs along the entire length of the valley; at times of lower groundwater level the flow is increasingly intermittent, and during the late summer and extended periods of drought the entire Wold Valley becomes dry.

Springs rise in the lower reaches of the dry valleys and flow over the glacial drift to form the tributaries of the River Hull. The tributary system can be divided into two sub-catchments: the West Beck and the Foston Beck. These converge near North Frodingham to become the River Hull, which then flows south across the Holderness

Figure 1.1 Main physiographic features of the region.



Plain and through Kingston-upon-Hull to join the Humber. The River Hull is tidal below Hempholme Lock [TA 078 511]. A complex network of dykes, which considerably modify the catchment of the River Hull, drains the low-lying Holderness Plain.

Land use in the area is dominated by agricultural activity (Figure 1.3). Farming is dominantly arable over the Chalk outcrop and soils are light-textured and free-draining (rendzinas and brown earths). Soil thickness varies from about 0.2 to 1.0 m (Foster and Crease, 1974). Soils grade to more clayey compositions, with higher proportions of alluvium further eastwards where underlain by drift.

Cereal crops, mainly wheat and barley, dominate the arable production in the area; comprising about 60% of the 166 000 ha under arable crops. Grassland comprises about 15% of arable land, oilseed rape (7%) the remainder being sugar beet, potatoes, vegetables, peas and beans. Set-aside has also become important in recent years, amounting to some 10% of the arable land cover in the Etton and North Newbald catchments (Chilton et al., 1997). Pigs and poultry, much being free-range, dominate animal farming and sheep are also important, particularly in parts of the upland Wolds where the terrain is steeper. Dairy and beef production is important locally, as is glasshouse horticulture in the Hull–Beverley–Driffield area. Manufacturing is concentrated around the urban centres, particularly Hull, and is dominated by the food processing industry.

Groundwater has been exploited in Yorkshire for centuries through the use of springs and digging of wells especially in the Chalk where there is little surface water. Village wells can still be seen in many of the Wolds villages, often with an old ‘cow tail’ pump.

The city of Kingston-upon-Hull, (referred to as Hull) built as a ‘new’ town in the fourteenth century, relied on a large spring from the Chalk to provide it with a reliable water supply. The water was brought to the city along a canal and, even at this early stage of development, disputes over water rights occurred between the urban and the rural populations.

Victorian developments to provide an enhanced and ‘safer’ supply resulted in the construction of large pumping stations with shafts and adit systems dug into the Chalk, and the steam powered pumps to raise the water. These pumping stations provided large quantities of water but they also caused a lowering of the water table and the cessation of some spring flows.

The over-exploitation of groundwater for public water supply and industrial use in the Hull area of the Wolds resulted in saline intrusion from the Humber, which affected some of the industrial boreholes closest to the estuary. A reduction in industrial abstraction combined with a controlled abstraction regime has stabilised the situation. Other issues in the area include diffuse nitrate pollution and occasional occurrences of pesticides and organic compounds, such as chlorinated solvents, in groundwater.

Figure 1.2 Isohyets of long term average rainfall (1969–1990).

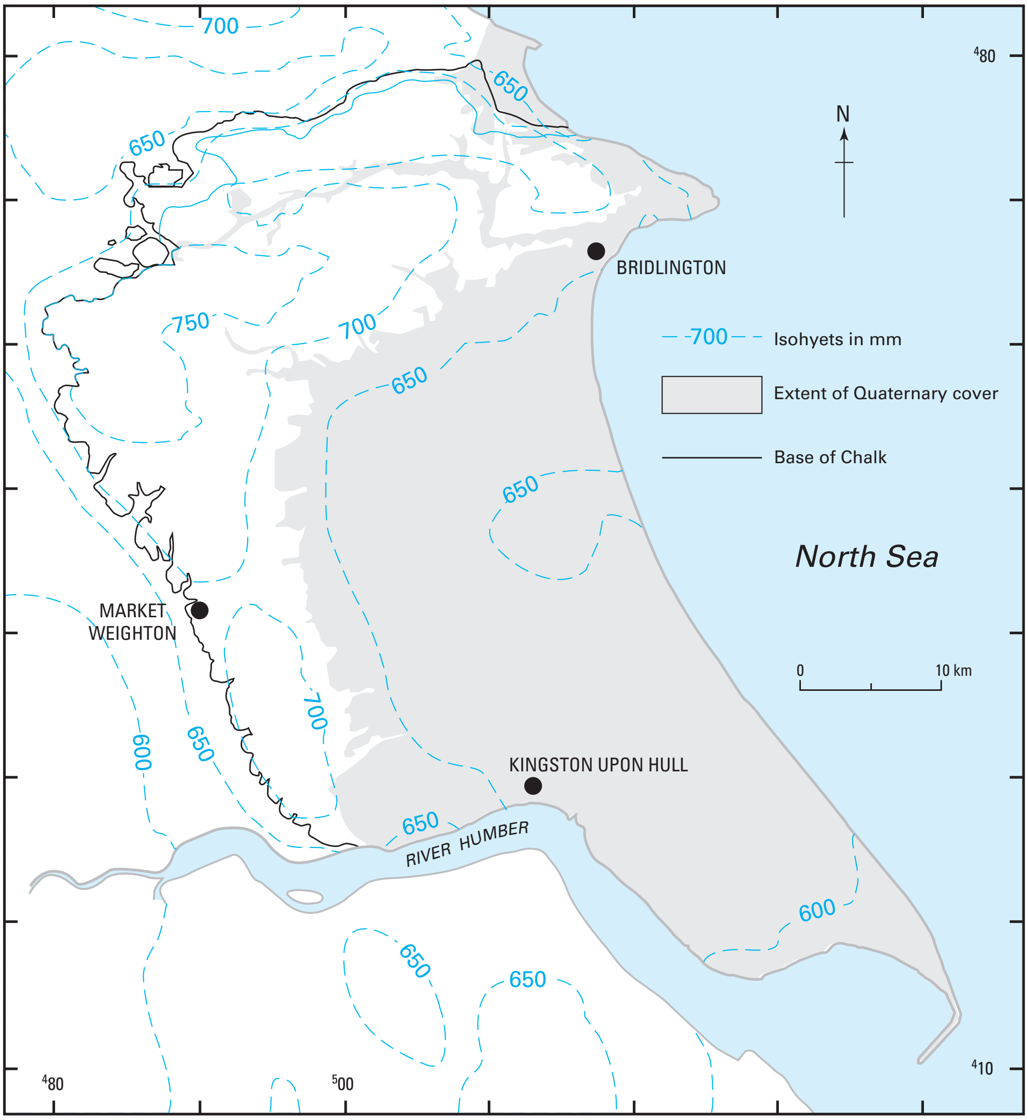
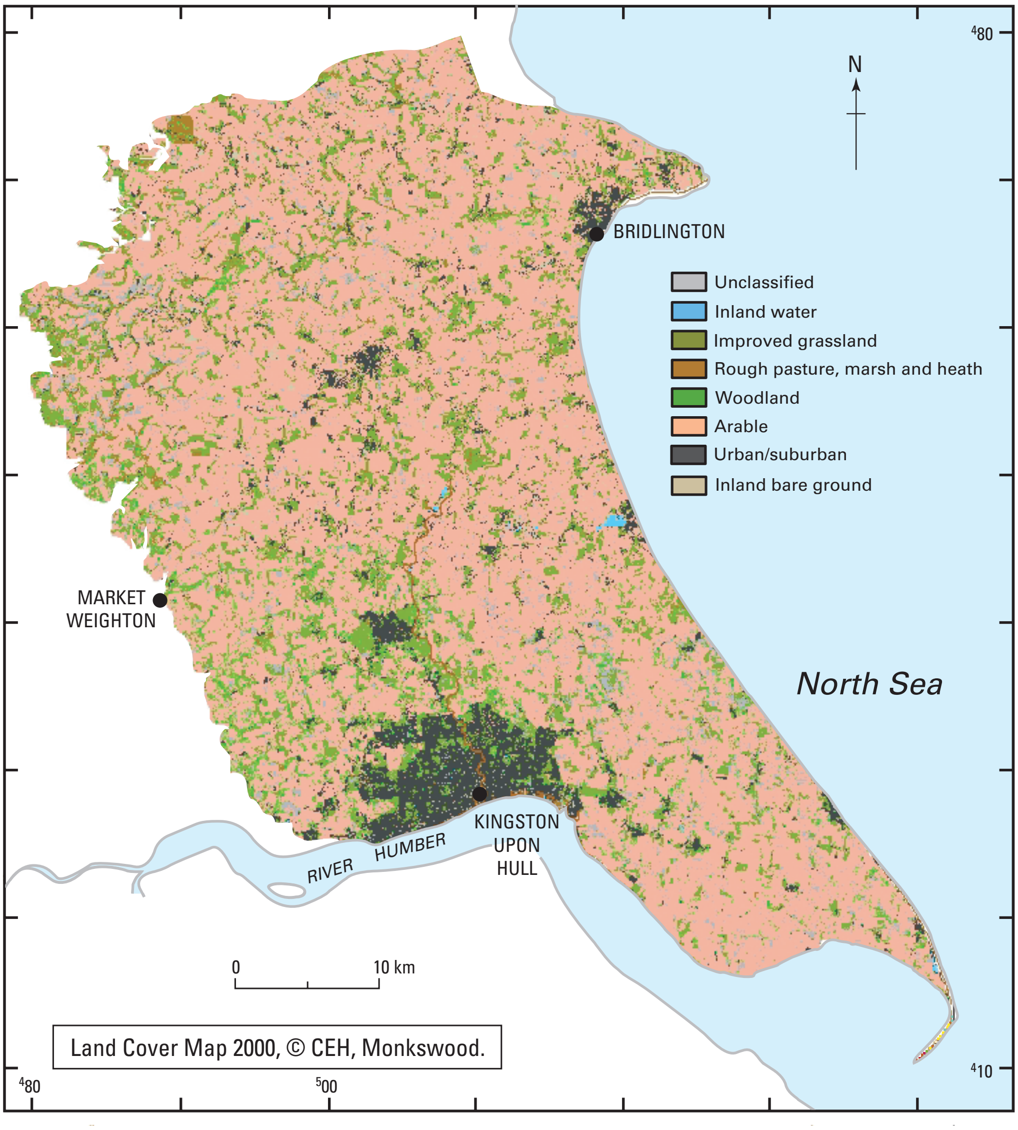


Figure 1.3
Distribution of major land-use cover.



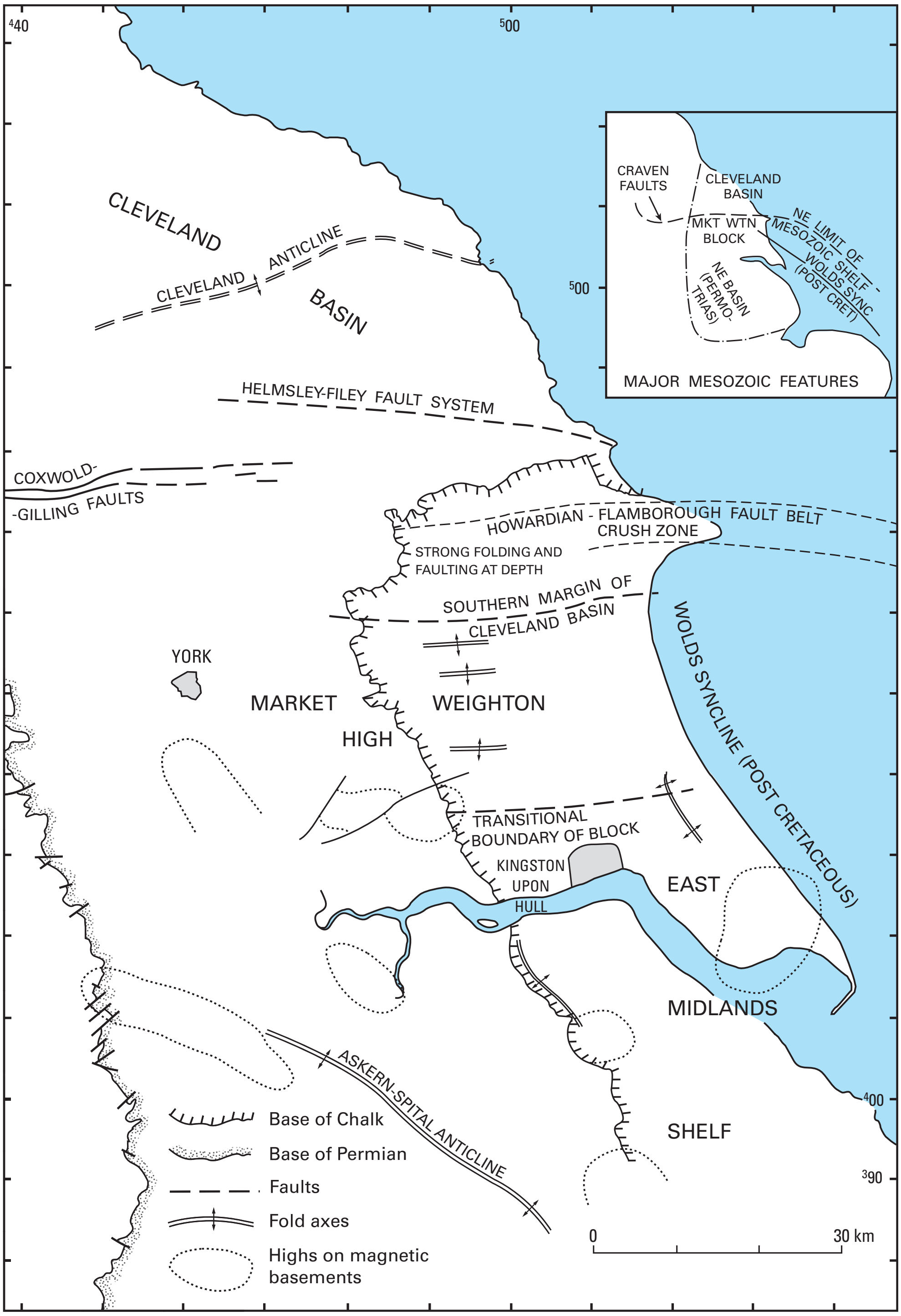
Land Cover Map 2000, © CEH, Monkswood.

2 The geological setting

2.1 GEOLOGICAL HISTORY OF THE REGION

Lower Palaeozoic sediments are present at depth across much of the region, with the most extensive basement rocks being of Carboniferous age (Kent, 1980b). During the Early Permian, desert conditions prevailed and dune sands were deposited and gravels accumulated in shallow wadis. Subsequent flooding by the Upper Zechstein Sea deposited sediments of variable facies including limestones, dolomites, marls and evaporites. The Zechstein Sea had withdrawn by the Early Triassic and a thick succession of sandstones, the Sherwood Sandstone Group, were laid down by rivers that flowed across the region. Later in the Triassic another hypersaline sea developed in the east, depositing the red mudstones, dolomites and evaporites of the Mercia Mudstone Group. In the latest

Figure 2.1 Regional tectonic features of Yorkshire.



Triassic, a transgression created open sea conditions in which the, largely argillaceous, Penarth Group was deposited. The transgression continued into the Jurassic period and the dark mudstones and thin, silty limestones of the Lias Group were deposited. Subsidence of the fault-bounded Cleveland Basin (Figure 2.1) led to the accumulation of substantial thicknesses of Lias sediments in north Yorkshire, whereas, lesser subsidence of the East Midlands Shelf to the south led to a somewhat thinner successions. The so-called Market Weighton High, near the northern margin of the East Midlands Shelf, was an area of particularly reduced subsidence and the Lias succession thins again in this area. The Middle Jurassic sediments are thickly developed in the Cleveland Basin but farther south the sediments belonging to the Inferior and Great Oolite groups thin and die out towards the Market Weighton High. Later Jurassic strata comprise sandstones and mudstones of the Ancholme Group, present in the Cleveland Basin and south Yorkshire but, again, absent across the Market Weighton High.

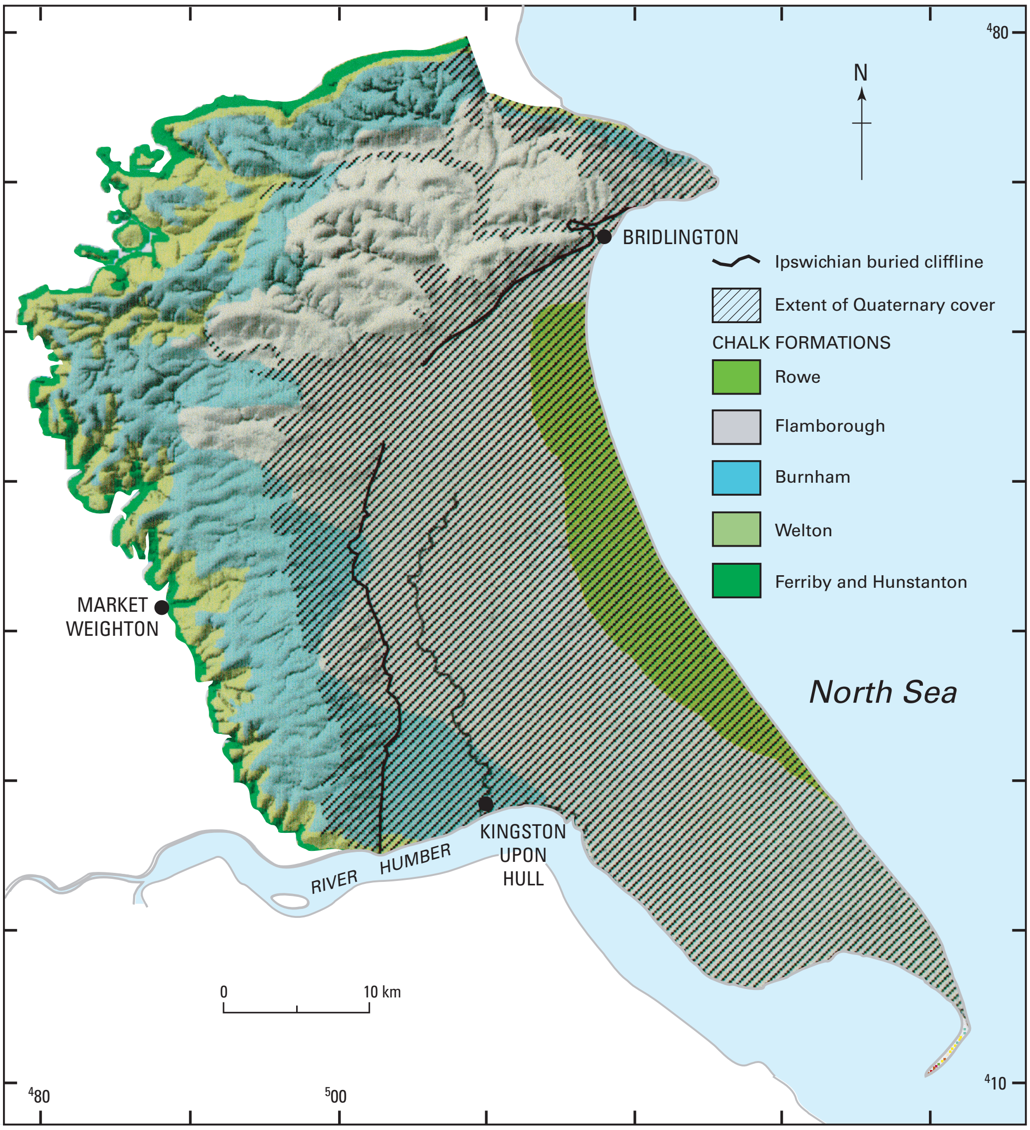
Late Jurassic and earliest Cretaceous deposits are absent due to Cretaceous erosion over most of the area. Younger Cretaceous beds rest directly on Jurassic strata, cutting down into the lower part of the Lias Group over the Market Weighton High. During the latter part of the Early Cretaceous, a marine transgression led to the deposition of the thin gritty sandstone of the Carstone Formation, succeeded by the Hunstanton Formation previously commonly known as the Red Chalk. The transgression continued into the Late Cretaceous period with deposition of several hundred metres of white chalk. By this time the Market Weighton High had more or less stabilised, but thickness variations in the component formations of the Chalk Group suggest that it still influenced subsidence rates.

A general phase of uplift occurred in the Late Cretaceous and Tertiary periods across most of the British Isles causing folding of the Chalk in the Yorkshire region. As a result, the rocks form a gentle syncline that dips to the south-east. The Chalk land surface was modified significantly by glacial erosion and deposition from ice sheets and melt-waters during the Quaternary. Holocene (or Recent) deposits include the silts and peats of Holderness and Humberside and reworked coastal material continues to be deposited along the Holderness peninsula at Spurn Head.

2.2 REGIONAL STRUCTURE OF THE CHALK

The Chalk Group forms the Wolds scenery of the Yorkshire and the spectacular cliffs, over 100 m in height,

Figure 2.2 Top of the Chalk Group showing the distribution of the formations, the extent of the Quaternary cover and the buried cliff line.



where the Wolds meet the coast between Flamborough and Speeton. The Chalk is buried beneath Quaternary deposits in the eastern part of the region, mainly Devensian (late Pleistocene) tills, sands and gravels of glacial origin, and Holocene (post-glacial or Recent) coastal and marsh sediments. These Quaternary deposits, forming the lowland areas of Holderness, are commonly some 20 to 30 m thick along the coast, and locally exceed 50 m in the southern part of Holderness. A former sea-cliff, of pre-Devensian age, can be traced beneath this cover several kilometres inshore of the present coastline; it meets the modern coast at Sewerby, near Bridlington, and intersects the Humber at Hessle and Barton. Figure 2.2 shows the surface topography in which the buried cliff-line is clearly visible through the overlying drift deposits.

Because of the predominantly eastward dip, the greatest thickness of Chalk preserved onshore occurs beneath Holderness, with over 500 m present at Hornsea, where the youngest Chalk strata of the region are found. Succeeding beds are represented offshore, where the succession expands to over 800 m of Chalk some 40 km off the coast in a Late Cretaceous basin adjoining the Sole Pit Trough.

The structure contours of the base of the Chalk in Yorkshire and North Lincolnshire are shown in Figure 2.3. The Chalk is folded into a very broad, open syncline, known as the Wolds Syncline (Donovan, 1968), which plunges very gently (average about 1°) towards the east and south-east along an axis between Driffield and Bridlington. The syncline extends into the North Sea and the eastern limb abuts the Flamborough Anticline and the Dowsing Fault Belt, approximately 50 km offshore (Donovan and Dingle, 1965; Kent, 1980a, 1980b). Across much of the southern and central part of the region the Chalk forms the south-western limb of the syncline and dips fairly uniformly to the north-east, away from the escarpment of the Wolds, with an average dip of approximately 1° (i.e. 15 to 20 m per kilometre). In the north-east of the region the Chalk forms the north-eastern limb of the syncline and dips to the south-west.

Kent (1974), Neale (1974), and Foster and Milton (1976) also described a series of minor fold axes that plunge concordantly with the main synclinal structure. Gentle synclines occur in the Chalk in the vicinity of Southburn [SE 99 54] and Beverley [TA 03 40], and there are anticlines at Kelleythorpe [TA 02 56] and Scarborough. Neale (1974) has suggested that they are all controlled by structures in the underlying Jurassic rocks.

Contours on the base of the Chalk to the south of the Humber are offset slightly by the Caistor Monocline, in North Lincolnshire (Barker et al., 1984; Berridge and Pattison, 1994), an east–west trending structure that can be traced eastwards from the Chalk outcrop through to the coast at Grimsby (Berridge, 1986; Berridge and Pattison 1994).

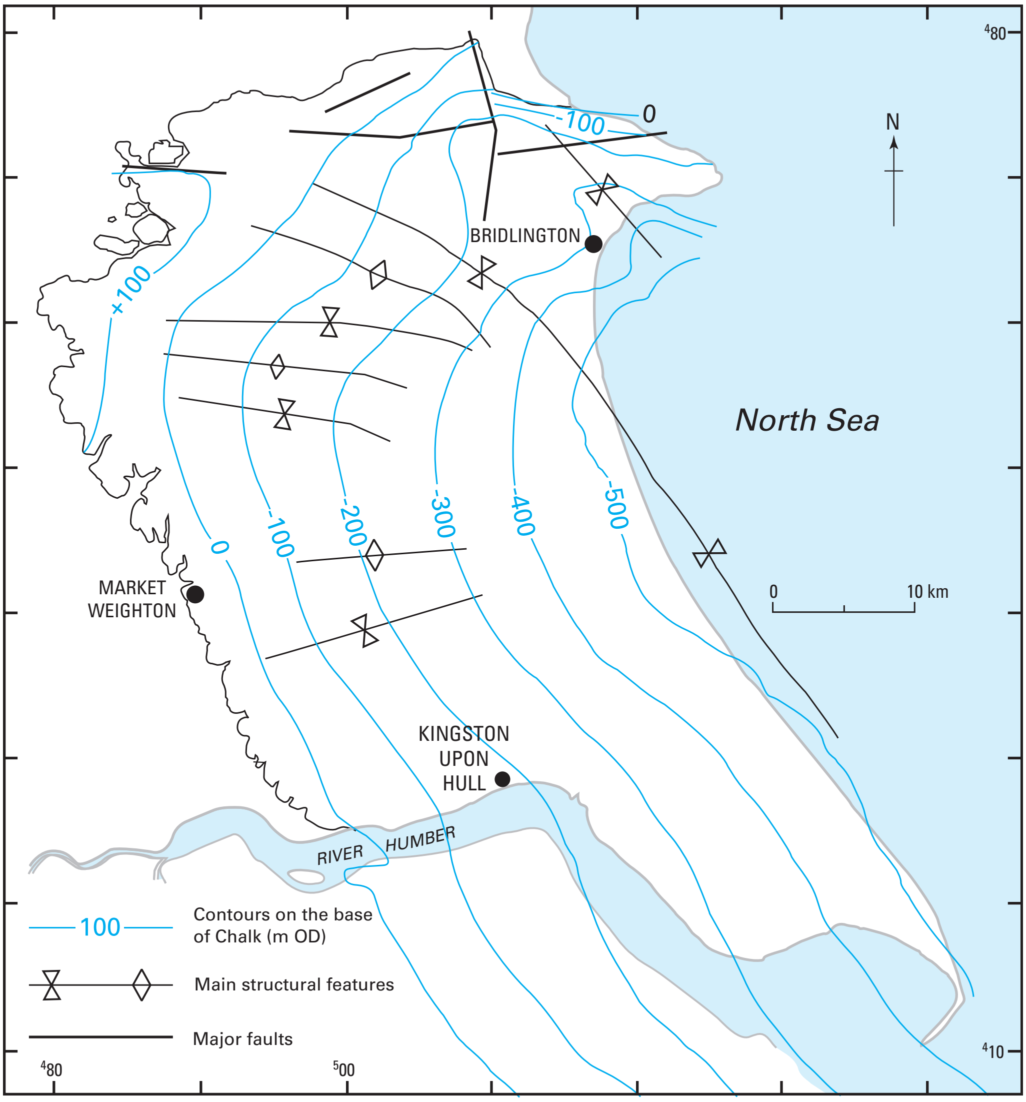


Figure 2.3 Structure contours on the base of the Chalk Group showing the main structural features.

An apparently complementary offset in the structure contours on the base of the Chalk across the River Humber was thought by Versey (1946) to be due to a 'Humber Fault'. However, the offset is now believed to relate to cambering of the Chalk strata into the Humber Valley (Gaunt et al, 1992), but seismic data from the mouth of the Humber Estuary (McQuillin et al., 1969) suggest the presence of a north-facing monocline beneath the Humber. A minor east–west trending fold is seen near Winestead, immediately north of the Humber (Berridge and Pattison, 1994). This fold is associated with an underlying pre-Cretaceous fault with a downthrow to the north.

The Market Weighton High marks an area of relative uplift that affected Jurassic and Early Cretaceous sedimentation. The Chalk Group is considerably thinner here, the changes being particularly noticeable in the lower parts of the group. To the north of this area, the dip swings round towards the south-east, and at Flamborough, the formation dips 3 to 5° to the south or south-south-west. This zone of steeper dips is associated with a zone of minor faulting and flexuring that can be traced westward across the Wolds towards Malton. Known as the Howardian–Flamborough Fault Belt (or Crush Zone), it relates to the buried southern margin of the Cleveland Basin (Kirby and Swallow, 1987; Rawson and Wright, 1992; Peacock and Sanderson, 1994) in which a thick succession of Jurassic and Lower Cretaceous sediments accumulated and were uplifted (inverted) during later Cretaceous times. The most northerly Chalk outcrops of the region lie on the margins of the Cleveland Basin; the lower part of the Chalk Group expands significantly into the basin, and is substantially thicker than in the areas of the Market Weighton High. Higher parts of the succession may also have been affected, but they are no longer preserved.

Part of the Howardian–Flamborough Fault Belt is exposed on the coast where a fault zone runs east–west through the middle of Selwicks Bay [TA 254 708]. It is associated with local steepening of bedding, brecciation, extensive calcite veining and the development of vuggy porosity. Patsoules and Cripps (1990) and Rawson and Wright (1992) suggested a minimum downthrow to the north across this zone of approximately 20 m. Farther north the Old Dor disturbance, or Bempton Shatter Zone [TA 213 733], is a 300 m wide zone of contorted beds with dips as high as 70°. There is little vertical displacement across this zone (Kirby and Swallow, 1987). A quarry at Langtoft [TA 012 659] shows dips of up to 50° associated with a zone of brecciated and calcite-veined chalk, and structures have been interpreted as reflecting re-activation of the east–west trending Langtoft Fault. Rawson and Wright (1992) have also described a shatter zone exposed in a quarry at Foxholes [TA 012 735], where bedding dips at about 70° to the north.

North–south oriented faulting occurs inland from Flamborough Head. The Hunmanby Fault (Figure 2.3) trends north–south between Fordon and Hunmanby, has a downthrow to the east and displaces the Chalk escarpment to the north of Hunmanby. The fault is believed to have been active in the Early Cretaceous period as it apparently controlled the thicknesses of the Speeton Clay and the Hunstanton Formation (Neale, 1974). In the extreme north-west of the Wolds, borehole evidence suggests the presence of a large fault of unknown orientation in the vicinity of Thixendale and Burdale (Foster and Milton, 1976).

Smaller folds and faults are common throughout the Chalk. These disturbances are seen in quarry or cliff exposures but have little surface expression. Where exposed, these small structures often occur in areas of flat-lying strata and consist of narrow belts of strong folding and intensified fracturing but without appreciable throws (Foster and Milton, 1976). Some of these structures probably result from the development of ground ice during the glacial phases of the Quaternary Period. Rawson and Wright (1992) have described minor folding from the north end of Selwicks Bay, mainly developed above décollement horizons formed by thin marls. It is thought that these small-scale folds associated with local displacements on marls may be common throughout the entire Wolds Syncline.

2.3 CHALK LITHOLOGY AND FAUNA

The Chalk Group comprises carbonate-rich sediments, which were deposited in a shelf sea that covered much of north-west Europe for some 40 million years in the later part of the Cretaceous period. Chalk, the predominant sediment of the Chalk Group 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), foraminifera tests, and shell debris from larger creatures such as bivalves and echinoderms. At some current-winnowed horizons the chalk is composed largely of this coarser shell debris, with little or no coccolith component.

The English Chalk is best known from its southern outcrops in the Chilterns, North and South Downs, and from the coastal sections of Kent and Sussex, which fall within the so-called Southern, or Anglo-Paris Basin, Province. The Chalk of Yorkshire and Lincolnshire, and beneath the adjoining North Sea, falls within a loosely defined Northern Province and in many ways has more in common with correlatives in Germany and areas farther east than with the Chalk of the Southern Province. There are significant differences in the fossil faunas in the two provinces, with a generally lower diversity in the north, which may suggest accumulation in deeper waters. In some cases, different zonal index fossils have been used in the two provinces. More importantly, there are differences in the lithological characteristics of the strata and in details of the stratigraphy, such that it is appropriate to use different lithostratigraphical classifications.

The chalks of the Northern Province are typically hard and thinly bedded compared with the relatively soft, more massive chalk of the south. This hardness is a result of pressure solution of carbonate, and its redeposition as calcite cement in the pore spaces of the sediment. Stylolites (intricately sutured bed junctions), also common in northern chalks, are another manifestation of solution at specific horizons in already lithified sediments. 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.

Tabular flints are more common in the Chalk of the Northern Province than in southern England, and the flints are typically pale grey or white in colour, in contrast to the dark grey or black nodules of the Chalk in the southern Province. The flints may also have poorly defined margins, merging with the surrounding chalk, and may be difficult to see in exposures.

Most of the Chalk is extremely pure. However, the lower part (Hunstanton and Ferriby Chalk formations) is characterised by marly chalks and marls containing a substantial proportion of clay minerals such as montmorillonite and illite, together with small amounts of detrital quartz and feldspar. The chalks higher in the sequence are generally purer with non-carbonate contents typically only about two per cent, although the clay minerals may be concentrated in discrete marl seams. These, though typically no more than a few centimetres thick, are generally persistent laterally, and are valuable in correlation, particularly because of the distinctive peaks (high gamma, low sonic, low resistivity) which they produce on geophysical borehole logs (Barker et al., 1984; Murray, 1986). Some of the marl bands probably represent contemporaneous volcanic ash falls (Pacey, 1984), but others may result from a temporary increase in the supply of terrigenous detritus. Mortimore and Wood (1986) and Gaunt et al. (1992), discuss the likely correlation between the marls found in Yorkshire and those in the Southern Province.

Flints, a form of cryptocrystalline quartz, are generally associated with the purer chalks. Flint formed at an early stage of diagenesis, though at some depth below the sea-floor (Clayton, 1984). The silica was derived from the skeletons of sponges, radiolarians and diatoms, which dissolved in the generally alkaline environment of burial. Decomposing organic matter gave rise to localised acidic conditions in which the silica was re-precipitated, 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, particularly *Thalassinoides*, where the shape of the flint nodule reflects the original burrow morphology. Giant vertical flints known as 'paramoudras' formed around the tiny burrow-trace *Bathichnus*. 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 and form useful marker-horizons, and like marl seams, are often very prominent on borehole geophysical logs (low gamma, high sonic, high resistivity). In addition to the nodular and tabular forms, flint may also occur as sheets, lining fractures at various angles to the bedding.

The fossils found in the Chalk indicate that the sediments were deposited in a fully marine subtropical environment. Much of the succession is relatively barren of macrofossils, and those that do occur are forms such as brachiopods, inoceramid bivalves and echinoids, which have calcite shells. Fossils such as gastropods and the biostratigraphically important ammonites, with aragonite shells, are extremely rare. This is probably a result of early dissolution of their shells and may be an indication of deposition in relatively deep water (perhaps up to 300 m deep). Because of the rarity of ammonites in much of the higher part of the succession, the traditional zonation of the Chalk is based on a combination of brachiopods, bivalves, crinoids and echinoids. In most cases, the boundaries of these zones are poorly defined, and their precise relationship to the internationally recognised ammonite zones is uncertain. For this reason, detailed correlation is best achieved using lithological marker bands, notably the marl seams.

2.4 THE STRATIGRAPHICAL SUCCESSION OF THE CHALK

2.4.1 Background

The Chalk Group of England has traditionally been divided into three 'formations', the Lower, Middle and Upper Chalk (Table 2.1; Jukes-Browne and Hill, 1903; 1904). These units are based essentially on the recognition of marker beds including the Melbourn Rock and the Chalk Rock, which both occur at significant boundaries in the Southern Province. These marker beds do not occur in the Northern Province, and consequently the traditional classification of the Chalk has been difficult to apply. For this reason, the main part of the Chalk succession, as originally mapped by the Geological Survey in the nineteenth century, was subdivided into three parts based only on the presence or otherwise of flints.

Wood and Smith (1978) introduced a revised scheme of classification of the Chalk Group, which divided the Chalk Group of the Northern Province into formations, in ascending order, the Ferriby, Welton, Burnham and Flamborough Chalk formations, respectively some 25 m, 50 m, 150 m and 260 m in thickness. In the updated scheme, the basal part ('Red Chalk') of the Ferriby Chalk Formation is treated as a separate entity named the Hunstanton Formation. The current recommendation (Hopson, 2005) is that the Hunstanton Formation is excluded from the Chalk Group and is the uppermost formation of the Lower Cretaceous. However, for practical purposes in this report, the Hunstanton Formation is included with the Chalk Group in Figures 2.2 and 3.6 where it lies directly over Jurassic formations. Above the Flamborough Chalk Formation, an additional unit termed the Rowe Chalk Formation is recognised beneath the Quaternary cover in the coastal area of Holderness. These units are based on gross lithological characteristics, such as the presence or absence of flints, and so the classification can be applied with a minimum of specialist knowledge. The formations can also be identified from conventional geophysical logs. The outcrop and subcrop of the component formations of the Chalk Group are indicated in Figure 2.2. It should be noted that only in the southern part of the region (BGS 1:50 000 sheets 80 and 81; Gaunt et al., 1992; Berridge and Pattison, 1994) have they been resurveyed. Elsewhere, the lines are based on an interpretation of BGS maps mostly dating from the nineteenth century, and/or have been calculated from the interaction of structure contours with topographic, or rockhead contours. The chronostratigraphic and lithostratigraphic classifications of the northern and southern provinces are compared in Table 2.1 based on detailed descriptions given in Sumbler, 1999.

2.4.2 Hunstanton Formation

The Hunstanton Formation is about 3 m thick in the south of the region, typically 1 m thick over the Market Weighton High but as thick as 25–30 m in the Cleveland Basin. The formation comprises the so-called Red Chalk, made up of marls and both rubbly and massive chalks that are typically pink to brick-red in colour due to iron staining, mainly as disseminated hematite. The upper part of the formation is less marly and more massive than the lower part, and tends to be paler in colour and prone to discoloration.

2.4.3 Ferriby Chalk Formation

The Ferriby Chalk Formation, corresponding approximately with the Lower Chalk of the Southern Province, is about 20 to 25 m thick in the south but thins over the Market

Table 2.1 Lithostratigraphical classification of the Chalk Group of Yorkshire (Northern Province) compared with that of southern England (Southern Province).

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
		Gonioteuthis quadrata	FLAMBOROUGH CHALK	Chalk without flints		Culver Chalk
	Sphenoceramus lingua	*Offaster pilula*				Newhaven Chalk
	Uintacrinus anglicua					
SANTONIAN	*Marsupites testudinarius*					
	Uintacrinus socialis					
	Hagenowia rostrata	*Micraster coranguinum*	BURNHAM CHALK	Chalk with flints		Seaford Chalk
CONIACIAN	*Micraster cortestudinarium*					Lewes Chalk
TURONIAN	*Sternotaxis plana [Holaster planus]*					
	Terebratulina gracilis	*Terebratulina lata*	WELTON CHALK		MIDDLE CHALK	New Pit Chalk
	Rhynchonella cuvieri	*Mytiloides labiatus*				Holywell Chalk
CENOMANIAN	*Sciponoceras gracile*	*Neocardioceras juddi*	Plenus Marls Member	Marly chalk without flints		
	Actinocamax plenus	*Metoicoceras geslinianum*			LOWER CHALK	Plenus Marls Member
	Holaster tecensis	*Calycoceras guerangeri*	FERRIBY CHALK			Zig Zag Chalk
	Holaster subglobosus	*Acanthoceras jukesbrownei*				
		Acanthoceras rhotomagense				
		Mantelliceras dixoni				West Melbury Chalk
		Mantelliceras mantelli	Base of Chalk Group			Glauconitic Marl Member
ALBIAN			HUNSTANTON	Red chalk	Upper Greensand and Gault	

Weighton High, to only about 10 to 15 m. It thickens rapidly at the margin of the Cleveland Basin to the north, and is about 35 m thick at Speeton, and perhaps more the 50 m further inland. The formation differs from the overlying chalk because of its marly (argillaceous) nature, which limits its potential as an aquifer.

The formation comprises generally grey, predominantly marly chalks, which weather to a buff colour in exposures, and give rise to rather marly soils. The succession is flintless throughout. As well as marly chalks with some discrete marl bands, 'gritty' bioclastic chalks and hard, cemented chalks also occur. The Totternhoe Stone, formerly known in this region as the Grey Bed (Jukes-Browne and Hill, 1903), comprises dark grey or brown sand-grade chalk largely composed of inoceramid shell debris. The top of the Ferriby Formation is marked by an erosion surface, which equates with that beneath the Plenus Marls in the Southern Province, (the Plenus Marls are the uppermost unit of the Lower Chalk).

2.4.4 Welton Chalk Formation

Massive or thickly bedded chalks containing flint nodules, as distinct from tabular flints, dominate the Welton Chalk Formation. The formation is approximately 53 m thick at the type locality of Melton Bottoms or Welton Wold Quarry [SE 970 282], in Lincolnshire. It may thin slightly across the Market Weighton High, perhaps to as little as 40 m in places, but thickens towards the Cleveland Basin, and is about 55 m thick in the Bempton and Buckton cliff sections between Flamborough and Speeton (Mitchell, 2000). The formation crops out on the steep slopes of the Wolds escarpment, and for this reason has a generally rather narrow outcrop area (Figure 2.2). Soils on this part of the escarpment are generally brown clayey loams with much flint and subordinate chalk debris.

The base of the Welton Chalk Formation is defined by an erosion surface that is often highly irregular, and may be stained with iron minerals and glauconite. Above, is a complex unit of buff to green and khaki coloured marls and marly chalks, the Plenus Marls Member, which is generally less than 0.5 m thick. It is about 1 m thick in the north of the region, for example in the cliffs to the south-east of Speeton and up to about 1.4 m thick inland. A few centimetres of very dark grey to black or purplish, bituminous marl constitutes the 'Black Band' towards the top of the Plenus Marls Member.

The beds immediately above the Plenus Marls Member are rich in shell debris, and contain pebbles of chalk at some levels and a number of thin marl seams. They correspond with the upper part of the Melbourn Rock and the overlying part of the Holywell Member of the Southern Province.

Above these basal shelly chalks, the bulk of the Welton Chalk Formation is composed of extremely pure, white chalks which, in general, are softer than those of the overlying Burnham Chalk Formation. Characteristically, this part of the formation contains flint-bearing beds, which are some 43 m thick at the type locality (Whitham, 1991) and about 50 m thick on the coast.

2.4.5 Burnham Chalk Formation

In contrast to the massive chalks of the Welton Chalk Formation, the Burnham Chalk Formation is characterised by thinly bedded chalks with tabular and discontinuous flint bands. The formation has an extensive outcrop, forming the crest and plateau areas of the Yorkshire Wolds. The chalks in the lower part of the formation are hard, and form a conspicuous topographical feature, and soils characteristically contain abundant flint debris (including carious flints, which are common at some levels), together with angular fragments of hard, white chalk.

North of the Humber, the Burnham Chalk Formation is about 140 m thick (Whitham, 1991). However, geophysical logs from boreholes in the area of the Market Weighton High indicate that the formation thins to 85 to 100 m, reflecting the continued influence of this structure. The entire formation is exposed in the cliffs at, and just to the north of Flamborough Head. This section has not been recorded in detail, and the thickness is uncertain, but may possibly be up to about 150 m thick (Sumbler, 1999).

The flints of the Burnham Chalk Formation are mainly tabular, in some cases up to 0.3 m or more in thickness. Flint nodules, such as those that typify the Welton Chalk Formation, are relatively scarce, although, large, elongate paramoudra flints occur at some levels. The lowest few metres of the formation are characterised by hard chalks and are particularly flinty, with thick, closely spaced, tabular flints. As in the Welton Chalk Formation, a number of marl seams form widespread marker horizons and there are, several bands of thinly laminated chalk which are also useful for correlation.

2.4.6 Flamborough Chalk Formation

The Flamborough Chalk Formation is the youngest formation to outcrop in this region. By comparison with the underlying Welton and Burnham Chalk formations, it is essentially flint-free. It is also less hard than the underlying chalks, being lithologically similar to the chalks of southern England.

The formation is present between Flamborough in the north and Grimsby in the south and extends eastwards beneath the North Sea. The basal 160 m of the formation is well exposed in the cliffs between Flamborough Head and Sewerby, which constitute the type section. Equivalent, and perhaps slightly higher beds, totalling about 220 m in thickness (Whitham, 1993) crop out inland near Driffield. Elsewhere in the region, the formation is concealed beneath Quaternary deposits, and for this reason, the stratigraphy of the Flamborough Chalk Formation, particularly of its unexposed, higher beds, is poorly known. This situation is aggravated by a paucity of geophysically logged boreholes, particularly close to the type section.

At the type section, the formation comprises white, flint-free chalks with numerous marl seams typically 1 to 3 cm in thickness. These occur with an average frequency of almost one per metre, far more than in the underlying chalks. Some of the thicker marls which are named as marker horizons vary in thickness, or split into multiple bands when traced laterally over fairly short distances. Whitham (1993) subdivided the succession at the type section into three members, the South Landing, Danes Dyke and Sewerby members, each of which has different lithological characters. The **South Landing Member**, is about 21 m thick, and comprises hard, massive chalks with sporadic thin marl seams. Some of the chalks are so hard that they have been used locally as a building stone. The base of the member (and of the Flamborough Chalk Formation) is marked by the top of the High Stacks Flint, seen on the foreshore near High Stacks, Flamborough Head [TA 258 704].

The **Danes Dyke Member** is about 67 m thick, and comprises thinly bedded, alternating hard and soft chalks with stylolites, and with marl seams (86 in total). It is overall less hard than the underlying South Landing Member, and the marls are far more abundant.

The **Sewerby Member**, constitutes the youngest chalks exposed on the coast. It is dominated by massive chalks, although the lower part comprises thinly bedded chalks with stylolites, much like the bulk of the underlying Danes Dyke Member, but marl seams are less common than in the Danes Dyke Member. About 72 m of beds are seen on the coast with slightly higher horizons probably being represented in quarries inland, although precisely how these inland sections relate to the coast is not certain.

2.4.7 Rowe Chalk Formation

Between Hornsea and Withernsea, the total thickness of Chalk strata above the Burnham Chalk Formation is approximately 300 to 350 m. Geological and geophysical log data from hydrocarbon wells suggest that the largely flint-free chalks typifying the Flamborough Chalk Formation are of the order of 260 to 280 m thick and are overlain by some 70 m of flint bearing chalks (Sumbler, 1999). These flinty strata continue eastwards beneath the North Sea where the youngest material has been named the Rowe Chalk Formation (Lott and Knox, 1994). The base of this unit lies approximately at the base of the *Belemnitella mucronata* Zone. Specimens of the index belemnite have been found in the tills which cover the Chalk of Holderness (Wood, 1980).

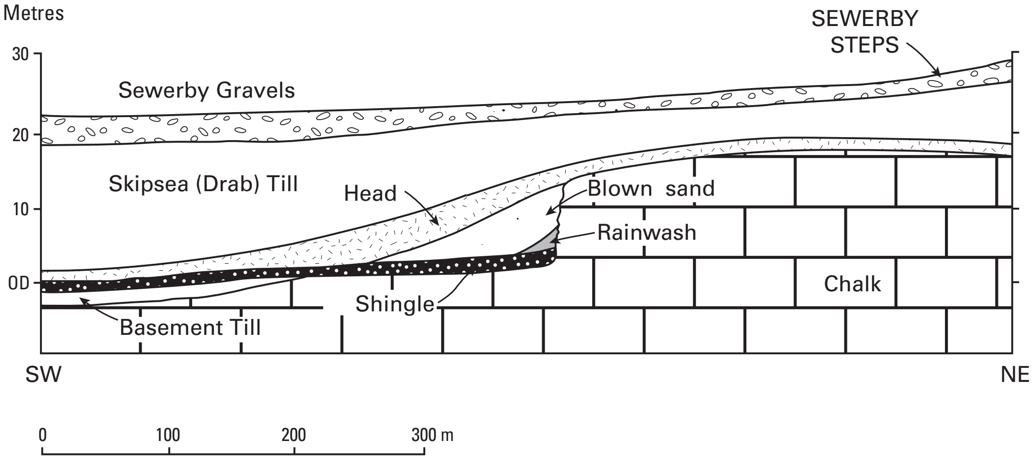
2.5 QUATERNARY DEPOSITS

The Tertiary period was a time of extended uplift with folding and tilting of the main Wolds Syncline. As a result, the Wolds underwent prolonged denudation and considerable thicknesses of the uppermost divisions of the Chalk were removed. The Palaeogene topography was later substantially modified during the Quaternary period, in those parts of the region that were invaded by glacier ice, or affected by permafrost and periglacial weathering.

2.5.1 Distribution of Quaternary deposits

The distribution of the Quaternary deposits is discontinuous and is influenced by the pre-existing topography at the time of deposition. The mapped units, are therefore distinguished on the basis of lithology and mode of origin, but can be fitted into a general chronological framework described by Berridge and Pattison, 1994. The most widespread Quaternary deposits of the region are of Devensian and Holocene age. Older Quaternary deposits may be preserved locally, principally beneath the extensive cover of Devensian material in Holderness.

Figure 2.4 Diagrammatic section of the buried cliff at Sewerby (after Catt and Penny, 1966).



In general, the Chalk dips eastwards beneath a thickening Quaternary cover of mainly glacial origin. The composition is largely boulder clay (till), although chalky gravel is also present, e.g. in the Wetwang embayment [SE 960 580] and along the buried coastline. The Quaternary deposits are generally less than 10 m thick in the west but rapidly increase in thickness to the east of the buried cliff line, which represents the position of the coastline during Ipswichian (pre-Devensian) times (Figure 2.2). To the east of this feature, the thickness of the Quaternary deposits is quite variable; 20 m is typical, but it reaches 55 m in some places. The total thickness exceeds 20 m along the Humber coast estuary, of which the cumulative thickness of clay in the sequence is about 5 m, thickening to over 10 m in the south and east (Hawkins et al., 1998).

The eastern third of the Wolds is partially covered by glacial till which tapers to a feather-edge at its western margin, close to the presumed limit of the ice sheet. Glacial till probably extended some distance farther west, but has subsequently been removed by erosion. To the west of the feather-edge, scattered remnants of Quaternary deposits occur over much of the Wolds, but these deposits rarely exceed 1 m in thickness.

Glacial sands and gravels locally overlie the Chalk, and although they are generally poorly exposed, good examples can be seen in the buried channels at Danes Dyke [TA 215 691] and South Landing [TA 232 692]. These deposits consist of moderately well sorted to very poorly sorted, bedded and cross-bedded, cemented chalk sands and gravels. At Danes Dyke and South Landing the deposits are about 5 m thick in the centre of the channels, pinching out over the shoulders. A section along the Holderness cliff shows that the glacial sands and gravels may also occur in widespread, thin sheets (Berridge and Pattison, 1994).

2.5.2 Buried Chalk topography

There are comparatively few borehole records or geophysical interpretations with which to define accurately the Chalk surface beneath the Quaternary cover. The data that are available are shown in Figure 2.5. Apart from the dry valleys of the Wolds, the main erosional features on the surface of the Chalk are the buried coastline and a network of buried channels. The latter are narrow and deeply incised and in some areas are poorly defined by scarce data. Evidence from the south of the Humber shows

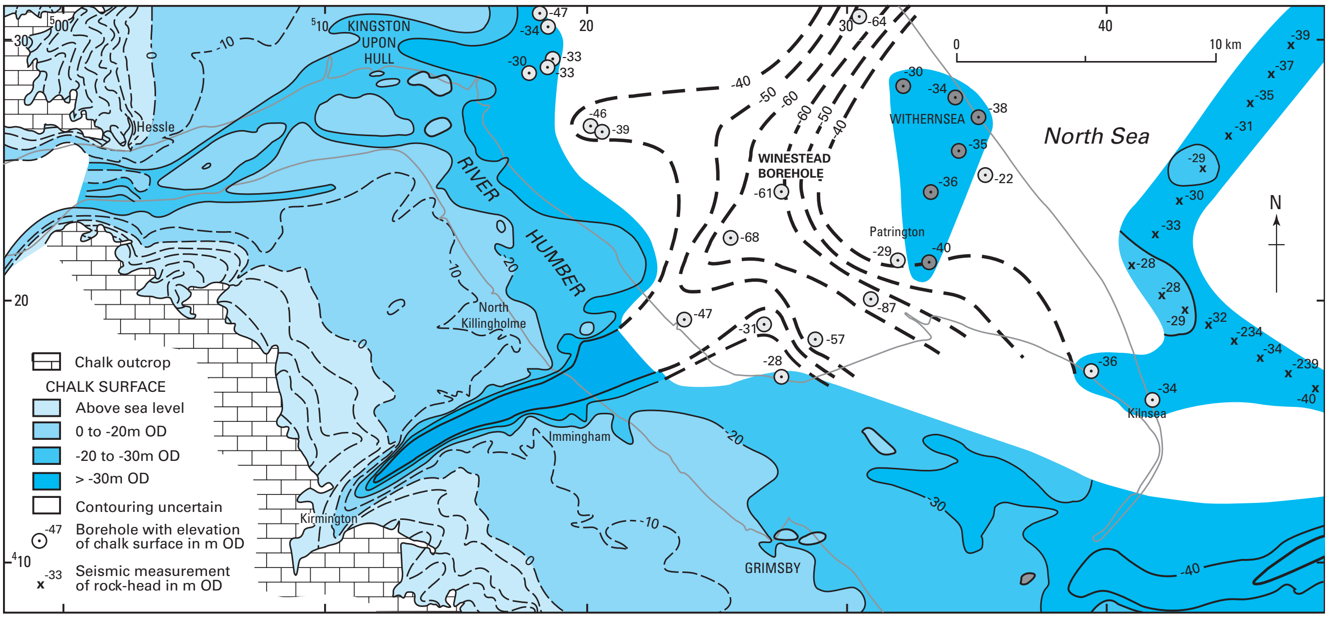


Figure 2.5 Topography of the outcrop and surface of the Chalk subcrop (m below OD) in the Humber area (based on Berridge and Pattison, 1994).

Plate 1 Chalk wave-cut platform at Sewerby, near Bridlington. The Chalk is overlain by glacial till.

that a planar Ipswichian platform grades gently seawards from the base of a buried cliff.

The buried coastline runs from Bridlington along the eastern edge of the Wolds to the Humber, east of Hessle and Barton. The size and form of this feature is variable. At Sewerby it is approximately 15 m in height (Figure 2.4 after Catt and Penny, 1966 and Rawson and Wright, 1992) but near the Humber it is less distinct. The feature is associated with the Ipswichian interglacial (Catt and Penny, 1966; Berridge and Pattison, 1994), with a relative sea level of approximately 1.5 m above OD.

Numerous channels of differing size and orientation cut across the buried Chalk surface. The origin of these channels is uncertain but several hypotheses have been put forward, including subaerial erosion and interglacial processes. A number of small, but pronounced, buried channels have been identified to the immediate east of the Wolds. These appear to be an extension of the dry valley network seen at outcrop, and imply that the formation of the valleys preceded deposition of the Quaternary. Such buried channels are present beneath Bridlington, Hornsea (Foster and Milton, 1976) and Ulrome [TA 16 56] (Aspinwall, 1995a). Foster and Milton (1976) suggest that these may have been developed by subaerial erosion and that they are analogous to the dry valleys in the Wolds, although they also indicate that they could be compared to the buried 'tunnel' valleys of East Anglia. Two examples are exposed at South Landing [TA 232 692] and Dane's Dyke [TA 215 691] on the coast between Sewerby and Flamborough Head. The channels are filled with Quaternary deposits and the feature at Dane's Dyke is associated with a small disturbance zone in the Chalk, possibly the result of permafrost action prior to burial. However, Rawson and Wright (1992) have interpreted them as interglacial meltwater channels and have suggested that the disturbed ground may have formed a line of weakness that was exploited by glacial meltwaters.

It appears likely that some buried channels were formed during glacial periods. Evidence from offshore seismic investigations (personal communication, P Balson) suggests that the largest channels are Anglian in age, with smaller Devensian channels cross-cutting them. These offshore channels are generally discontinuous and randomly placed.

The Kirmington Channel is a major feature, probably of Anglian age (Berridge and Pattison, 1994). The channel has been proved in Lincolnshire between Brocklesby [TA 14 11] and Immingham, and is an almost straight, east-north-east trending incision carved into the Chalk. It is about 2 km wide and up to 50 m deep, the depth of its base increasing towards the coast, such that it is approximately 75 m below OD at Immingham. The continuation of the channel under the Humber Estuary and beneath Holderness is largely conjectural with few boreholes acting as control points (Figure 2.5). The Kirmington Channel is assumed to be part of a 'tunnel valley' produced by catastrophic release of meltwater under great hydrostatic pressure close to the edge of an ice sheet (Berridge and Pattison, 1994). The majority of the infill would have occurred immediately after the valley was formed. The relationship of other channels to the Kirmington Channel is uncertain; however, as tunnel valleys are typically simple in form, these channels are more likely to be separate entities, rather than tributaries of the Kirmington feature.

Geomorphological traces of some of the englacial drainage channels associated with the deposition of glacial and fluvioglacial deposits are clearly preserved in the Withernsea Till outcrop in Holderness. Here, as in the Wolds, there is a lattice of channels in which certain trends are dominant. One of these is parallel to the presumed ice front, although another trend suggests funnelling into pre-existing major valleys normal to the ice front, which are now mainly filled with alluvium.

Across the region, the surface layers of the Chalk have also been affected by Pleistocene cryoturbation and solifluxion 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; Price, 1987). The effect of this shallow weathering process is an up-profile increase in joint frequency and aperture. Upwards of this the Chalk becomes friable and rubbly (chalk 'bearings'). In the extreme case, the Chalk disintegrates to a structureless mass with angular blocks in a matrix of weathered chalk ('putty chalk'); when wet the matrix may take on a paste-like consistency. The existence and nature of this layer affects infiltration and recharge. Cryoturbated weathered chalk mantle passing upwards into glacial sands can be seen at Danes Dyke, Flamborough Head. At a local scale the thickness and nature of this heavily weathered horizon

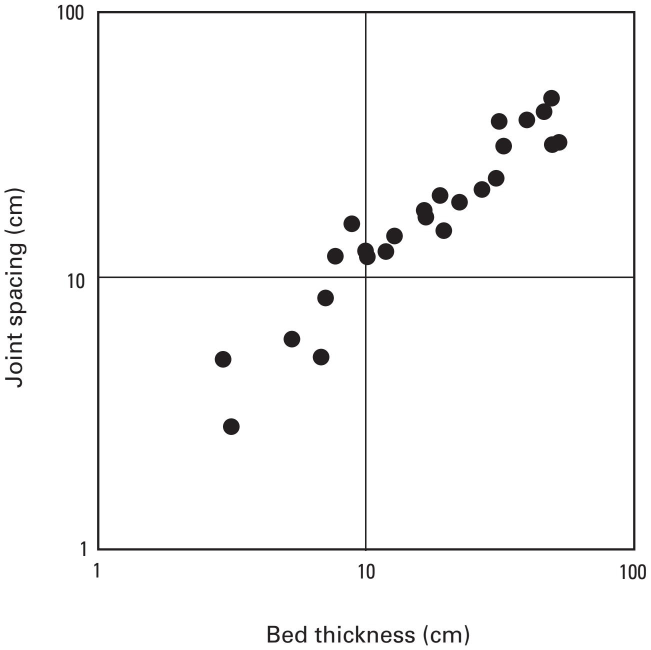


Figure 2.6 Illustration of the relationship between mean bed thickness and mean joint spacing. The measurements were made on 26 beds from Dane's Dyke, Flamborough Head that range in thickness from 3 to 53 cm.

may vary significantly, and there is a reported maximum thickness of about 10 m (Allen et al., 1997). However, to date, despite its potential hydrogeological significance, there have been no quantitative studies of the physical characteristics of the weathering profiles of the Chalk in the region.

2.6 FRACTURES IN THE CHALK AQUIFER

The larger fault zones in the Chalk of Yorkshire have been described in the context of the regional structure. However, the Chalk contains a fracture system consisting of a number of fracture sets over a very wide range of scales, and in each fracture set there is variability in parameters such as fracture size, spacing, orientation and aperture.

BOX 1 DEFINITIONS OF FRACTURE NOMENCLATURE

Three specific types of fracture can be distinguished in the Chalk, i.e. bedding plane fractures, joints and faults (Bloomfield, 1996). *Bedding plane fractures* 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. *Joints* are fractures where the shear displacement is negligible, and *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. Consequently, differences in their genesis are reflected in differences in their spatial distributions (Gillespie et al., 1993). The term *joint set* can be used to refer to a population of parallel or sub-parallel joints, and the term *fracture system* can be used to refer to all fractures in a rockmass.

2.6.1 Joints

In flat-lying sedimentary sequences the most commonly observed joint pattern at surface exposures is that of three approximately orthogonal joint sets, with one joint set parallel to bedding. These features may be regionally extensive and the most well-developed joint set is commonly co-incident with the regional compressive stress direction and perpendicular to the least principal stress. Bevan and Hancock (1986) described five fracture styles, the most common being vertical extension joints and conjugate steeply inclined joints (pairs of joint sets with an acute angle, commonly between 40° and 60°). They suggested that this regional Chalk joint system developed during the late Neogene to Recent in response to Alpine compression in north-west Europe. Woodward and Buckley (1976) described fracture orientations from seventeen sites throughout Yorkshire and noted that the dominant strike directions were north-west to south-east and east-north-east to west-south-west and concluded that these fractures reflect the broad regional synclinal structure of the region. However the fracture orientation trends described by Woodward and Buckley (1976) are probably fault trends and not the regional joint trends. Patsoules and Cripps (1990) identified six different joint sets with the principal joint set oriented between 100° and 130°.

The depth to which the regional joint set is developed is uncertain and may vary depending on lithostratigraphy, burial and uplift history, and proximity to faults. However, a fracture log of a borehole at Carnaby Moor [TA 1505 6486] indicates jointing in the Chalk down to depths of 100 m below ground level.

In sedimentary sequences the mean spacing of joints from a single joint set, within a single bed, has been shown to be proportional to the thickness of the sedimentary layer (Ladeira and Price, 1981; Narr and Suppe, 1991), although the thickest beds may depart from this relationship. Cross-joints (later, second generation, joints formed at a high angle to the initial joint set) may also exhibit mean spacings proportional to the spacing of the initial joint set (Gross, 1993; Rives et al., 1994). If cross-joints are present, ladder- or grid-like orthogonal joint systems develop.

Figure 2.6 shows a cross-plot of mean joint spacing against mean bed thickness for 26 beds at Flamborough Head. Bed thicknesses were recorded in the range 0.3 to 0.52 m with joint spacing in each bed related to the log of the bed thickness (from Bloomfield, 1997). Patsoules and Cripps (1990) performed five scan-line surveys between Selwicks Bay and High Stacks on the southern side of Flamborough Head and noted joint spacings in the range 0.15 to 0.33 m. Although the scan-line surveys were short, in the range 4 m to 10 m, compared to the average fracture spacing and only very small numbers of fractures were sampled these values are broadly consistent. Joint trace lengths are typically in the range 10^{-2} to 1 m. Joint apertures are generally relatively small compared to the aperture of bedding plane fractures and are usually much less than 10^{-3} m.

2.6.2 Faults

A detailed study of minor faulting within the Howardian-Flamborough Fault Belt was undertaken by Peacock and Sanderson (1994), who described the orientation, spacing and displacement across minor faults along the southern coast of Flamborough Head in the 6 km section between Sewerby and High Stacks. They identified 1340 extensional faults with displacements in the range 0.005 m to 6 m and spacings in the approximate range 1 m to 70 m. The majority of faults are separate or discrete surfaces, but some of the faults are grouped to form complex zones of fracturing. The average dip of the faults to the south of Flamborough Head is 64°. This is consistent with previously reported values for the Chalk of north-west Europe (Bevan, 1985; Bevan and Hancock, 1986; Ameen and Cosgrove, 1990; Koestler and Ehrmann, 1991). Peacock and Sanderson (1994) noted a wide variation in the dip directions of the small faults, with individual faults often showing sinuosity and strike variations in excess of 10°. Conjugate faults with dip-slip and oblique-slip slickensides are common, with both older and cross-cutting younger faults exhibiting no preferred orientation.

Peacock and Sanderson (1994) modelled the development of faulting at Flamborough Head in three stages. They inferred a period of early approximately north–south extension across large basement controlled normal fault zones, such as at the Selwicks Bay disturbance, followed by the development of smaller, exposure-scale, faults accommodating general horizontal extension. As they developed, the smaller faults linked up the larger-scale east–west trending normal faults to form a single, wide, extensional fault zone. Finally, Peacock and Sanderson recognised compressional re-activation of the larger faults.

Faulting is exposed at Ruston Parver Quarry [TA 069 615]. These faults are up to 15 m in length, with spacings of the order of 5 m and maximum displacements of 0.1 to 0.2 m. Most of the faults are normal or conjugate faults, many with strike parallel slip slickensides. The faults are generally at a high angle, i.e. 60° to 90°, and do not have a preferred orientation.

Woodward and Buckley (1976) recognised two types of joints, 'major joints' with surface areas in the range 1 m^2 to >100 m^2 and 'minor joints'. They restricted their fracture spacing measurements to the 'major joints'. They noted that the 'minor joints' were commonly confined to a single beds but that the major joints 'commonly traverse entire quarry faces' (Foster and Milton, 1976). They reported that fracture spacing did not appear to be stratigraphically or lithologically controlled and noted typical spacings for the 'major joints' in the range from 0.8 m to 1.4 m. It is likely that the 'major joints' of Woodward and Buckley are faults with small displacements. Woodward and Buckley (1976) also recorded the average spacing of bedding plane fractures and stylolites, these ranged from 0.3 m to 1.7 m and 0.03 m to 0.2 m respectively.

The damage zones within, and adjacent to, fault planes form zones of fracture porosity and may act to localise groundwater flow in the saturated zones. Dilational jogs between two segments of a fault strand may act as conduits for preferential groundwater flow. In addition, when faults pass through relatively incompetent beds the linear damage zone at the intersection of these two surfaces may also act to concentrate groundwater flow.

2.6.3 Bedding plane fractures

The morphology of bedding plane fractures is highly variable. They can range from relatively planar, laterally extensive single fractures with locally large apertures (>0.01 m) 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 offers a preferred groundwater flow horizon.

Shear across marl seams during uplift is commonly associated with fracturing in the Chalk immediately adjacent to the seams. It is likely that preferred groundwater flow horizons occur not only through the bounding fractures associated with the marl seams but also through the fractured matrix immediately adjacent to the marls. This hypothesis is supported by the observation that borehole flow logs for the Chalk of Yorkshire and Lincolnshire show that marls and flint bands may act as preferred flow horizons. To date there are no quantitative measurements of bedding plane fracture characteristics for the region.

3 Hydrogeology

3.1 INTRODUCTION

The outcrop of the Chalk aquifer in Yorkshire extends from Flamborough Head in the north to the Humber Estuary in the south. In the north and west of the area, the Chalk outcrop forms the Yorkshire Wolds, with a steep western escarpment and a gently dipping eastern slope. The dip slope is partially covered by Quaternary deposits, which become thicker to the east (Figure 3.1). Regional groundwater movement tends to follow the dip of the Chalk, the major groundwater divide approximately follows the line of the Chalk escarpment. Groundwater flowing down-gradient from the Wolds either emerges as springs near the edge of the Quaternary deposits, or is pumped from the partly-confined aquifer.

The aquifer is unconfined across the Wolds, but becomes confined to the east where it is covered by glacial till. The unconfined-confined boundary generally coincides with the position of the buried cliff-line, to the east of which is a considerable thickness of cover (see Figure 2.2). The Chalk beneath Holderness is very little used as an aquifer due to the restricted groundwater circulation, and the poor water quality.

The Yorkshire Chalk aquifer was studied in considerable detail in the early 1970s in connection with investigations into the occurrence of nitrate in the aquifer, the potential for developing a river augmentation scheme as well as the control of saline intrusion along the Humber Estuary (Foster and Milton, 1976). A groundwater model was developed for the northern part of the Chalk in the early 1980s and this was used as a basis for a numerical model covering the whole of the Yorkshire Chalk in the mid-1990s.

3.2 HYDRAULIC PROPERTIES OF THE AQUIFER

3.2.1 Introduction

The aquifer properties of the Chalk of Yorkshire are dissimilar to the chalks of southern England owing to their greater degree of cementation and hardness. They have

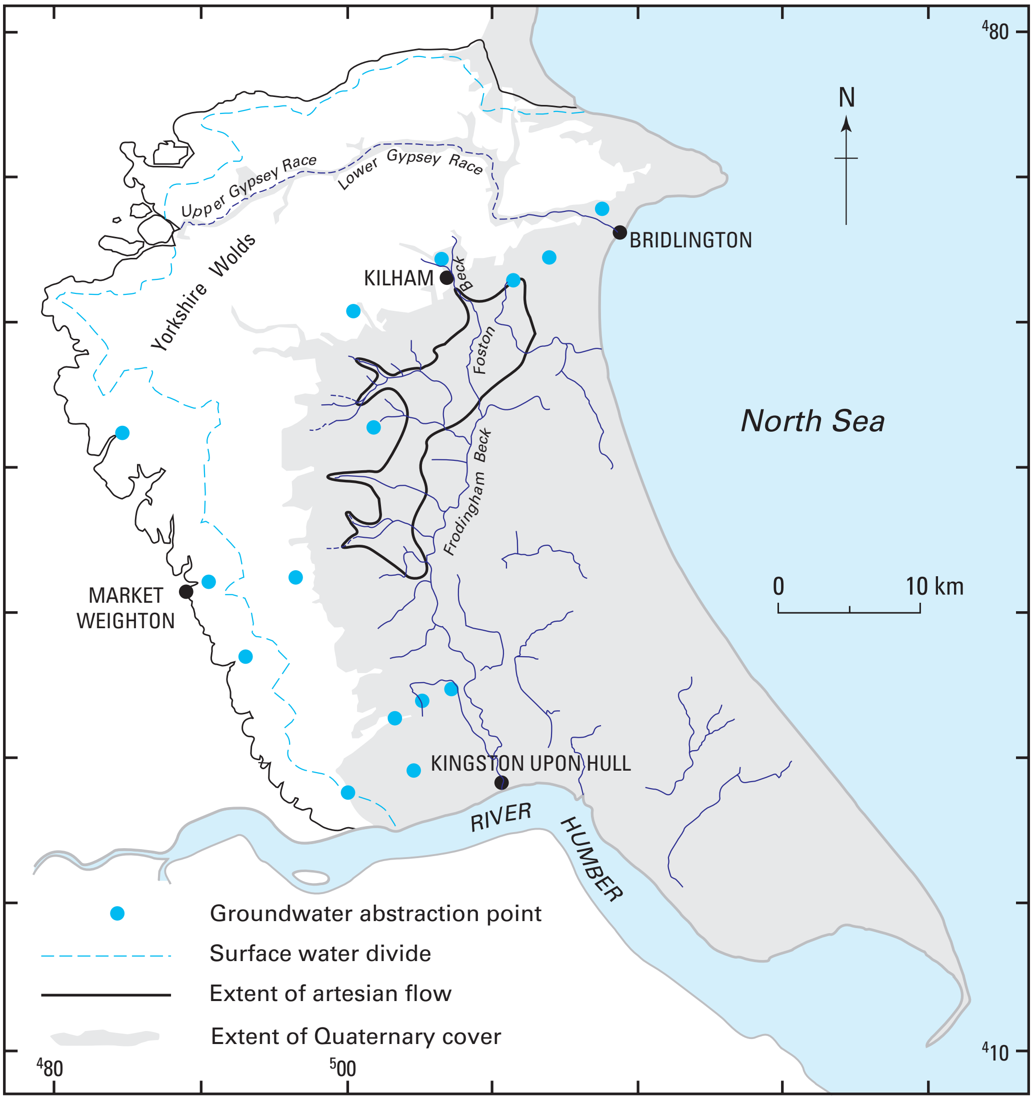


Figure 3.1 Map showing the outcrop of the Chalk, the confining Drift cover and surface drainage. (based are Foster and Milton, 1976).

different degrees of fracturing and different matrix properties, and this is reflected in the ability of the aquifer to transport water and contaminants through both the unsaturated and saturated zones. It has also been suggested that the greater hardness of the Chalk has tended to result in the formation of rubbly chalk 'bearings' under periglacial conditions, rather than the finer-grained, impermeable 'putty' chalk found in the south of England (Price et al., 1993; Younger et al., 1997).

The matrix of the Yorkshire Chalk is characterised by a combination of small grain size, small pore-throat size, high effective porosity and low occluded porosity. Typically, white chalk contains a biogenic carbonate component, approximately 96% to 99% by volume (Hancock, 1993), and an inorganic non-carbonate component of 1% to 4% by volume. The biogenic component of chalk is principally skeletal fragments of haptophyta (coccolith-bearing algae). These skeletal fragments are preserved as coccospheres, up to 25 μm in diameter, or more commonly as coccoliths, 10 to 20 μm in diameter, or as disaggregated laths about 0.1 to 1 μm in size. The Chalk also contains subordinate skeletal fragments of foraminifera, inoceramid bivalves and bryozoa, typically in the size range 10 to 100 μm.

3.2.2 Porosity development and distribution

Systematic collection of aquifer properties data for the major British aquifers was carried out during the 1990s (Allen et al., 1997). This study identified data for 87 pumping tests from 68 sites in the Chalk aquifer in Yorkshire. White chalks commonly have porosities in the range 20% to 45% at outcrop. Chalks with high clay contents or cemented chalks from hardgrounds may have porosities of less than 10%, although hardgrounds typically have porosities in the range 10% to 20% (Bloomfield et al., 1995). Hardgrounds originate through a variety of processes ranging from reduced sedimentation rates to compaction, cementation and burial diagenesis processes, including stylolite formation. At the regional scale, matrix porosity (and permeability) vary systematically with the lithostratigraphic sequence and trends in matrix porosity reflect the former maximum burial depth or the diagenetic grade experienced locally (Scholle, 1977; Scholle et al., 1983; Hillis, 1995).

The rate of change in porosity with distance above the base of the Chalk in Yorkshire, about 0.1 per cent per metre, is similar to that seen in other onshore Chalk profiles from southern England (Bloomfield et al., 1995; Bloomfield, 1997). A summary of porosity and pore size data is presented in Table 3.1.

The decrease in matrix porosity with depth results from the interaction of primary sedimentary characteristics, such as grain size, fabric and mineralogical composition, with diagenetic processes such as mechanical compaction and pressure solution (Scholle, 1977; Scholle et al., 1983; Bloomfield, 1997). Mechanical compaction predominates during the early stages of burial diagenesis, reducing an initial 60% porosity by 10% for only a few hundred meters burial. Pressure solution, or solution transfer diagenesis, is the reduction of matrix porosity through the dissolution and re-precipitation of minerals under conditions of non-hydrostatic stress. This process predominates during the later stages of diagenesis under greater thicknesses of overburden, when matrix porosity is reduced to the range 45% to 35% or less. The extensive development of stylolites, flasar structures and marl seams, which can be seen at many surface exposures in the Chalk of Yorkshire,

Table 3.1 Porosity and pore size measurements of Yorkshire Chalk.

Formation	**Number in sample (n)**	**Mean porosity (%) (range)**	**Mean pore size (d_{50}). (μm)**	**Standard deviation (sd)**	**Reference**
Flamborough Chalk					No data
Undifferentiated Flamborough and Burnham Chalk	191	35.4 (3.3–45.3)		6.8	Bloomfield et al., 1995
	7		0.41	0.08	Data for 'Northern Province' from Price et al., 1976
Burnham Chalk		23.9 (17.7–36.4)			*M. coranguinum* zone, Selwicks Bay, Bell et al., 1990
Welton Chalk	62	18.9 (6.7–31.4)		4.6	Bloomfield et al., 1995
		21.8 (16.2–36.4)			*T. lata* zone, Thornwick Bay, Bell et al., 1990
	8		0.39	0.08	Data for 'Northern Province' from Price et al., 1976
Ferriby Chalk		20.6 (17.2–30.2)			*H. subglobosus* zone nr Speeton, Bell et al., 1990

indicate a large depth of burial and past active pressure solution diagenesis. By way of contrast, Hancock (1993) suggested that most of the outcrop Chalk of southern England has only ever been affected by mechanical compaction.

There are two porosity/permeability regimes in Yorkshire consistent with the change from dominantly mechanical compaction to pressure solution compaction (Scholle, 1977; Scholle et al., 1983; Bloomfield, 1997). Figure 3.2 shows normal probability plots of porosity and gas permeability data for the region held on the BGS Aquifer Properties Database (Bloomfield et al., 1995; Allen et al., 1997). These show two distinct populations consisting of chalks with porosities greater than about 30% and matrix permeabilities greater than about 1 mD (dominantly mechanical compaction) and a second population with porosities less than 30% and permeabilities less than 1 mD (dominantly pressure solution compaction).

It has only been possible to assign samples to either the Flamborough and Burnham Chalk formations or the Welton and Ferriby Chalk formations because of the relatively poor stratigraphic control on the samples. However, it can be seen that samples from the Flamborough and Burnham Chalk formations are found in both populations but that samples from the Welton and Ferriby Chalk formations are found only in the population with lower porosities. This suggests that the mechanical compaction-pressure solution/compaction boundary lies at the regional scale somewhere in the Flamborough or Burnham Chalk formations and that the Welton and Ferriby Chalk formations have undergone pressure solution.

At a more local scale ‘tectonic hardening’ of the matrix may be the reason why the headland at Flamborough has been resistant to erosion. Mimran (1978) described porosities in the range 8% to 17% for chalk samples from an unspecified ‘disturbed zone’ on Flamborough Head. Field observations suggest that there has been extensive cementation of the chalk matrix near the larger fault structures in the Howardian–Flamborough Fault Belt, and this too may account for reduced porosities at Flamborough Head. The chalk on the wave-cut platform beneath the sea cliffs contains numerous fine calcite veins and has a marble-like appearance.

3.2.3 Permeability

Harder chalks are brittle and may fracture more cleanly than softer chalks. The harder chalks also have more uniform joint openings making the harder chalks of northern England frequently more permeable than those of southern England (Price, 1987). Intergranular permeability measured in the laboratory from core samples is of the order of 10^{-4} m d^{-1}. However, the bulk permeability of the Chalk aquifer is dependent also on fracture permeability and this may be of the order of 0.01 to 10 m d^{-1} for individual fractures. Foster and Milton (1974) suggested a value for bulk permeability for the major flow horizons in the unconfined Chalk of around 200 m d^{-1}. The University of Birmingham (1978) used permeability values in their numerical models ranging from 4 to 170 m d^{-1}. These values were assumed to be representative of all the Chalk succession, with the lowest value relating to the concealed Chalk aquifer beneath Holderness.

Much of the secondary fracture-enhanced permeability development in the Chalk is believed to have developed during the Pleistocene period (University of Birmingham,

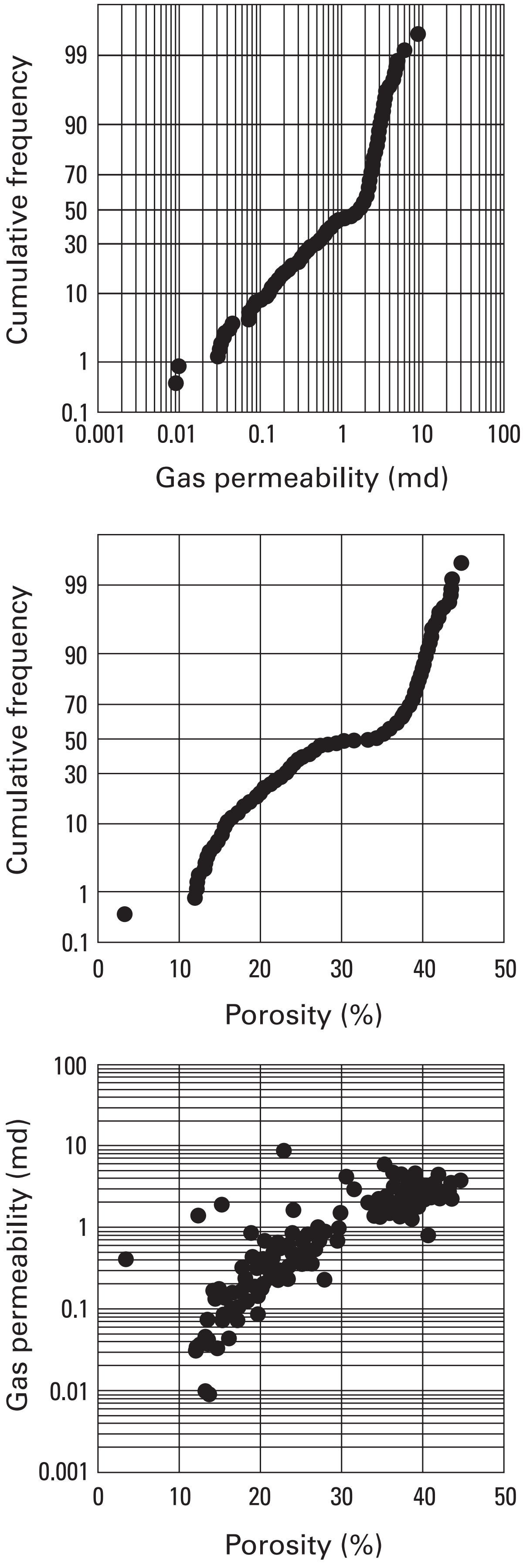


Figure 3.2 Normal probability plots of a) gas permeability and b) porosity data held on the Aquifer Properties Database (Bloomfield et al. 1995, Allen et al. 1997); c) cross-plot of gas permeability vs porosity.

Table 3.2 Pumping test results from three sites in the Yorkshire Chalk aquifer (Jones et al., 1993).

Site	Transmissivity $m^2\ d^{-1}$	Storage coefficient
Hutton Cranswick	95 to 145	9 to 23×10^{-4}
Kilham	c. 5000	45×10^{-4}
Elmswell Slack	540 to 970	40×10^{-4}

1985). Fracture development would have been most active during the interglacial periods when recharge and groundwater circulation would have been greatest. Based on evidence from both borehole logging and pumping tests, three major zones of karst-type solution development have been recognised in the unconfined Chalk of Yorkshire. The uppermost one lies 20 to 30 m above the present water table and is probably of Hoxnian age (University of Birmingham, 1985); it has been removed by erosion in many of the dry valleys and is not of significance to groundwater flow. The next zone is hydrogeologically important as it has developed around the present level of water-table fluctuations and affects present day shallow groundwater flow. The lowest zone lies approximately 20 m below the present water table and frequently defines the effective base of the aquifer (Foster and Milton, 1974). This lower zone is probably contemporary with the buried channel system described in Chapter 2, and shown in Figure 2.5.

Since the main component of flow occurs in the upper 30 to 40 m of the saturated zone, where the permeability is best developed, the effective thickness of the aquifer is considerably less than that of the Chalk Group itself. The pronounced layering of permeabilities means that well yields depend on whether the main fractures intersected are saturated or are above the water table. The permeability layering is most pronounced towards the main Chalk springs in the Wold Valley and modelling has shown that storage layering appears to be of significance only in the vicinity of the springs (University of Birmingham, 1985). East of the spring-lines and of the buried cliff-line the fracturing is less well developed (Foster and Milton, 1976; University of Birmingham, 1985).

Low-flows of streams are entirely controlled by groundwater levels in the Chalk aquifer. The Lower Gypsy Race is dominated by seepage flows between Rudston [TA 095 670] and Boynton [TA 137 679] (University of Birmingham, 1985); where the very subdued peaks which occur during dry years suggest that the main transmissive fractures actually become dewatered during low water table conditions.

3.2.4 Transmissivity

Wide variations in transmissivity are common to all Chalk aquifers, as groundwater flow through these aquifers is controlled by the presence of joints or fractures enlarged by solution. Hence, although the Chalk sequence attains a thickness of around 500 m in the south-east of the region, the thickness of the 'active' aquifer through which significant flow occurs is considerably less. Foster and Milton (1976) suggested there is some groundwater flow below the local base level, and in fact below OD, but not necessarily throughout the entire thickness of the Chalk Group. Variations in transmissivity at borehole scale will also occur, depending on the degree to which flow to the borehole intersects zones of enlarged fractures.

The development of transmissivity in the Chalk reflects past marine transgression and glaciation, as well as the inherent joint pattern within the rock. In unconfined conditions, a major solution-enhanced fracture zone tends to be created in the zone of water table fluctuation. These zones may be fossil, reflecting past base levels and water tables, or contemporary. For example, a transmissivity of 1000 $m^2\ d^{-1}$ was derived from a test at Etton at near-minimum groundwater levels (Foster and Milton, 1976). Six months later, with groundwater levels 7 m higher in the zone of water table fluctuation, the transmissivity had increased to 2200 $m^2\ d^{-1}$. Geophysical borehole logging suggested that at the near minimum water levels, in October 1970, the bulk of the water pumped was derived from a 5 to 8 m thick zone, located between 14 and 23 m below OD, possibly related to a previous, lower base level. Pumping tests on the unconfined aquifer, therefore, need to be interpreted with caution.

Transmissivity data from a number of sources were collected as part of a national survey (Allen et al., 1997). In Yorkshire, values range from less than 1 $m^2\ d^{-1}$ to over 10 000 $m^2\ d^{-1}$ (Figure 3.3). The geometric mean is 1258 $m^2\ d^{-1}$ and the interquartile range is 500 $m^2\ d^{-1}$ to 5968 $m^2\ d^{-1}$. The aerial distribution of the transmissivity data is shown in Figure 3.4.

Pumping test results from three boreholes in Yorkshire at the end of the 1988–1992 drought period are reported in Table 3.1 (Jones et al., 1993). Groundwater levels were then at exceptionally low levels but were starting to rise in response to recharge. Pumping tests carried out previously at Kilham, when groundwater levels were higher, indicated a transmissivity of 7500 $m^2\ d^{-1}$. This reflects a decrease in transmissivity at low groundwater levels due to dewatering of active flow horizons, similar to that observed at Etton (Foster and Milton, 1976).

High transmissivity values have also been recorded for boreholes located in dry valleys, although these may be partly attributable to the contribution from chalk bearings, a coarse breccia-like chalk deposit formed through periglacial processes (Younger et al., 1997). This occurs, for example, in the Great Wold Valley and the Kiplingcotes Valley,

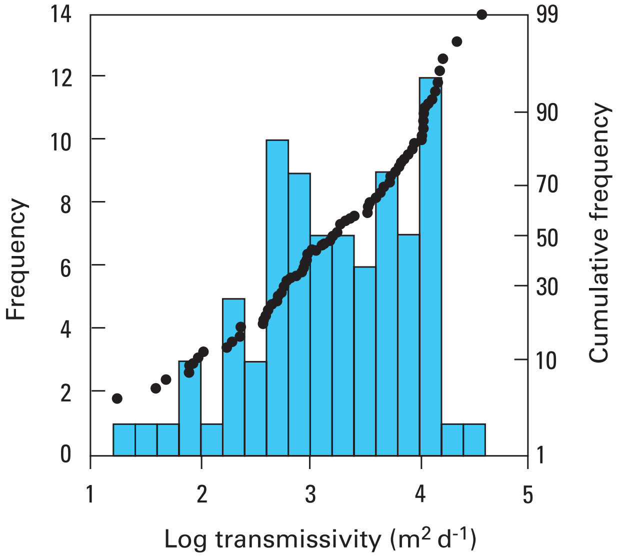


Figure 3.3 Frequency distribution of transmissivity values from pumping tests in the Chalk aquifer in Yorkshire.

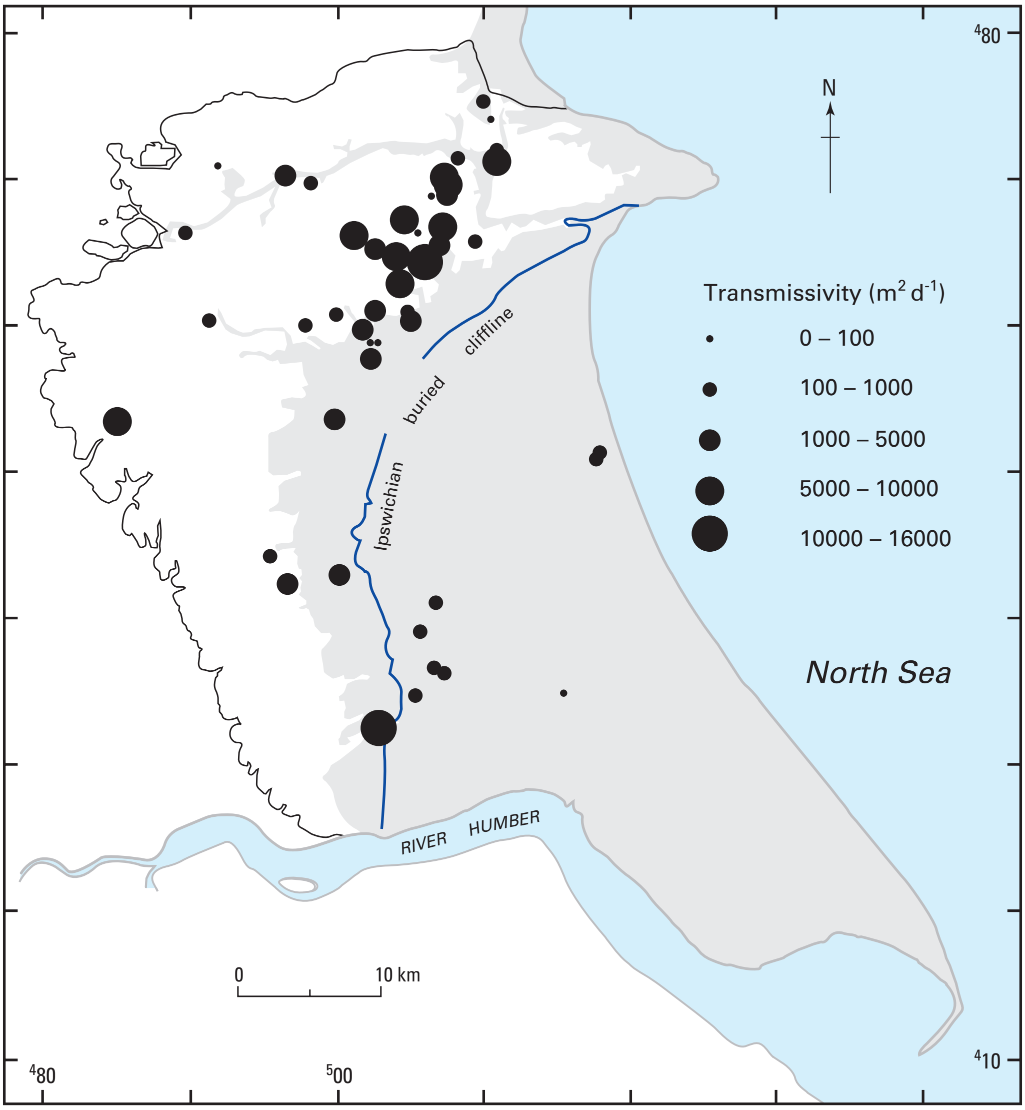


Figure 3.4 Distribution of transmissivity values measured in the Chalk aquifer.

where the water table lies in the chalk bearings. The University of Birmingham (1985) reported transmissivities of up to 8000 m^2 d^{-1} along the Wold Valley, an order of magnitude higher than those on the Octon Ridge to the south. Foster and Milton (1976) reported values of over 6000 m^2 d^{-1} around Haisthorpe, but these could be due to enlargement of fractures by marine erosion at the time of formation of the now buried cliffs (Figure 3.4), or to the concentration of flow towards the springs which emerge along the line of the buried cliff. The highest transmissivity values are found to the west of the buried cliff line away from the Quaternary cover (Figure 3.4). The distribution also suggests that the boreholes with the highest values tend to be located on the outcrop of the Flamborough Chalk Formation (see Figure 2.2). Interestingly, this Formation is lithologically most similar to the Chalk of southern England.

Transmissivity values tend to be low east of the edge of the Quaternary cover. Transmissivity is less than 50 m^2 d^{-1} beneath Holderness where there is little groundwater circulation and only limited scope for the enlargement of fractures by solution. Little is known about the aquifer properties in the structurally disturbed northern part of the Yorkshire Wolds, as there are very few groundwater abstractions and borehole construction in such distorted strata is difficult. A series of wells along the Hunmanby Monocline suggest a fairly low transmissivity of about 350 m^2 d^{-1} (Chadha and Courchee, 1978).

3.2.5 Storage coefficient

Allen et. al. (1997), collected and collated all available values of storage coefficient, omitting values greater than 0.1 as they could be erroneous or even reflect values in adjacent formations. The remaining values ranged from 1.5×10^{-4} to 1.0×10^{-1} (Figure 3.5). The geometric mean is 7.2×10^{-3} and the interquartile range is 1.5×10^{-3} to 1.8×10^{-2}. Higher storage coefficients (above 0.01) are associated with the presence of chalk bearings at the top of the confined Chalk.

Foster and Milton (1974) used laboratory centrifuge tests to demonstrate that gravity drainage of chalk pores was minimal, and concluded that they made little contribution to the useful storage of the aquifer. Recession analysis of groundwater levels, indicated that the Chalk comprised layered storage elements with specific yield values of 0.010, 0.015 and 0.005 to 0.010 respectively.

3.3 THE CHALK AQUIFER IN THE WATER CYCLE

3.3.1 Introduction

The hydrogeological regime in Yorkshire varies from the unconfined Chalk of the upland Wolds, through semi-confined conditions in the Hull catchment, to confined Chalk underlying Holderness. The majority of the Chalk

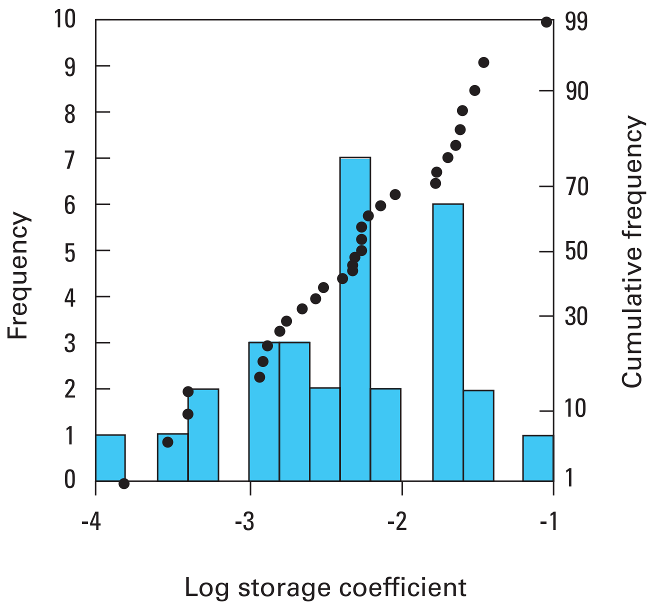


Figure 3.5 Frequency distribution of storage coefficient values from pumping tests in the Chalk aquifer in Yorkshire.

dips at an angle of about 1° to the east. Although low, this angle is steeper than the surface topography so progressively younger formations crop out in an easterly direction. The Welton and Burnham Chalk formations form the largest areas of outcrop in the west and north, the Flamborough Chalk Formation becoming increasingly exposed in the northern Wolds. The relative positions of the formations are shown in Figure 2.2 and in the section through Beverley in Figure 3.6. The location of the zone of groundwater level fluctuation is also shown. The Chalk is little used as an aquifer beneath Holderness due to the restriction of groundwater movement, and the consequent lack of development of fractures as well as the poor water quality. The unsaturated zone in the Yorkshire Wolds varies in thickness from less than 10 m in the Wold Valley to over 120 m on the higher ground. Seasonal head variations are small in the confined aquifer, but may be as much as 30 m in the unconfined aquifer. Fluctuations of about 10 m have been reported in the dry valleys (Robertson, 1984).

Groundwater flow is down hydraulic gradient from the Wolds, and either emerges as springs at the edge of the drift cover or the base of the Chalk escarpment, or is pumped from the semi-confined aquifer. The consistent hydraulic gradient towards the coast in the Flamborough area suggests that discharge of chalk groundwater takes place to the North Sea, either on the beaches, or below low tide level (Foster and Milton, 1976). There is a network of dry valleys across the Wolds, although there is little surface drainage, as the water table rarely intersects the ground surface. The only significant flow occurs in the Gypsey Race along the Great Wold Valley. Springs occur just south of the Chalk outcrop, and these flow over the glacial deposits to form tributaries of the River Hull.

3.3.2 Recharge

Recharge to the Chalk aquifer is a complex combination of slow matrix flow and rapid bypass flow. The quantity and timing of recharge is controlled by;

- the effective rainfall
- the thickness and permeability of overlying Quaternary deposits
- the thickness of the unsaturated zone
- the potential for rapid bypass flow

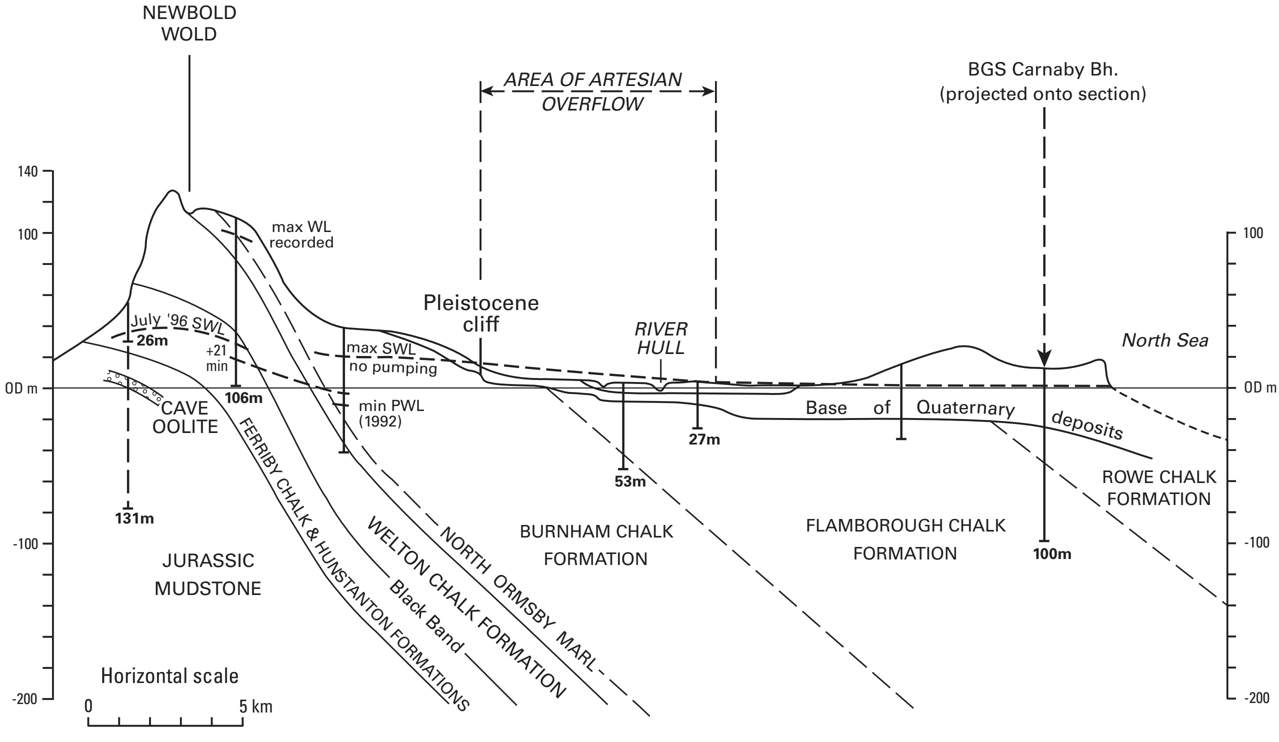


Figure 3.6 East–west cross-section through Beverley showing the Chalk formations and groundwater levels.

The unsaturated zone is extensively fractured, both vertically and horizontally, and local perched bodies of water are uncommon. Clay bands within the Chalk may, however, act locally as confining layers (Barker et al., 1984), and may control recharge pathways in the unsaturated zone. Percolation may not always be entirely vertical to the water table, as subhorizontal flow may occur along some of the more permeable horizons such as bedding planes or top of hardgrounds.

The small pore throats of the chalk matrix inhibit gravity drainage, so that the matrix remains almost fully saturated below the rooting depth of plants. As pressure potentials rise within the unsaturated zone during a recharge event, the vertical hydraulic conductivity increases as the fracture system begins to transport water to the water table. However, fractures appear to only retain and conduct water during, and for limited periods after, major infiltration events.

As with the chalks of the Southern Province, it is likely that fracture flow is initiated either after prolonged rainfall has reduced suction heads in the unsaturated zone, or after periods of intense rainfall (Jones and Cooper, 1998). Work at various sites in the south of England suggested that fracture flow only occurred when matric potential rose above –50 cm water; the frequency with which this happened depended not only on the input, but also on the hydraulic conductivity of the matrix (Wellings and Cooper, 1983). Sites with high matric hydraulic conductivity experienced fracture flow less frequently, as the matrix alone could accommodate the infiltration.

Zaidman et al. (1999) measured matric potentials in the Kilham area and used geophysical techniques to investigate tracer movement through the unsaturated zone. Tracer was applied at a rate of approximately 49 mm d^{-1} over a period of 57 hours. The very low hydraulic conductivity of the matrix in the area (less than 1 mm d^{-1}) suggests that the unsaturated chalk is likely to experience fracture flow regularly. In 1997/98, matric potentials were above –50 cm water throughout the profile for much of the 12 month period studied. The tracer experiments confirmed that fracture flow occurred at 20 m depth within the first day of the study, indicating transport was taking place through the whole joint system.

The estimation of recharge is important, as it is required for abstraction licence allocations as well as input to dynamic groundwater flow models for the area. Over many years, numerous estimates of recharge have been made, most have used the soil-water balance approach, some have used baseflow separation techniques, but none have incorporated bypass flow mechanisms.

Mean annual rainfall in the area ranges from over 750 mm in the Wolds uplands to less than 600 mm over Holderness. Potential evapotranspiration averages 425 mm a^{-1} (Berridge and Pattison, 1994). The long-term average infiltration in the Yorkshire Wolds has been estimated at about 300 mm a^{-1} (Versey, 1948; Green, 1950; Gray 1952; Foster and Crease, 1974), although estimates from baseflow separation have ranged from 100 to 605 mm a^{-1} (Foster and Milton, 1976). Recharge usually occurs between October and March; however, occasional small recoveries of groundwater levels during June and July suggest that minor recharge events may occur at other times, even when there is a significant soil moisture deficit (Foster and Milton, 1976).

Comparison of estimates of recharge is difficult due to the fact that different authors may have used different outcrop areas, and may have incorporated recharge through Quaternary cover in a variety of ways. Recharge estimates for a number of years are shown in Table 3.3 (Foster and Milton, 1976; Aspinwall and Co., 1995a).

Comparison of estimates from baseflow separation and water balance approaches for the period from 1962/63 to 1969/70 shows the following anomalies (see Figure 3.7):

- During dry years, the baseflow approach estimates recharge to be less than that of the water balance approach, but during wet years this trend is reversed.
- During 'average' years (recharge estimates between about 200 and 375 mm a^{-1}) the two approaches give similar results.

Foster and Milton (1976) attributed the differences to substantial infiltration through the till, particularly on the flanks of the Yorkshire Wolds and in the Hull Valley outside the confined area of the aquifer. It may also be due to changes in the size of the groundwater catchment contributing to baseflow between wet and dry years. It has been postulated that actual evapotranspiration may be over-estimated during the spring, the difference being greatest when there is a wet spring and the soil moisture deficit (SMD) develops later than in an average year (Cooper, 1985; Jones and Cooper, 1998).

Many of the temporal features of recharge are reflected in the long-term groundwater hydrograph from Dalton

Table 3.3 Recharge estimates for 1962/63 to 1991/2 for the area of the Chalk in Yorkshire.

Year	Recharge (mm a^{-1}) (Baseflow separation)	Recharge (mm a^{-1}) (Water balance approach)
1962/63*	200	213
1963/64*	274	254
1964/65*	100	201
1965/66*	605	483
1966/67*	350	343
1967/68*	287	257
1968/69*	551	424
1969/70*	427	363
1975/76		79
1976/77		409
1977/78		229
1978/79		346
1979/80		289
1980/81		376
1981/82		208
1982/83		265
1983/84		249
1984/85		243
1985/86		309
1986/87		202
1987/88		206
1988/89		204
1989/90		116
1990/91		195
1991/92		112

* Estimates from Foster and Milton (1976). All other estimates from Aspinwall and Co. (1995a) based on a recharge area of 1100 km^2

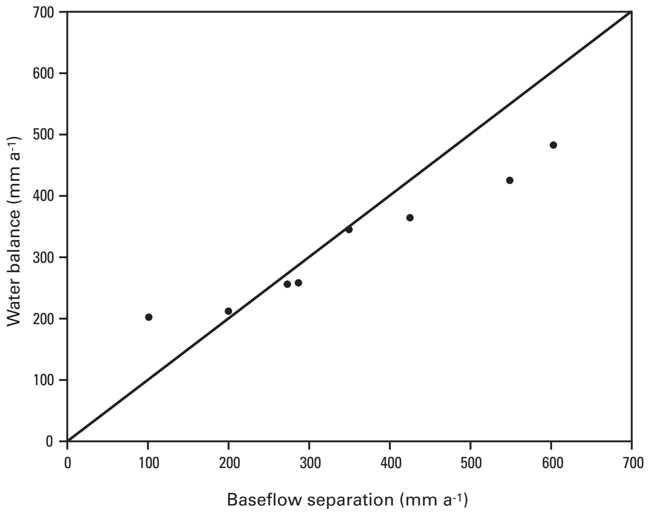


Figure 3.7 Comparison of annual recharge estimates (water balance vs baseflow methods) for the Yorkshire Chalk over the period 1962/63 to 1969/70.

Holme (Figure 3.8). For example, the very low recharge in 1975/76 is shown by minimal recovery of groundwater levels in 1976. The following year's high recharge is shown by recovery of groundwater levels in February/March 1977 almost to the maximum ever recorded. Similar events occurred in 1988 to 1990 and 1995 to 1997. Other low recharge events are found in the historic record.

Rates of infiltration vary according to the permeability of surface strata, and are, therefore, influenced by the presence or absence of Quaternary deposits. The till can possess limited, but significant permeability where it is weathered, of limited thickness, or where it contains sand or gravel lenses. In such cases, recharge, as high as 50 mm a^{-1}, is possible (Foster and Milton, 1976; University of Birmingham, 1985).

This factor has been incorporated in recharge calculations in various ways; for example, Gray (1952) allowed an arbitrary 50 mm a^{-1} of recharge to occur in all areas with greater than 9 m of till. Conversely, the University of Birmingham (1985) allowed no recharge to areas where the thickness of cover was greater than 5 m. However, Aspinwall (1995) assumed infiltration occurred through the Quaternary as it thins towards the outcrop of the Chalk, and recommended further fieldwork to determine recharge rates through these deposits.

For the purpose of licensing calculations, the Environment Agency estimates recharge using the standard Penman soil-water balance approach. The rainfall values used are the long-term average, determined during a water resources survey carried out in 1963 (Finch et al., 1995). The reduction in recharge due to Quaternary cover is accounted for as follows:

- if the cover is greater than 5 m thick the recharge is reduced to 50 mm
- if the thickness is greater than 10 m thick the recharge is reduced to 25 mm.

The moisture balance approach generally underestimates recharge (Foster and Milton, 1976; Downing et al., 1978; Rushton and Ward, 1979; Ward, 1976; Philips, 1978; Jones and Cooper, 1998). One of the main problems is that summer recharge is assumed to be zero despite the partial recovery of water levels in some boreholes during some summers (Rushton and Ward, 1979). In addition, summer groundwater recessions are normallly less than expected (Phillips, 1978; Lewis et al., 1993). The anomalies could be due to either rapid by-pass flow through secondary fractures, or the time delay between infiltration occurring at the surface and the effects being observed at the water table. Rushton and Ward (1979) proposed an alternative recharge mechanism allowing recharge to occur even when a soil moisture deficit existed.

Aspinwall (1995) used the concept of negative baseflow (described later in this chapter). This concept may account for a variety of additional recharge mechanisms, including overland and through-flow infiltration through the leaky Quaternary cover, by-pass flow through fractures, as well as river leakage. On a regional scale these distinctions may not be important, but may be critical for groundwater protection zone delineation and local groundwater studies, particularly where recharge through Quaternary cover is important.

Overall, recharge to the Chalk is complex and is not adequately represented by a simple soil water balance mechanism. Numerous other factors need to be considered in order for models to simulate reality more closely and to assess the potential for aquifer contamination.

3.3.3 Influence of Quaternary processes and deposition

The lithostratigraphy and distribution of the Quaternary cover in Yorkshire, and the effects of Quaternary processes on the Chalk itself, are important to the understanding of the hydrogeology of the Chalk. There are two main ways in which events during the Quaternary period have affected the present-day hydrogeological regime:

1) *Through modification of the Chalk during the Quaternary period.* For example erosion and weathering of surficial Chalk to produce chalk bearings or putty chalk at levels that are now in the saturated zone and may influence groundwater flow. The same features in the unsaturated zone could inhibit groundwater recharge. Buried channels and the buried cliff line are also important features. In addition, the presence of thick ice cover during the Quaternary

BOX 2 SOURCES OF 'EXTRA' GROUNDWATER

Analyses of pumping test data from sites in the Chalk aquifer frequently show a leaky aquifer response, even where the Chalk is unconfined (Jones et al., 1993; MacDonald, 1997).

There could be several potential sources of this 'extra' water, namely:

- leakage from the chalk bearings and more permeable layers in the boulder clay
- upward leakage from the Chalk at depth
- delayed drainage from the de-watered matrix and small fractures of the unsaturated zone
- leakage from a constant head boundary e.g. surface water, fracture zone etc.

Pumping tests alone cannot identify the source of the additional water. However, the limited test data and the hydrological settings suggest delayed drainage from the unsaturated zone as the likely dominant process (MacDonald, 1997).

period would have affected groundwater flow in the Chalk, and the presence of outwash drainage could also have affected recharge, as could different drainage patterns. Sea-level change has had a major impact on the evolution of the groundwater system, as base levels for much of the past 100 000 years were around 30 m below OD so that fossil zones of water table fluctuation are now well below present day levels (Edmunds et al., 2001).

2) *Quaternary deposits that affect present day recharge or groundwater flow*. For example low permeability deposits that confine the Chalk, and allow limited recharge or discharge and permeable deposits that may be hydraulically connected with, or independent of, the Chalk groundwater system. The lithological character of the Quaternary cover controls the relationship between the Chalk aquifer and surface watercourses in areas away from spring-heads (Foster and Milton, 1976).

There remains considerable uncertainty over the subdivision of some of the Quaternary deposits and new mapping is required over much of the area. Pumping tests on the Chalk beneath Quaternary deposits may yield ambiguous results and be difficult to interpret (University of Birmingham, 1985).

The distribution of permeable ‘chalk bearings’ (or chalk ‘head’) and impermeable ‘putty chalk’ is responsible for significant permeability variations in the Chalk aquifer. Williams, 1987, observed that putty chalk occurs on the upper surface of the chalk in elevated interfluve areas and beneath valley gravels in south-eastern England. Putty chalk is formed under periglacial conditions by repeated freezing and thawing in the zone above the perennial permafrost.

The harder chalk of Yorkshire, however, can respond to periglacial weathering to form coarse-grained breccia-like deposits known as ‘chalk bearings’, or ‘head’. This forms the floors of most of the dry valleys in Yorkshire and several pumping tests have established that they are in good hydraulic continuity with the Chalk (University of Birmingham, 1985). The chalk bearings have a higher storage coefficient than the unaffected Chalk, and hence they have a significant impact on the availability of groundwater supplies. A pumping test at Kilham indicated a recharge source and the chalk bearings in the Wold Valley might have been partially responsible (University of Birmingham, 1985). High permeabilities are also associated with the chalk bearings, for example, between 970 and 1260 m d^{-1} at North End near Great Driffield [TA 022 582] (Younger and McHugh, 1995). They also postulates that pre-Late Devensian weathering processes may be responsible for the high permeabilities associated with extensions of valley axes below the Quaternary cover.

Low permeability superficial deposits can reduce recharge and retard contaminant infiltration to the Chalk aquifer. Recharge to, and discharge from, the Chalk is restricted, and groundwater circulation is almost negligible beneath the low permeability deposits over much of east Yorkshire (Foster and Milton, 1976). As a result, permeability development of the Chalk in this area is inhibited. At distances of 10 km from outcrop, and throughout Holderness, the evidence available suggests a significant decrease in transmissivity towards the east. The groundwater has evolved chemically during slow transport to the east, with aerobic, often polluted groundwater at outcrop in the west, and older, reducing groundwater where the Chalk is confined in the east (Edmunds et al., 2001).

The Chalk becomes confined by low permeability drift about a kilometre to the east of the edge of the outcrop. Foster and Milton (1976) suggested that groundwater in the Chalk under artesian pressure would tend to discharge where the impermeable cover was thinnest, or where sand and gravel bodies were present. Over a long period of time,

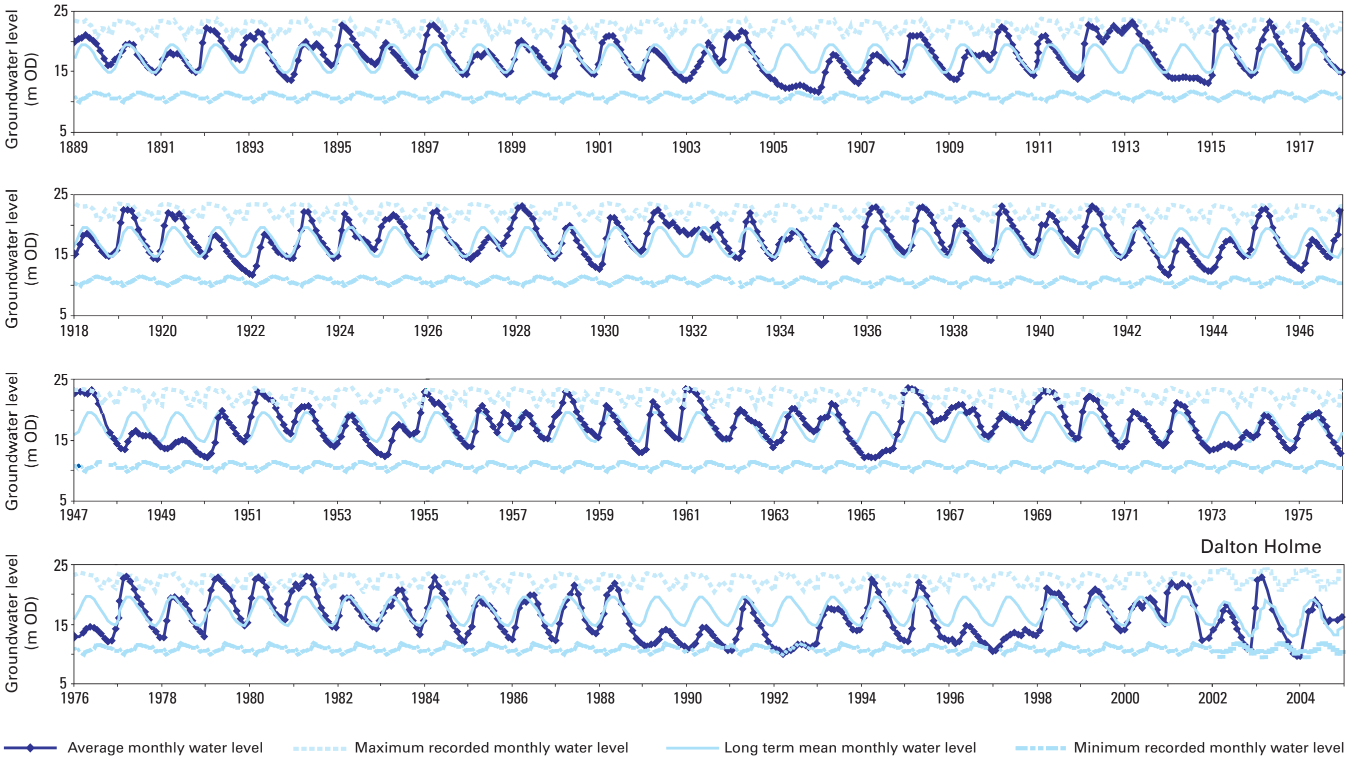


Figure 3.8 Groundwater level fluctuations at Dalton Holme Borehole, 1889 to 2002.

continued spring flow would tend to enhance permeability due to solution along fractures in the Chalk and removal of impermeable drift. Areas with spring discharges include the gravel deposits around Kilham, Great Driffield, and Leconfield, a little over a kilometre to the east of the outcrop.

A systematic evaluation of the superficial deposits in the Hull-Beverley area was carried out using data from 1563 boreholes (Hawkins et al., 1998). The thicknesses of weathered and unweathered clays, as well as the total thickness of the drift deposits, were used to produce thematic maps that assess the vulnerability of groundwater in the underlying Chalk aquifer. The maps can also be used to assess the distribution of drift over which recharge is likely to occur. Aquifer vulnerability is discussed further in Section 5.2.2.

Glacigenic sands and gravels form water-bearing deposits that are locally important and are more extensive than their outcrop area suggests because they are often overlain by till. Although the sands and gravels have been widely used for water supply in the past, the risk of pollution now limits their use. They act as a storage reservoir wherever they are in hydraulic continuity with the Chalk, and can significantly increase the storage available to the Chalk (Berridge and Pattison, 1994). Even thin layers of superficial deposits can have an important influence on recharge mechanisms.

Sands and gravels also occur as beds, lenses, channels and ridges at a number of levels in the till sequence, particularly towards the top (Foster and Milton, 1976). The geometry and character of the lenses is strongly dependent on their relation to the glacial system in which they were deposited. The shoreline deposits, the head and the loessic material within the deposits above the confined Chalk are thought to be in hydraulic contact with the aquifer (University of Birmingham, 1985). They are too thin to provide any significant storage, but they may allow two-way movement of water through the confining till cover and may contribute to the baseflow of surface watercourses. They may also significantly increase the transmissivity of the overall aquifer (Berridge and Pattison, 1994).

3.3.4 Groundwater storage

In an attempt to assess the volume of water stored in the British Chalk aquifer, Lewis et al, (1993), calculated the volume of the aquifer and estimated the components of storage, defined as;

- total storage: total volume of water (the product of rock volume and porosity)
- dynamic storage: drainable volume of water from the zone of natural water level fluctuations. This represents the volume that is discharged from the aquifer, either through natural discharge, or via abstraction
- drought storage: drainable volume of water for the interval from the minimum water level to 10 m below this level
- dead storage: drainable volume of water for the interval between 10 m below minimum water level and Ordnance Datum.

The calculated storage volumes for the Yorkshire Chalk aquifer are given in Table 3.4. The periods studied were selected using maximum groundwater levels (April 1975 and March 1988) and minimum groundwater levels (September 1976 and December 1990).

By way of comparison, the average annual infiltration was taken to be 275 × 10^6 m^3 and the annual average abstraction between 15 × 10^6 m^3 and 38 × 10^6 m^3, the former being given by Monkhouse and Richards (1982), and the latter by Aspinwall (1995). Although the estimated annual abstraction is in the range of the dynamic storage, it does not take into account the spatial variation of demands on the aquifer and careful management is still required.

Table 3.4 Calculated volumes of water stored in the Chalk aquifer, and overlying formations (after Lewis et al., 1993).

Storage	**Chalk (10^6 m^3)**	**Cover (10^6 m^3)**
Dynamic (1975/76)	14–30	10–53
Dynamic (1988/90)	21–57	9–50
Drought (1988/90)	27–70	24–130
Dead (1988/90)	26–46	0.2–1.2

At a national level, the model was validated against detailed studies of two catchments, the River Kennet and the River Itchen in the upper Thames Basin. These catchment studies indicated that the volume calculated as dynamic storage was significantly less than the volume attributed to baseflow. This was accounted for by additional water from delayed recharge. The concept of delayed recharge allows for some of the large volume of water stored in the permanent unsaturated zone (i.e. above the zone of water table fluctuation) to reach the water table. This unsaturated zone storage is transient and depends on antecedent recharge.

Foster and Milton (1976) also calculated volumes of water draining from the Chalk aquifer of Yorkshire, using baseflow hydrographs, and found a similar discrepancy to that found for the Chalk of southern England. Comparison of these volumes with infiltration values calculated from meteorological methods suggested that infiltration was underestimated as it was assumed that there was reduced or non-existent recharge through the till. Whatever the explanation, it is likely that the volume calculated as dynamic storage is an underestimate.

The mechanisms controlling the storage and release of water in the unsaturated zone have been the subject of much speculation. Price et al. (2000) attempted to characterise macropores and microfissures in the laboratory using mercury injection and resin impregnation techniques as well as acoustic measurements of samples as the effective stress was increased. Although samples were tested from only three sites, no confirmation could be found that microfissures and macropores contribute to drainage and permeability. However, a clear correlation between drainage from blocks and the block surface roughness and relative area was established for drainage from the unsaturated zone. More water drains from rougher surfaces and smaller blocks. The volumes of water required to explain the observed delayed drainage phenomenon can be accommodated by this mechanism.

Unsaturated zone storage contains significant volumes of water in the Chalk that need to be taken into account in resource assessment. For the same groundwater level, the volume of water stored in the unsaturated zone will be greater at the end of a recharge period than at the beginning. The zone also acts as a buffer in delaying the response of the water table to recharge and provides resilience to periods of drought through gradual drainage to the water table. It is postulated that flow in fractures need not be initiated from the surface and can occur at any level in the unsaturated zone when the suction in the chalk blocks falls to a level that permits water in the matrix to fill irregularities on fracture surfaces (Price et al., 2000).

3.3.5 Groundwater level fluctuations

The Environment Agency currently monitors groundwater levels in about 220 boreholes in the Chalk aquifer in Yorkshire at a variety of intervals depending on the planned use of the data. The longest record is at Dalton Holme Borehole [SE 9651 4530] (Figure 3.8). Measurements were first taken on 21 January 1889 and have continued at weekly intervals with very few breaks making it one of the longest records in the Britain (BGS/NRA, 1992). The groundwater level data from Dalton Holme, together with that from the Wetwang borehole contribute to the National Hydrological Monitoring Programme. This programme provides information on the state of the nation's water resources on a monthly basis.

Groundwater level contours for the Chalk aquifer in Yorkshire were compiled bi-annually by the National Rivers Authority between 1979 and 1990. From these records two dates were selected to represent 'high' and 'low' groundwater levels: March 1981 (Figure 3.9a) and January 1990 (Figure 3.9b). These show that the general direction of groundwater flow is from west to east, with the contours generally reflecting a subdued version of the topography. As would be expected, greatest depth to water is seen across the high ground of the Wolds, decreasing to the east and least in dry valleys. On the interfluves, the greatest depth to water recorded was 107 m below ground level at Low Mothorpe borehole [SE 893 670]. The differences between maximum and minimum groundwater levels range up to 50 m; the greatest values tending to occur beneath the higher ground.

The long-term record for the Dalton Holme borehole provides an historical perspective to groundwater levels in the area (Figure 3.8). Early records were taken at weekly intervals, although more recently recording takes place up to 40 times per year. Bennett (1996) analysed water level data as part of an investigation to predict groundwater levels from rainfall data. He noted that most annual minima occur between October and January, although a few minima occur in other months. He was able to account for 77% of the variance of the data using a simple regression analysis approach to predict annual minimum water levels from rainfall data. However, predictions differed from actual data during extreme wet or dry periods. Further work indicated that the current month's rainfall had little effect on groundwater levels for that month; instead, the aggregate rainfall from up to five months previously exerted a stronger control.

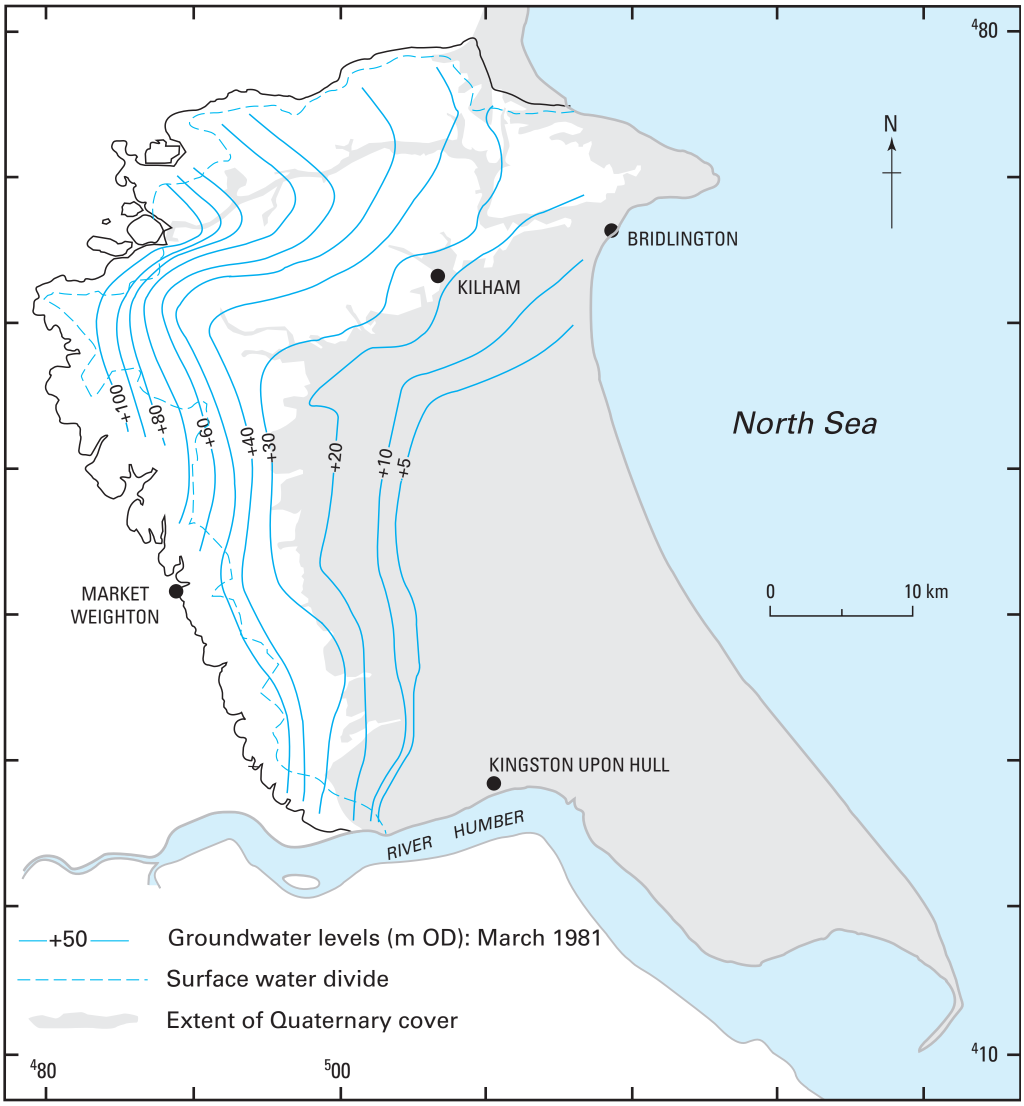


Figure 3.9a Water level contours in the Chalk aquifer, March 1981.

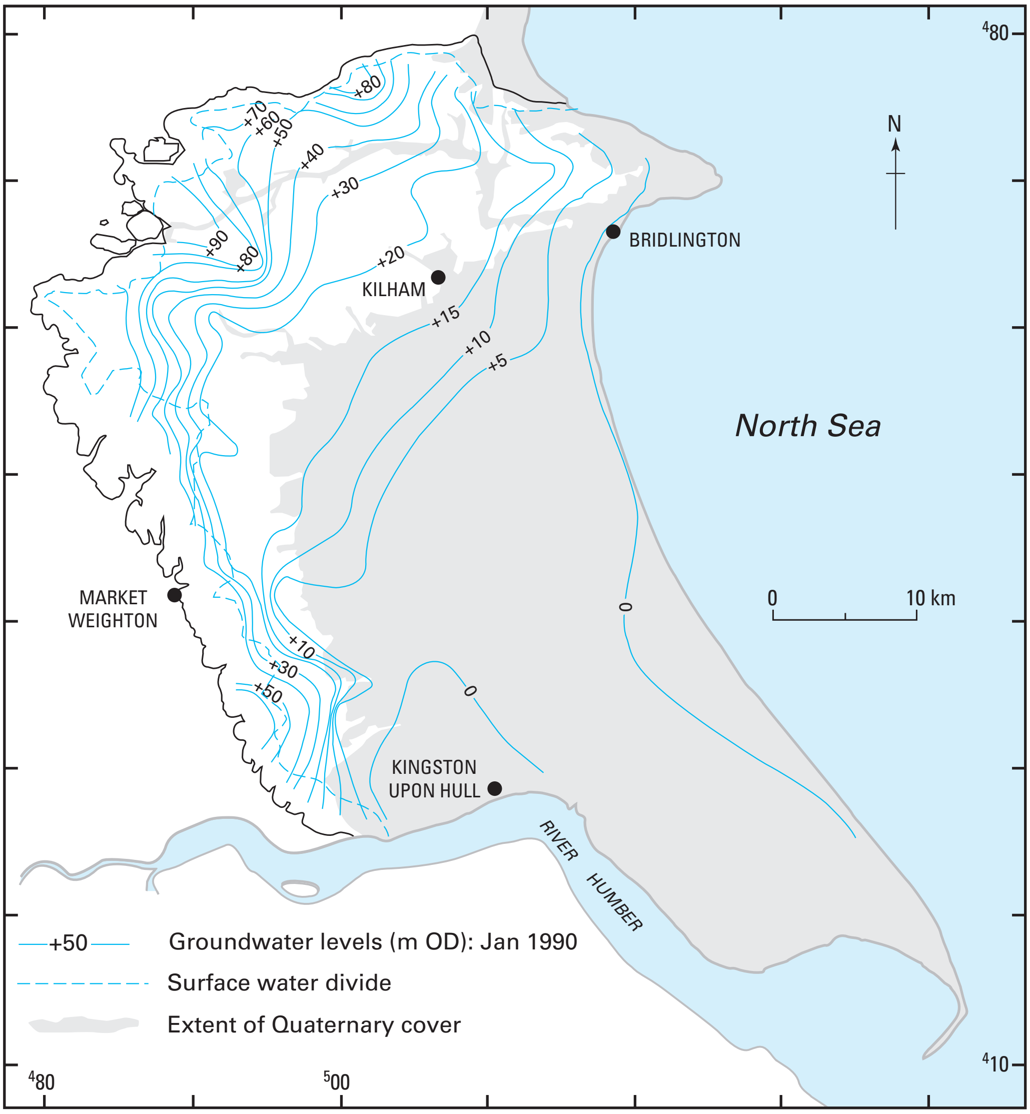


Figure 3.9b Water level contours in the Chalk aquifer; January 1990.

The area of artesian flow as defined by Foster and Milton (1976) for March 1970 for the upper Hull catchment is shown on Figure 3.1. Almost all the data showing groundwater levels above ground surface are located along stream or river valleys. These artesian groundwater conditions are subject to decline through major groundwater abstraction. A decline of groundwater levels was suggested by Younger et al. (1997) who observed that most of the springs between Beverley and Hull have dried up over the last century, mainly since sustained groundwater abstraction started at Cottingham in the 1930s.

There are a few locations (Dringhoe Manor [TA 151 555], Hornsea [TA 183 488], and Catfoss Manor [TA 144 469]) where the confined groundwater towards the east coast flows under artesian pressure. Other boreholes in the area do not flow at the surface. However, boreholes such as those drilled by British Gas north of Hornsea [TA 183 488] and the MOD boreholes at Lissett [TA 153 578] were not monitored until at least 1985, and, therefore, no records of the high maximum water levels recorded during the 1970s and early 1980s are available.

3.3.6 Streamflow and surface water/groundwater interaction

There is little surface drainage across the Wolds outcrop as the water table rarely intersects the ground surface. The exception is the Gypsey Race, along the Great Wold Valley (Figure 3.1) that flows along the entire length of the valley only during periods of high groundwater level. At times of lower groundwater levels the flow is intermittent, and in the late summer and during periods of drought, the entire Wold Valley becomes dry (Allen et al., 1997). Springs occur close to the edge of the confined aquifer, although there are some small springs at distances of up to 5 km into the drift cover. Springs feed streams that flow over the Quaternary cover to form tributaries of the River Hull (Figure 3.1). This tributary system can be divided into two: the West Beck and the Frodingham/Foston Beck catchments. The two streams join near North Frodingham to become the River Hull, which flows across the Holderness Plain and through Kingston-upon-Hull to join the River Humber. The River Hull is tidal below Hempholme Lock. A series of springs also occurs along the Chalk escarpment, emanating from the contact between the base of the Chalk and the underlying Jurassic clays (Foster and Milton, 1976). The locations of the springs are controlled by the disturbances associated with the formation of the escarpment and their effect on jointing in the Chalk.

The Gypsey Race is a complex watercourse. The Upper Gypsey Race originates in a number of small escarpment springs. These, uniquely, do not flow towards the Derwent River, but coalesce and flow back onto the Chalk outcrop as a result of topographic modifications (Foster and Milton, 1976). This section of the river is perched to some degree, but overall is influent and gradually decreases in flow due to leakage to the underlying Chalk (Figure 3.10). It normally has a flow of between 5.2 × 10^3 and 17 × 10^3 m^3 d^{-1} at Kirby Grindalythe and flows approximately 10 km to Weaverthorpe before disappearing completely as a result of streambed leakage. Maximum flows exceed 39 × 10^3 m^3 d^{-1}, when the Upper Gypsey Race may flow the length of the Great Wold Valley to join with the Lower Gypsey Race. Foster and Milton (1976) noted that the net hydrological effect of the Upper Gypsey Race is to generate groundwater recharge, estimated to be in the region of 9 × 10^3 m^3 d^{-1} in the Hull-Hempholme catchment, resulting in a recharge mound on the Chalk water table.

The Lower Gypsey Race appears to be a conventional water table river (Figure 3.10). It originates in various springs along the Great Wold Valley, and flows to the sea at Bridlington. At high Chalk groundwater levels, the contributory springs are to the west of Wold Newton down to Burton Fleming and more springs occur downstream of Rudston. Between Burton Fleming and Rudston the river flow appears to be fairly constant, varying locally between effluent and influent. There is a considerable quantity of discharge from the Chalk aquifer to the Lower Gypsey Race. During groundwater recession, the springs gradually decrease in flow, with the upper set of springs around Wold Newton eventually ceasing to flow. The springs in the Rudston to Boynton area normally flow for much of the summer, although these may also dry in the autumn. Complex flow conditions may occur for short periods during periods of rapidly rising groundwater levels (Foster and Milton, 1976).

The other major surface water courses in the area are the two tributaries of the River Hull: the West Beck and Frodingham Beck. The flow in the tributaries is maintained by springflow from the Chalk aquifer, although at higher flows, there is also a component of surface run-off and bank storage (Foster, 1974). Thus groundwater levels are the main controlling influence on flow.

The catchments of the tributaries were originally extensive marshland areas. Major changes occurred to the landscape with the construction of a drainage scheme and engineering river channels in the 18th and 19th centuries. The River Hull and its tributaries now act as high-level carriers, much of the river system is embanked with water levels higher than the surrounding land. The relationship between groundwater storage and streamflow is complex. The flow recessions of the West Beck and Foston Beck (tributary of Frodingham Beck) cannot be represented by a simple log-linear relationship (Foster, 1974). Instead the recessions split into a number of log-linear segments.

The study of Foston Beck by Foster (1974) was terminated due to the complexity of its relationship with the Gypsey Race to the north and east. However, the West Beck was studied in more detail. The bulk of the flow in the West Beck originates from a group of artesian springs south-west of Great Driffield. At times of high groundwater levels, the increase in pressure cannot be fully dissipated by increased flow at the springheads, and new springs and seepage areas are initiated at higher levels. The West Beck then flows south over the drift-covered chalk, until it coalesces with the Foston Beck to form the River Hull. Records indicate that the West Beck tributary contributes more than 80% of the inflow to the River Hull. The groundwater flow regime was interpreted by Foster (1974) to be caused by steadily increasing transmissivity towards the stream as a result of solution-enhancement of fractures in the Chalk.

The river-flow data for the West Beck was plotted against groundwater levels in boreholes upstream of the major springheads. If the aquifer behaves as a homogeneous, linear storage reservoir, these plots would be linear. However, the plots indicated that there was not a single linear relationship; rather there were at least two linear storage elements, corresponding to flows greater and less than 216 × 10^3 to 260 × 10^3 m^3 d^{-1}. There was also a third element for some boreholes for flows less than 86 × 10^3 m^3 d^{-1}. The data were interpreted as evidence of an overall layered hydraulic structure in the Chalk aquifer, with each storage element having a unique combination of transmissivity and storage.

A study by Halcrow (1998) highlighted several features about the aquifer/surface water interaction.

- Baseflow contributions maintain low flows at fairly consistent levels throughout drought periods, whereas wet periods can produce more than a fourfold increase in springflow.
- Baseflow contributions during dry periods extend the flow period during times of no recharge.
- Annual discharge can vary considerably from year to year.
- The timing and volume of flows depends as much on cumulative recharge, i.e. antecedent conditions, as the recharge during a particular period.

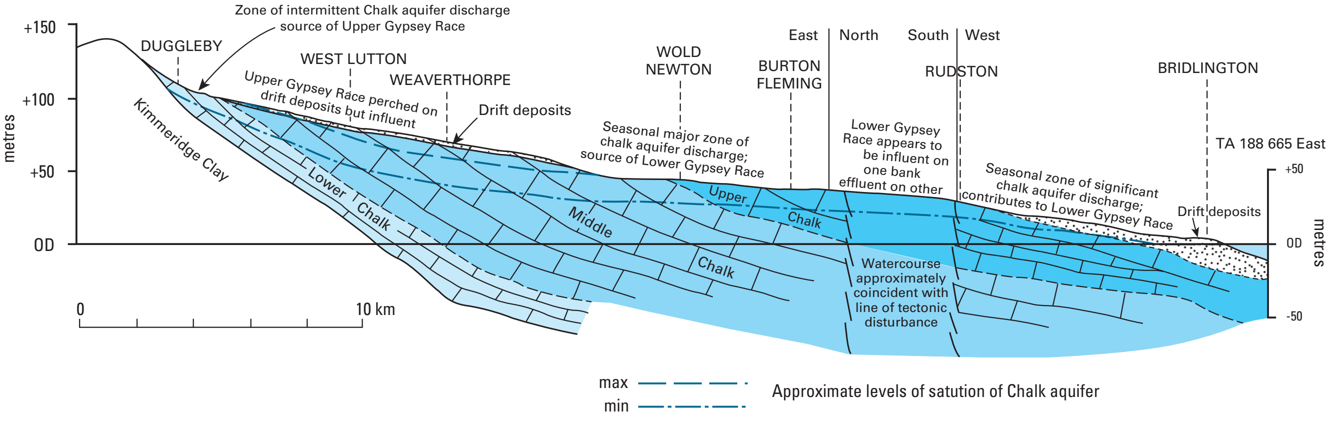


Figure 3.10 Hydrogeological profile along the Upper and Lower Gypsey Race (after Foster and Milton, 1976).

The early 1990s were characterised by periods of low flow every autumn, particularly in the West Beck. Halcrow (1998) showed that such low flows are directly attributable to lower than average rainfall, which reduces recharge and, as a consequence, springflow from the Chalk. Such low flows may result in a build-up of silt, and adversely affect the local aquatic community. Modelling of the groundwater regime indicated that even complete cessation of abstraction would not significantly benefit spring and streamflow in the upper reaches of the tributaries: the modelling predicted that flows at Hempholme would be reduced by less than 1% of the average total flow.

Halcrow (1998) also found that there was a marked increase in river flow beyond a certain ‘threshold’ groundwater level, and suggested this was a feature of the low storage, high transmissivity Chalk aquifer. They indicated that the groundwater level/surface water flow plots could be used to predict low flow periods. For example, whenever groundwater levels at Elmswell or Wetwang fall below 18 m above OD, low flow in the West Beck catchment is imminent. High flow problems were found to be more difficult to forecast, although flood risk was perceived to be greatest after heavy rainfall at times of raised groundwater levels.

3.3.7 Groundwater flow in the saturated zone

Groundwater movement on a regional scale tends to follow the dip of the Chalk and flow is perpendicular to the major groundwater divide that closely parallels the Chalk escarpment.

Groundwater flow along the Wolds escarpment is towards the west and a pronounced spring line occurs at the boundary between the Chalk and the underlying impermeable Jurassic strata. Localisation of springs is dependant on disturbances associated with the formation of the escarpment and their effect on the joint pattern of the Chalk (Foster and Milton, 1976). Control is further complicated where permeable drift is banked up against the escarpment, or where the Chalk is underlain by permeable Jurassic strata.

Studies during the 1970s revealed elevated tritium levels as well as higher nitrate concentrations in the spring waters from the escarpment than in the unconfined dip-slope groundwaters (e.g. Foster and Crease, 1974). This suggested that infiltration to the water table is more rapid in the escarpment area, either as a result of greater importance of rapid by-pass flow along fractures or a reduced thickness of the unsaturated zone, or both.

Some groundwater discharge probably reaches the North Sea directly through the land drainage system to the south-west of Bridlington. Analysis of water samples from some of the drains showed similar chemistry to Chalk groundwaters in the area (Foster and Milton, 1976). Changes in flow direction occur locally where affected by abstraction. In the Humber area, flow is concentrated southwards towards Hull as a result of abstraction. There is little groundwater flow in the Chalk aquifer beneath the Quaternary cover of Holderness.

Groundwater flow in the saturated zone is concentrated along fractures that have been enlarged by solution, rather than through the chalk matrix. There is extensive evidence that the chalk aquifer comprises layers with different hydraulic characteristics. Borehole logging carried out in Yorkshire as part of the river augmentation study (Robertson, 1984) identified major fracture zones and in some cases indicated whether they are likely to be dewatered during pumping or during times of low groundwater level.

Foster and Milton (1976) developed a schematic interpretation of the aquifer with a well fractured, high permeability layer in the zone of water-table fluctuation, and a second high permeability zone approximately 20 m below minimum water level (Figure 3.11).

The effect of dry valleys on groundwater flow and on aquifer properties is unclear. Solution enhancement of fractures is well developed in the valleys due to the concentration of flow, and it is thought that transmissivity

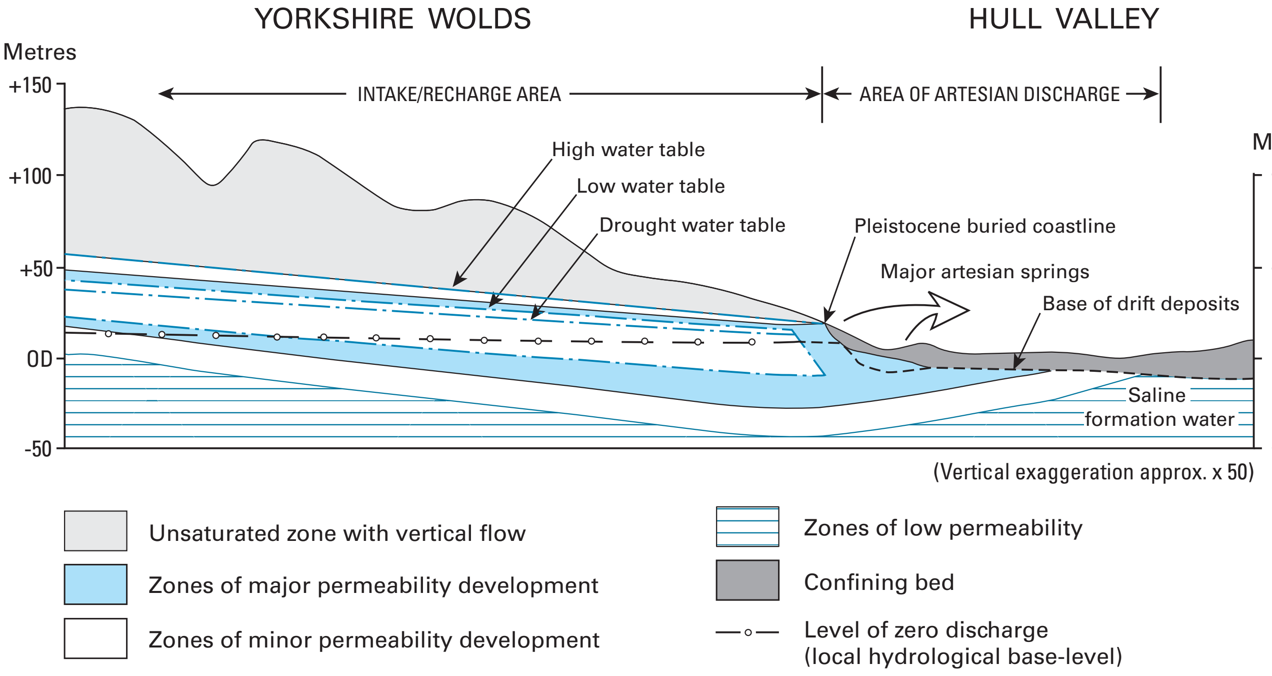
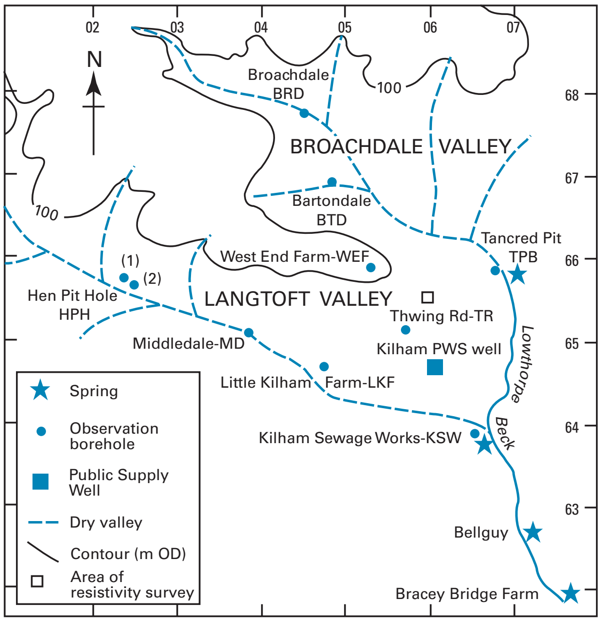


Figure 3.11 Schematic hydrogeological interpretation of the Yorkshire Chalk (after Foster and Milton, 1976).

BOX 3 TRACER TESTING AT KILHAM [TA 06 65]



A series of tracer tests were carried out to evaluate the hydrogeological conditions controlling groundwater flow in the vicinity of Kilham Pumping Station (Ward and Williams, 1995; Ward et al., 1997). Preliminary tracer tests focused on establishing hydraulic connection and groundwater velocities between observation boreholes along the dry valleys (the Langtoft and Broachdale valleys) up hydraulic gradient from the pumping station. Further tests were directed at extending understanding of the local groundwater flow, and utilised multiple injection and sampling points, including observation boreholes, the Pumping Station well, and springs. The latter phase of testing also involved drilling and testing a borehole on the interfluve between the two valleys.

The initial testing used injection points as high up the dry valleys as possible (Broachdale and Hen Pit Hole boreholes). Monitoring for tracer was carried out further down the valleys at Tancred Pit Borehole and spring, and Bartondale Borehole in the Broachdale Valley, and at Middledale and Little Kilham boreholes in the Langtoft Valley. The results indicated groundwater velocities (based on first arrivals) of up to 480 m d^{-1} for the Langtoft Valley, and 440 m d^{-1} for the Broachdale Valley, although tracer was not recovered in all boreholes sampled. The later phase of testing concentrated on the lower parts of the valleys, and the interfluve, with injection at Little Kilham Farm, West End Farm, and Tancred Pit boreholes, and sampling at Kilham Pumping Station well, Kilham Sewage Works, Bellguy springs, and Bracey Bridge spring. In this phase of testing, the only tracer recovered was that injected at West End Farm: this bypassed the Kilham Pumping Station well, and appeared downstream at Kilham Sewage Works, and the Bellguy springs. At the latter, two separate ‘packets’ of tracer appeared, suggesting there could be two distinct flow paths. The approximate groundwater velocities calculated were 130–150 m d^{-1} at Kilham Sewage Works, and 300–475 m d^{-1} (first arrival) or 125–140 m d^{-1} (second arrival) for Bellguy springs. These results are interesting, in that the tracer injected into the interfluve borehole was detected nearly 4 km away, but was not detected at the closer Kilham well only 1.5 km distant. Ward et al. (1997) suggested that the tracer did not enter the ‘true’ capture zone of the Kilham well, but passed either around or below it. Despite this, the tests prove rapid flow can occur through the Chalk on interfluves.

The testing also suggested that, in some cases, groundwater flow is restricted to bedding plane fractures, and in other cases, flow may occur across bedding planes. It is possible that vertical movement with regard to bedding planes occurs close to springs, where groundwater flow has been focused and has developed solution enhanced fractures.

tends to be higher along the valleys than in the interfluves. Flow velocities of up to 480 m d^{-1} have been estimated from tracer tests in the Langtoft and Broachdale valleys in the Kilham area (Ward and Williams, 1995; Ward et al., 1997) (Box 3.2). However, testing also suggested velocities of up to 475 m d^{-1} from an interfluve borehole to a spring below Kilham pumping station. Foster and Milton (1974) suggested rates of flow of up to 200 m d^{-1} in the Etton area.

Gamma, caliper and caliper-corrected resistivity logs as well as conductivity-temperature and flow logs were used by Buckley and Talbot (1994) to identify major active fracture horizons. The study indicated that solution-developed fractures tended to be parallel to bedding and were often developed just above relatively lower porosity bands that act as hydraulic barriers and concentrate groundwater flow. Correlation of five flowing horizons could be made between boreholes at the Kilham pumping station. These horizons were located in the boreholes at intervals of 4 to 9 m from elevations of +21 m OD to –9 m OD. The water level was at about +22 m OD so the fractures all contribute to flow to the boreholes. Less well-characterised flowing horizons occur in other boreholes in the area at intervals ranging from 2 to 10 m, but mainly between 2 to 5 m.

A 100 m cored research borehole drilled at Carnaby Moor into the Sewerby member of the Flamborough Chalk showed a high fracture density with an average spacing of 0.17 m. However, flow logging identified only five significant flowing horizons at depths of 42, 50, 56, 72 and 80 m (Bloomfield and Shand, 1998). The Chalk here is characterised by frequent marl bands and stylolitic horizons and an absence of flints. The matrix porosity values range from 18 to 28% with a mean value of 23%. This is lower than typical values of 35% for the Upper Chalk in northern England (e.g. Bloomfield et al., 1995) and this may reflect either the impacts of burial diagenesis or may be related to tectonic activity (Peacock and Sanderson, 1994).

Hydraulic continuity may exist between the Chalk aquifer and underlying units. These include the Inferior Oolite/Cornbrash, the Kellaways Beds, and the Corallian Limestone. Where the Chalk overlies minor Jurassic aquifers in Yorkshire, there is likely to be downward leakage from the Chalk, but the size of the spring flows from the Jurassic outcrop suggests that this transfer is probably extremely small.

3.3.8 Groundwater abstraction

Groundwater abstraction is important in both the confined and unconfined aquifers. Most abstraction boreholes are concentrated in a north–south line through Driffield and Beverley where the population is greatest, though abstraction from parts of the unconfined aquifer is also significant and supplies the rural population. The major licensed abstractor within the area is Yorkshire Water Services Ltd (Aspinwall and Co., 1995a). The history and extent of abstraction is described in the chapter on groundwater management.

The aquifer has been heavily developed for many years, resulting in the drying-up of dip slope Chalk streams and,

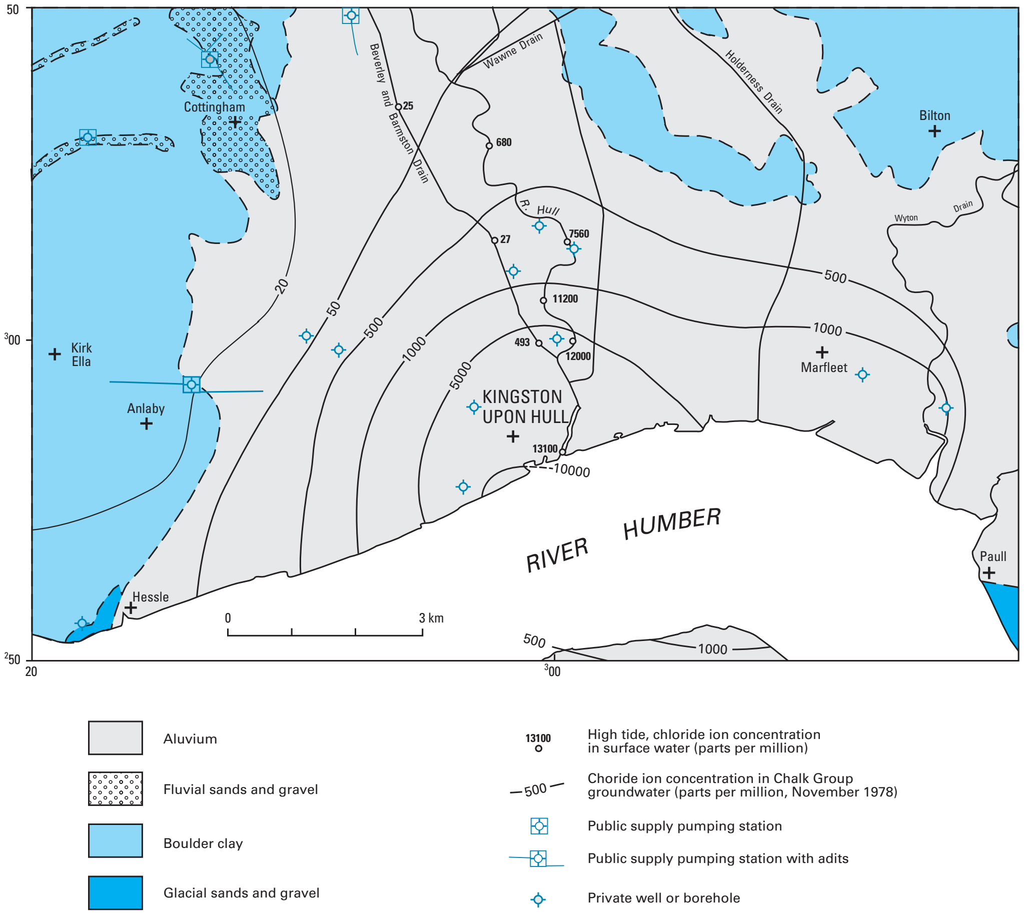


Figure 3.12 Extent of saline intrusion in the Kingston-upon-Hull area (after IGS, 1980).

in the Kingston-upon-Hull and Holderness areas, saline intrusion from the Humber Estuary (Foster and Milton, 1976; Chadha, 1986). North of Beverley, artesian flow has ceased and boreholes that were once artesian now require pumping.

Prior to 1976, total groundwater abstraction in the Kingston-upon-Hull area exceeded the estimated annual recharge for a period of at least 70 years. Heavy, continuous pumping significantly reduced the natural discharge of water in the area: the artesian area was reduced, and the piezometric surface lowered to more than 10 m below OD in places, and saline water intruded into the aquifer (Figure 3.12).

Monitoring between 1976 and 1980 suggested that, although the zone of mixing might have increased slightly, the saline front was almost static. It was thought that the situation was partly ameliorated by the fact that transmissivity decreases down dip to less than 200 m^2 d^{-1}.

The estimated actual abstraction from the Chalk aquifer in Yorkshire is 38 × 10^6 m^3 yr^{-1} (Aspinwall, 1995a). Major abstractions from the Chalk are given in Table 5.1. Typical yields from large diameter boreholes in the Chalk are around 4–7 Ml d^{-1}, varying considerably depending on the intersection of fracture zones. The limiting yield of a borehole is approached at drawdowns of around 20 to 25 m; hence the presence of fractures below this zone is important. Robertson (1984) found that in the Kilham area, the water table zone (20 to 40 m above OD) gave a relatively low yield; 80% of the yield was derived from the zone below this (0 to 20 m above OD).

The hydrogeological location of a groundwater source in the Chalk aquifer can have an impact on the yield and quality of the water abstracted. This was clearly illustrated by Chilton et al., 1997, in a study of trends in nitrate concentration in the Yorkshire Chalk aquifer. The hydrogeological settings at three representative sites are used to illustrate the controls on groundwater flow, catchments, transit times and hence quality (Figure 3.13). Understanding the flow and transport mechanisms helps to predict trends in water quality and the delineation of groundwater protection zones. These are discussed further in Chapter 5.

3.4 MODELLING THE CHALK AQUIFER

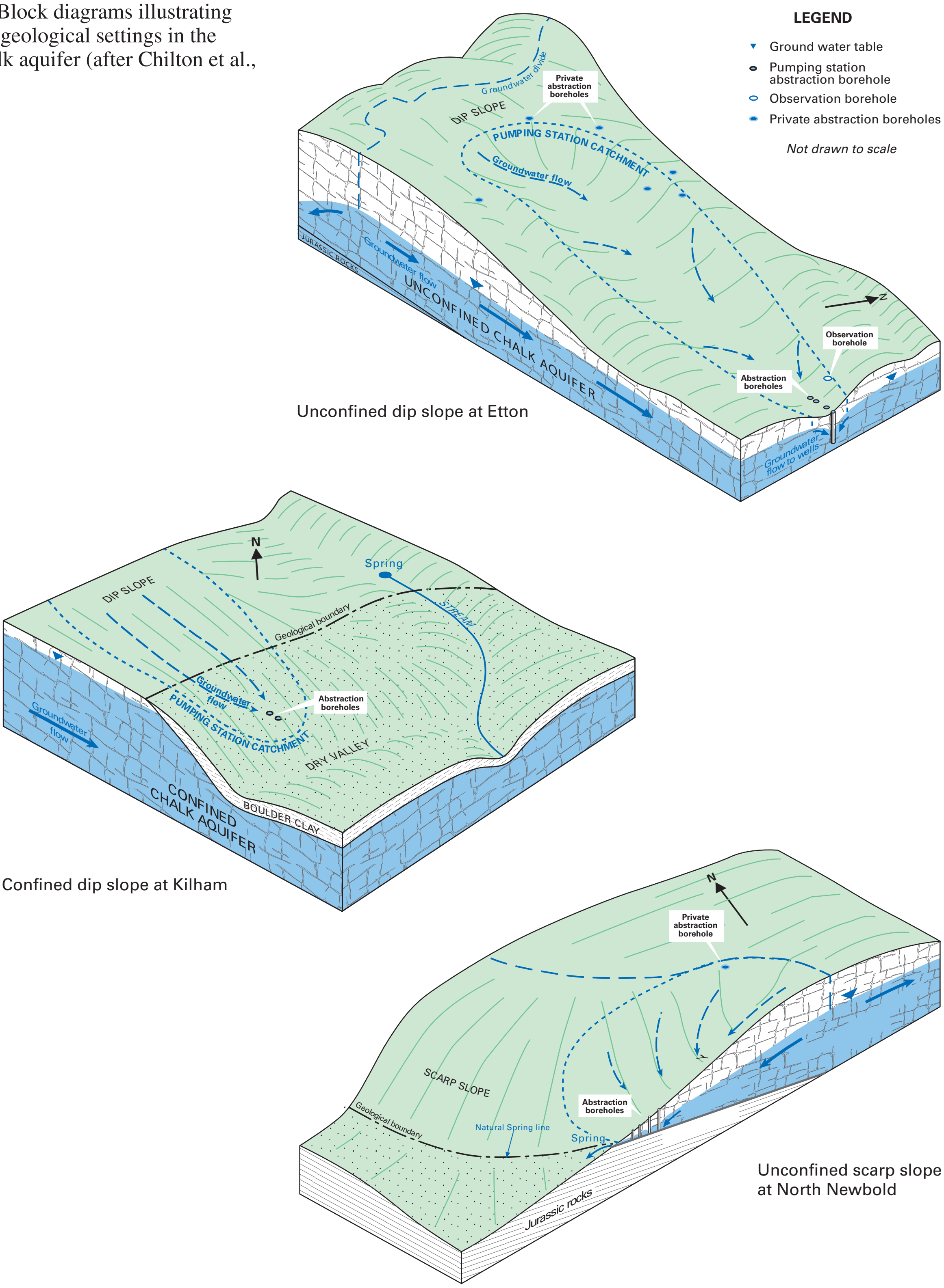
3.4.1 The conceptual model

Recharge to the Chalk aquifer through outcrop in the Wolds normally ranges from 300 mm to 350 mm. (Elliot et al., 1998). Movement through the unsaturated zone is largely through the matrix at a rate of up to 1 m a^{-1} and evidence for rapid by-pass flow is ambiguous. Delayed drainage and storage in the unsaturated zone have also yet to be quantified for the Chalk in Yorkshire.

Where the Chalk aquifer is confined to the east of the River Hull, beneath Holderness, recharge and transmissivity are low and there is little groundwater movement. Evidence for this is the low permeability of the Quaternary cover, the 'flat' potentiometric surface that fluctuates little, low yielding boreholes and brackish to saline groundwater, some considered to be Ipswichian in age. However, to the west of the River Hull, the deposits are more permeable in places, enhanced by spring discharge through these deposits.

The thickness of the unsaturated zone ranges from a few metres in the bottoms of valleys to about 120 m beneath the higher ground forming the Wolds. Annual groundwater level fluctuations beneath the Wolds can be as much as 30 m. Within this zone of groundwater level fluctuation, the fracture permeability is commonly enhanced and provides

Figure 3.13 Block diagrams illustrating different hydrogeological settings in the Yorkshire Chalk aquifer (after Chilton et al., 1997).



Unconfined dip slope at Etton

Confined dip slope at Kilham

Unconfined scarp slope at North Newbold

the main conduit for groundwater movement. Additionally, sub-horizontal zones of enhanced permeability have been identified at approximately 20 to 30 m above and 20 m below the current zone of fluctuation. These zones are likely to be related to previous sea levels during the Quaternary period. As the strata dip gently to the east and south-east, the zones of solution-enhanced permeability cut across the formations in the Chalk Group. The lower two zones of enhanced permeability are the main active flow zones and they appear to merge beneath the Quaternary cover near the Pleistocene buried cliff line. This line of high permeability is also associated with major spring line discharge through more permeable areas in the Quaternary cover.

The matrix porosity of the Chalk aquifer ranges between 20 and 45% with a mean value of about 35%. The mean matrix permeability measured on core samples is of the order of 10^{-4} m d^{-1}. However, the groundwater potential is in the fracture permeability, where solution-enhanced, in the unconfined aquifer. The bulk permeability of major flow zones is around 200 m d^{-1} and transmissivity values can range from 1 m^2 d^{-1} to over 10 000 m^2 d^{-1}, although the mean value is around 1300 m^2 d^{-1}. East of the buried cliff

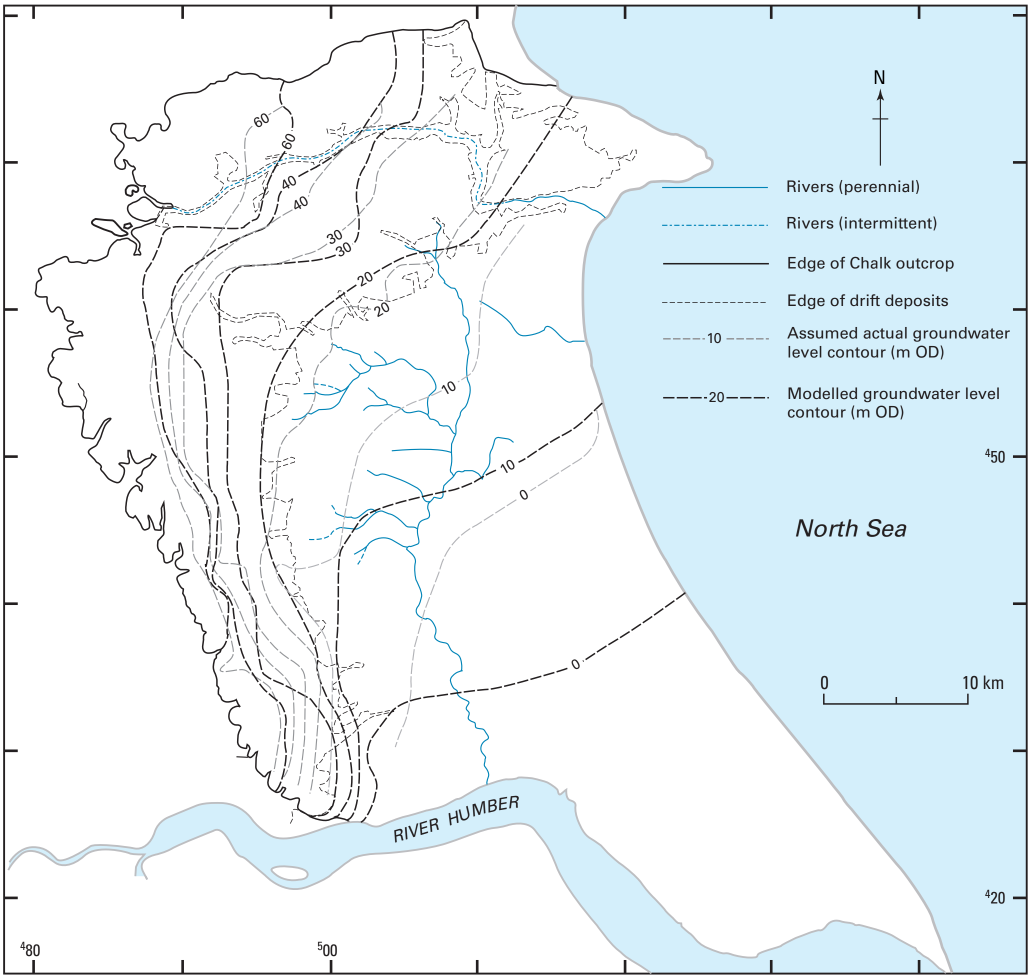


Figure 3.14 Observed and modelled groundwater levels in the Yorkshire Chalk aquifer in April 1990 (after Salmon et al., 1996).

line in the confined part of the aquifer, the transmissivity is less than 50 m^2 d^{-1} and the groundwater becomes increasingly brackish.

Chalk bearings, resulting from the break up of the Chalk surface through ice action, are found along the floors of most of the dry valleys. As the bearings have high storage coefficients and permeabilities they can have a significant influence on the local hydraulic properties of the aquifer. Lenses and beds of glacigenic sands and gravels in the Quaternary deposits overlying the Chalk formations can also influence the transmissivity and storativity.

Discharge of groundwater also occurs at the junction between the Chalk Group and the underlying Jurassic clays near the base of the Wolds escarpment. The groundwater flow lines to these springs are short as the groundwater divide is likely to closely follow the topographic high of the Wolds. The short travel times are confirmed by geochemical and isotopic evidence. The Chalk aquifer may be in hydraulic contact with underlying Jurassic limestones and sandstones. However, from the limited evidence available this contact is of little hydraulic significance.

Groundwater abstraction for industrial, domestic and agricultural uses has resulted in drying up of springs with a consequent reduction in flow in the River Hull. Additionally, over-abstraction has caused saline intrusion into the aquifer beneath Kingston-upon-Hull. The situation is now managed to ensure that the saline front is stabilised and elsewhere abstraction is restricted to ensure that environmental needs are sustained.

Quantification of the components of the water balance for a numerical model of the Chalk aquifer (Aspinwall, 1995a) for the period 1975–1992, concluded that of the annual average recharge of 719 Ml d^{-1}, 14% (105 Ml d^{-1}) was abstracted, largely for public supply, 31% (226 Ml d^{-1}) flowed to the North Sea and the Humber to balance saline intrusion, and about 55% (408 Ml d^{-1}) discharged to springs to maintain river flow. This model is described further in the following section. The majority of recharge (92%) to the north of Northing 450 rapidly discharges as spring flow to rivers whereas, the recharge in the southern half of the aquifer is captured in major abstractions or flows to discharge in the Humber (Aspinwall, 1995a).

3.4.2 Numerical models

Several groundwater modelling studies have been undertaken on the Yorkshire Chalk aquifer. The studies have attempted to translate the conceptual model of the aquifer, into quantified numerical models that can be used as predictive management tools.

The University of Birmingham (1985) carried out a study of the Yorkshire Chalk that examined flow mechanisms within the aquifer and constructed a regional groundwater model of the northern part of the aquifer, down to northing 450. The model was then used to examine various groundwater resource management options.

The regional hydraulic gradient is low (0.001) and remains so even at times of high outflow. Water table fluctuations range from 10 to 30 metres, the largest of these being in zones of lower transmissivity. In contrast, the potentiometric head in the confined Chalk varies by less than 1 m, suggesting little recharge is occurring beneath the thick Quaternary deposits overlying Holderness.

The Gypsey Race spring-flow proved difficult to model, given its intermittent flow and marked permeability layering within the Wold Valley, as well as the uncertain nature of the valley infill deposits. Groundwater conditions in the Wold valley and eastwards in the Hunmanby area are not well understood. Hydraulic connection with the underlying Jurassic aquifers and the Chalk aquifer is thought to be extremely small and, therefore, insignificant for modelling purposes (University of Birmingham, 1985).

Based on the University of Birmingham (1985) model, but extended to cover all the Yorkshire Chalk down to the Humber, a model of the Yorkshire Chalk aquifer was constructed (YORKMOD) for both the National Rivers Authority and Yorkshire Water Services Ltd. The model was calibrated against observed groundwater heads and spring-flows for the period between 1975 and 1992 (Aspinwall, 1995; Salmon et al., 1996).

The conceptual model produced is similar to those of Foster and Milton (1976) and University of Birmingham (1985) with two high-permeability, solution-enhanced fracture zones in the unconfined aquifer merging into a single zone in the confined aquifer (Figure 3.12). Although the main flow mechanisms are understood, the permeability and storage associated with the fracture zones still remain uncertain. Thus, calibration of the model was against observed groundwater levels and spring-flows, giving a plausible distribution of lateral and vertical aquifer characteristics. Both models use a finite-difference distributed method with a layered permeability function that allows permeability and storage to vary with depth.

The boundaries imposed on the model are:

- a fixed head boundary representing equilibrium between sea level and the Chalk aquifer some distance beyond the coast to the east
- a no-flow boundary, corresponding to the faulted northern limit of the Yorkshire Chalk
- a no-flow boundary, corresponding to the northern and western limits of the Yorkshire Chalk
- a fixed head boundary representing the known hydraulic continuity between the sea and the Yorkshire Chalk beneath part of the Humber Estuary.

The uniform 1 km grid spacing used in the University of Birmingham model was decreased to 250 m in the vicinity of features of special interest, and increased in areas where a dense network of modelled groundwater heads is not required, such as within the confined zone.

Recharge is calculated by the standard Penman soil-water balance approach, using daily rainfall data averaged on a monthly basis. This is input by way of a recharge factor matrix, rather than inputting a fraction of rainfall at each nodal point. Apart from recharge and abstractions, all other flows are head-dependent and generated within the models, as is the change in aquifer storage. Spring discharge is modelled to occur when the groundwater head exceeds a reference head, usually approximating river level. This discharge is calculated as a function of head difference, hydraulic characteristics and streambed deposits. Calibration indicated that streambed thickness and permeability could be assumed to be about 0.5 metres and 1 m d^{-1} respectively. Groundwater abstraction for the larger area covered by this model was estimated at 105 Ml d^{-1}; 99 Ml d^{-1} of which is accounted for by Yorkshire Water public supply abstractions.

The junction between the two hydraulically active fracture zones in the Chalk, which has been placed at the minimum groundwater level, is an important component of this model. Permeability and storage estimates are input for the two main flow horizons in the unconfined Chalk, and the combined main flow horizon in the confined Chalk (Figure 3.16). This is an improvement on the University of Birmingham model, as it now represents the Chalk below the zone of water table fluctuation as a thinner, high permeability zone rather than as a relatively thick, low permeability zone.

The model was tested against a number of steady-state hypothetical scenarios as well as groundwater heads at twenty observation boreholes and spring flows which were compared with river gaugings at Elmswell Beck and Hempholme Lock. Calibration of the model was achieved by altering aquifer permeability and storage within agreed ranges. A permeability of 0.1 to 100 m d^{-1} was assumed beneath the higher outcrop and 100 to 2000 m d^{-1} beneath lower outcrop and the Wetwang embayment. The base of the range of storage coefficient was set at 1% and the effective aquifer thickness was assumed to be at least 30 m. The model was most sensitive to changes in aquifer thickness and recharge particularly over the southern Chalk outcrop and in the vicinity of the River Hull spring flows.

The groundwater heads calculated by the models agreed to within 0.03 metres. However, these simulations did not require involvement of spring-flow or time-variant head conditions, as these were considered to be modelled adequately because monthly zero water balances were achieved. Groundwater levels in the summer were overestimated by 0.1 metres on average, and winter levels were underestimated by an average of 1.8 m. Sixteen of 20 calibration borehole sites achieved the calibration criterion of ± 5 m. Aerially, a reasonable simulation of the groundwater flow direction and hydraulic gradient was achieved (Figure 3.14). However, in the vicinity of springs and the lower western outcrop the modelled gradient is too shallow with differences of several metres. Comparison of the observed and modelled baseflow at both Hempholme Lock and Elmswell Beck is satisfactory although flow does tend to be underestimated during the 1988–90 period of drought.

Some of the limitations of the model were addressed through further refinement during 1995 and 1999 to improve the modelling of flows in the River Hull and to investigate the impact of groundwater abstractions on spring flows in the northern part of the Chalk aquifer. The latter was undertaken as part of a multifunctional review of the Hull Headwaters (Halcrow, 1998).

4 Groundwater chemistry

The description and discussion of the groundwater quality of the Chalk aquifer in this chapter is based on a regional survey carried out in the spring of 1996 (Smedley et. al., 1996). This work was supplemented by historical data and additional sampling carried out as part of the Etton nitrate study in May 1996 (Chilton et al., 1997). Results from typical analyses of the different types of groundwater are given in Table 4.1.

Samples were collected from boreholes and springs across the aquifer to obtain information about the regional variations in water quality. Some samples were collected from a range of depths in the same borehole in order to obtain information about vertical water-quality trends. Sampling density was greater in some areas than others due to the distribution of licensed-abstraction sites. Sample points are shown in Figure 4.1.

4.1 REGIONAL HYDROGEOCHEMISTRY

Carbonate reaction, redox processes, saline intrusion and pollution are the main influences on the regional variation in Chalk groundwater chemistry. Most of the elements considered are affected by more than one of these processes so the regional trends in chemical composition are complex. The distribution of groundwater types is summarised in Figure 4.2 as a west–east cross-section running through Beverley.

The distribution of Quaternary cover has an important impact on groundwater chemistry as well as flow in the aquifer. Groundwaters from the unconfined Chalk outcrop area are aerobic and show prominently the effects of pollution, with elevated concentrations of NO_3-N, Cl and SO_4 in particular. Concentrations in excess of 10 mg l^{-1}, 30 mg l^{-1} and 50 mg l^{-1} respectively are common. Beneath argillaceous Quaternary cover, especially to the east of the buried cliffline, groundwaters become progressively more reducing and show evidence of progressively increasing residence time with distance from outcrop.

In the confined aquifer close to the coast, particularly the low-lying Holderness area, groundwater becomes increasingly saline. Electrical conductivity up to 17 mS cm^{-1} has been observed in this part of the study area. Earlier studies have suggested that the saline water underlying Holderness is a stable body of water dating from the Ipswichian Interglacial (University of Birmingham, 1978). This suggests that there is minimal flow in this part of the Chalk. Saline water in the Hull area is reported to represent a mixture between old and modern water, the modern component pre-dating the 1950s (University of Birmingham, 1978).

4.1.1 Carbonate processes

Groundwater from the Humberside and Yorkshire Chalk is typically hard, with high Ca and HCO_3 concentrations and pH values buffered between 6.7 and 7.8 (mostly between 7.0 and 7.5). With the exception of a few of the springs from the westerly limit of the Chalk outcrop, the groundwaters tend to be at or near saturation with respect to calcite, reflecting rapid equilibration with the carbonate matrix. A few of the springs from the outcrop area, which are saturated with calcite, have pH values at the high end of the observed range (7.7–7.8). These have lower pCO_2 values than the groundwater from boreholes and wells from the rest of the aquifer (Figure 4.3). This might result from variations in landuse: parts of the western escarpment have relatively steep slopes such that soil cover is likely to be thin and microbial activity less pronounced than in cultivated areas further east. The compositions of the spring waters may also be explained by degassing of CO_2. This would result in precipitation of calcite and would generate higher pH values and lower HCO_3 concentrations such as those observed for some of the spring samples. Only the groundwaters from the confined aquifer are saturated with respect to dolomite.

The regional distribution of total hardness values (reflecting mainly Ca and Mg, but also SO_4 concentrations) is given in Figure 4.4. Groundwater pH values are generally lower in the confined aquifer and relatively high in some of the spring samples on the westerly margin of the Chalk outcrop. Concentrations of HCO_3 and Mg show a notable increase in the confined aquifer, particularly samples from the Holderness and Brandesburton [TA 12 48] areas. The higher concentrations are found in the more saline waters and are believed to reflect both the influence of mixing of fresh Chalk groundwater with trapped seawater and prolonged residence time in the aquifer (and hence reaction with the rock matrix). Increases in HCO_3 are also related to redox processes since total dissolved inorganic carbon increases as a result of oxidation of organic matter.

The highest observed Mg concentration from a sample from Holderness is 626 mg l^{-1}, a value roughly half that of modern seawater (the Cl concentration is also about half that of seawater). The HCO_3 concentration of this and other samples from Holderness is greater than 400 mg l^{-1}, considerably higher than that for seawater (140 mg l^{-1}; Hem, 1992). Such high concentrations are common in near-coastal confined Chalk groundwaters and are believed to reflect enhanced carbonate reaction following mixing of fresh Chalk groundwater with seawater. Mixing of calcite-saturated waters may lead to undersaturation of the mix with respect to calcite because of potential differences in end-member pCO_2 values, non-linear dependence of activity coefficients on ionic strength and potential for formation of ion pairs (e.g. $CaSO_4$; Wigley and Plummer, 1976). Resultant undersaturation would promote calcite dissolution in the mixing zone. This is also believed to be the main control on regional variations in Sr concentration in the aquifer (Figure 4.5).

The highest observed Sr concentration in the confined aquifer was 27 mg l^{-1}, a value far in excess of the seawater concentration of 8 mg l^{-1} (Hem, 1992). The excess Sr in the groundwater must have been derived by reaction of the chalk and this implies a prolonged residence time for this reaction to proceed. However, the Sr concentration cannot give information about the age of the infiltrated seawater component.

Table 4.1 Typical analyses of groundwater in Yorkshire.

Sample locality	Units	960352 Elmswell Wold	960356 Burton Agnes 2	960369 North Newbald 1	W300382 Haggs House Farm	W300430 Spring, Oak Plane	W300431 Fairydale Spring	W300432 Oakhill Springs	W300433 Embankment Cross Springs	960372 Needlers	960373 Seven	960376 Manor	960378 Sandsfield Farm	W300390 Meaux Abbey Farm	W300411 British Gas 3
Sample type		**Borehole**	**Borehole**	**Borehole**	**Borehole**	**Spring**	**Spring**	**Spring**	**Spring**	**Borehole**	**Borehole**	**Borehole**	**Borehole**	**Borehole**	**Borehole**
Easting		49987	51095	49218	50355	48855	48700	48752	48110	50935	51470	52558	51294	50960	51787
Northing		46136	46340	43715	43123	47102	46310	46621	46390	43100	42950	43059	44643	44055	45153
Temperature	ºC	9.5	9.6	9.5	10.5	9.2	8.7	8.4	8.7	12.4	11.7	11.6	10.3	10.4	10.8
pH		7.36	7.26	7.46	7.36	7.44	7.74	7.22	nd	7.10	7.25	7.20	7.24	7.12	6.74
Eh	mV	425	377	389	367	442	nd	nd	nd	64	78	nd	95	211	168
DO	mg l^{-1}	9.4	7.6	10.6	9.5	nd	nd	nd	nd	<0.1	<0.1	nd	<0.1	<0.1	0.2
SEC	µS cm^{-1}	501	585	389	533	421	654	591	745	2680	6810	17200	2650	1480	3570
Ca	mg l^{-1}	90.8	100	92.6	106	85.9	129	123	125	143	181	252	95.8	110	123
Mg	mg l^{-1}	1.57	3.96	1.70	4.12	1.27	6.04	2.03	2.54	63.7	180	626	66.6	29	59.4
Na	mg l^{-1}	9.7	13.4	9.5	10.7	8.6	13.4	6.6	30.3	447	1500	4910	510	205	922
K	mg l^{-1}	0.77	1.67	0.45	1.16	0.42	1.86	0.26	1.24	11.4	50.4	155	32.2	7.10	22.2
HCO_3	mg l^{-1}	204	262	162	266	177	161	185	154	377	406	428	445	401	428
SO_4	mg l^{-1}	21.9	22.3	39.8	17.8	22.3	126	36.6	52.2	86.3	362	1287	143	104	164
Cl	mg l^{-1}	22.3	25.8	29.3	20.8	19.5	22.1	34.5	82.4	860	2690	8890	802	223	935
NO_3-N	mg l^{-1}	9.1	7.5	12.7	6.78	7.01	12.8	17.9	20.1	<0.5	<0.5	9.5	<0.5	<0.2	<0.2
NO_2-N	mg l^{-1}	<0.003	<0.003	<0.003	<0.01	<0.01	<0.01	<0.01	<0.01	<0.003	<0.003	0.085	<0.003	0.02	<0.01
NH_4-N	mg l^{-1}	<0.02	<0.02	<0.02	<0.03	<0.03	<0.03	<0.03	<0.03	0.74	2.82	10.60	1.39	0.76	1.19
TOC	mg l^{-1}	1.68	1.93	1.02	nd	0.65	0.7	0.88	1.3	2.07	4.03	6.11	5.37	nd	nd
Si	mg l^{-1}	2.87	3.47	2.70	3.18	2.77	3.09	1.74	2.22	4.33	4.36	2.31	5.24	6.43	3.88
P	mg l^{-1}	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	0.5	0.8	0.5	<0.2	0.2
Fe	µg l^{-1}	<6	<6	<6	<6	<6	<6	<6	17	2717	3053	3021	3444	407	832
Mn	µg l^{-1}	<0.2	<0.2	<0.2	0.6	<0.2	<0.2	<0.2	16	76	152	184	123	176	78
Sr	µg l^{-1}	327	396	229	240	208	446	208	306	1950	4721	27200	2978	732	1964
Ba	µg l^{-1}	38.2	98.2	42.0	50.7	30.8	18.2	11.8	24.8	77.5	41.2	28.6	127	65.8	33.3
F	µg l^{-1}	70	70	80	150	90	150	90	80	880	2200	3800	730	280	300
Br	µg l^{-1}	93	95	97	nd	nd	nd	nd	nd	2920	9280	29000	2730	nd	nd
I	µg l^{-1}	1.2	1.5	1.9	nd	nd	nd	nd	nd	103	271	508	169	nd	nd
As	µg l^{-1}	<4	0.40	0.98	<1	<1	<1	<1	<1	46.9	1.74	0.45	0.69	<4	13
Li	µg l^{-1}	0.4	1.1	0.5	1.1	0.8	9.0	0.3	1.2	15.0	45.4	116	17.2	7.4	18.60
B	µg l^{-1}	10	20	7.7	17	6.5	25	7.4	9.0	157	994	2220	376	207	648
Cr	µg l^{-1}	<0.07	<0.07	<0.07	0.45	0.04	0.15	0.21	0.04	0.73	1.88	4.14	0.39	0.18	0.51
Co	µg l^{-1}	<0.01	<0.01	<0.01	0.16	0.07	0.09	0.07	0.15	8.87	0.67	1.54	0.19	1.75	4.24
Ni	µg l^{-1}	3.9	3.8	2.2	2.8	1.1	5.4	1.2	1.2	15.2	4.5	11.3	1.7	5.6	16.2
Cu	µg l^{-1}	3.9	4.2	3.3	2.3	<0.4	<0.4	0.48	0.45	nd	nd	nd	nd	<2	12
Zn	µg l^{-1}	7.5	6.3	5.4	153	<15	<15	<15	<15	nd	nd	nd	nd	6	9
Rb	µg l^{-1}	0.76	0.67	0.63	0.58	0.35	2.22	0.08	0.34	3.76	8.54	43.2	3.86	2.32	6.12
Mo	µg l^{-1}	<0.08	<0.08	<0.08	0.11	<0.08	0.39	<0.08	<0.08	0.86	1.28	4.08	0.86	0.42	1.43
U	µg l^{-1}	0.07	0.18	0.10	0.14	0.08	0.24	0.10	0.11	0.05	0.05	0.12	0.03	0.59	0.27

nd: not determined

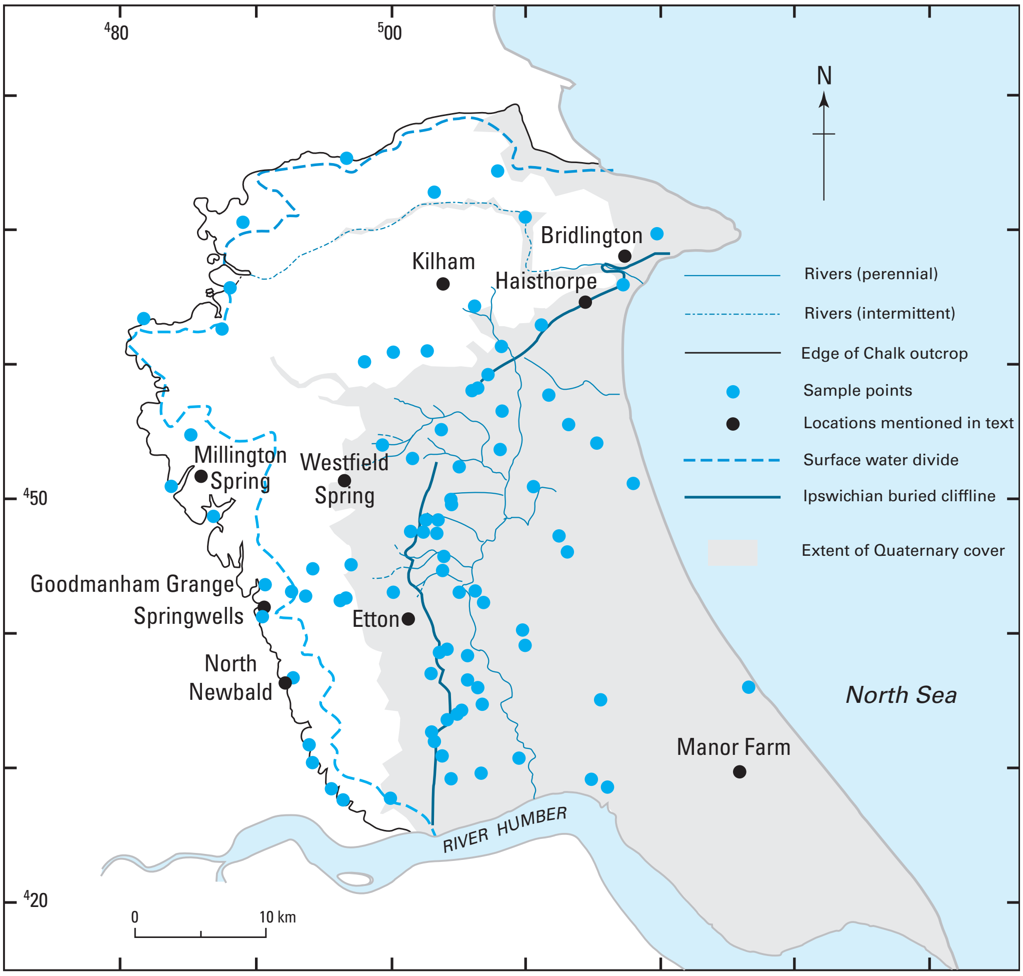


Figure 4.1 Location of sites used for groundwater sampling in relation to outcrop of the Chalk, Quaternary cover and the buried cliff line.

4.1.2 Redox processes

The impermeable Quaternary cover has a profound impact on the mobility of some elements in the Chalk groundwaters. Maps of the distribution of Eh values and dissolved oxygen (DO) are given in Figures 4.6 and 4.7. Fewer data points are available for these determinands because of the need to take measurements in an anaerobic flow-through cell in line at the wellhead or spring outlet. The distributions show that most of the groundwaters are aerobic with Eh values >300 mV and dissolved oxygen concentrations close to saturation (ca. 10 mg l^{-1} at ambient temperatures). Even groundwaters in the north–south tract between Beverley and Driffield are aerobic. These groundwaters are below the Quaternary but in this region the cover is mostly arenaceous. A distinct redox boundary exists some 5–10 km east of the edge of the Quaternary deposits, roughly corresponding with the location of the buried coastline, eastwards of which, the Quaternary cover is thickest and dominated by clay. Downgradient of this boundary, the groundwaters become more reducing. The lowest Eh value measured in the aquifer was –13 mV. The reducing groundwaters are generally those with elevated salinity.

Distributions of two of the most important redox-influenced elements from a water-quality viewpoint, Fe and Mn are very similar. Iron distribution is given in Figure 4.8. Only groundwaters from the confined aquifer (approximately east of the River Hull) have high concentrations of these elements (Fe >500 µg l^{-1}, Mn >50 µg l^{-1}). Some sites from the unconfined aquifer and from the Beverley–Driffield area have Fe concentrations above detection limits. These may be due to the presence of small amounts of colloidal Fe (not particulate as all samples were filtered) as dissolved Fe should only be stable at very low concentrations under the given redox conditions.

Arsenic mobility in water is strongly influenced by both redox potential and pH. Sorption, particularly onto iron oxides, is also often an important factor. Since pH variations are relatively small in the Chalk groundwaters, the regional distribution is considered to be controlled dominantly by local Eh conditions. Arsenic in the Chalk is likely to be in association with pyrite and Fe oxide. However, the highest concentrations are found in the reducing groundwaters where the potential for pyrite oxidation at the present day is minor due to the shortage of available oxidising agents (oxygen, NO_3, Fe(III)). The most likely source of the As is, therefore, Fe oxide, either by desorption under reducing conditions or by dissolution of Fe oxide itself and consequent release of As and other trace elements. It is possible that the Fe oxide present in the Chalk may result from past pyrite-oxidation events when hydrogeological conditions were different from those at the present day (e.g. lower sea levels during Pleistocene glacial periods).

Uranium is commonly found in small concentrations in carbonate minerals and in association with phosphorite (Edmunds et al., 1992). The element is strongly redox-controlled. It is more mobile in water in its oxidised, hexavalent, state. Uranium mobility is also enhanced by formation of carbonate complexes. Under reducing conditions, as a tetravalent form, it may sorb onto Fe

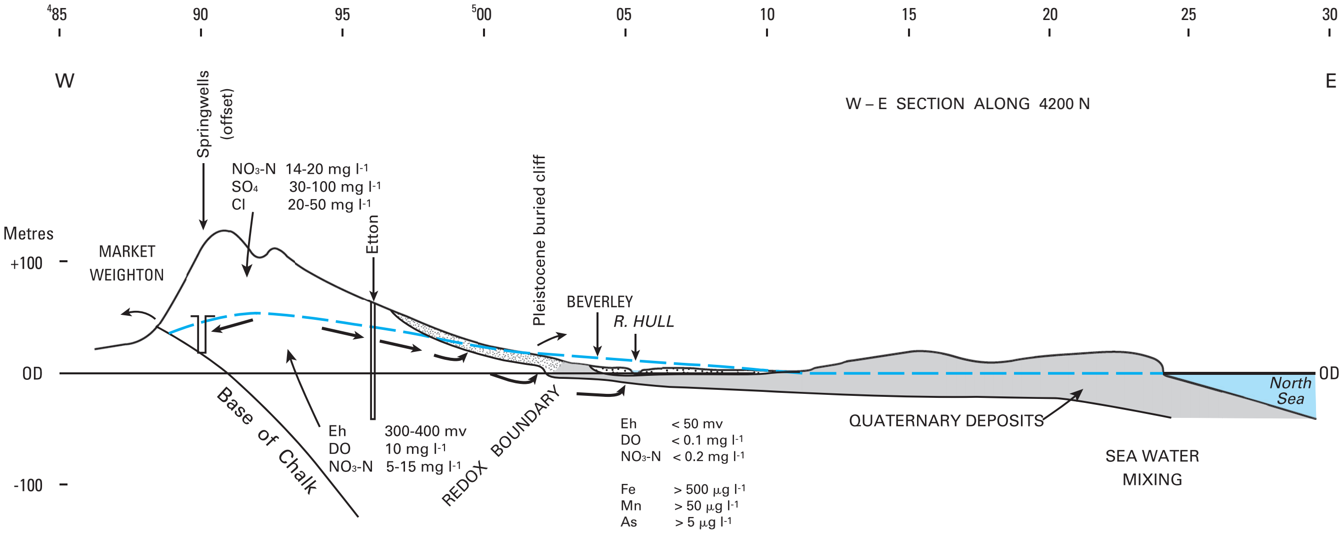


Figure 4.2 West–east cross-section through Beverley summarising the changes in groundwater quality in relation to groundwater flow.

oxide, or if present in sufficiently high concentrations, may precipitate as uraninite.

Concentrations of U in the Chalk groundwaters are low, up to only 1 µg l^{-1}. Highest concentrations are found close to the redox boundary, in oxidising waters in the Hull–Beverley area and just downgradient in the westerly part of the confined aquifer. Concentrations are low in reducing groundwaters from the Holderness area, reflecting the low solubility of uranous minerals. Concentrations are also low in the oxidising, unconfined aquifer in the Wolds area, including the escarpment springs. The regional pattern of U concentrations is believed to reflect the residence time of groundwaters in the Chalk, combined with the redox characteristics: springs from the westerly escarpment have travelled along shallow flow lines in the Chalk and have short residence times in the aquifer. Groundwaters from boreholes further east have longer flow paths and a greater degree of matrix reaction and equilibration has been possible. The U trends therefore reflect increasing residence time along the flow path, followed by reduction (to U(IV)) and precipitation or sorption beyond the redox boundary.

4.1.3 Mineral reaction, residence time and seawater mixing

Mineral reaction has been partially discussed in previous sections in the context of carbonate processes and redox controls. The dominant reactions involve carbonate minerals and are important controls on pH, HCO_3, Ca, Mg and Sr in particular. Iron oxide is likely to be an important control for the distribution of transition metals (especially Fe and Mn) and As. Pyrite may contribute further transition metals and As to solution, although for reasons stated above, oxidation of this mineral is likely to be minor in the reducing aquifer.

Phosphorite, present in disseminated granules throughout the Chalk and particularly in hardgrounds, is an important source of dissolved P. Apart from two high concentrations in the unconfined aquifer (Kilham pumping station and Westfield Spring), the highest concentrations are found in groundwaters from further along the flow path in the confined part of the aquifer. Seawater has a P concentration of only about 0.09 mg l^{-1}, a value much lower than the highest concentrations observed in the Chalk groundwaters. The highest concentrations result from reaction of groundwater with the aquifer matrix and hence may reflect enhanced residence time in the aquifer. High concentrations in the unconfined aquifer probably relate more to pollution. This is discussed further in Section 4.3.

Clay minerals, present in higher concentrations in the marls, are potential sources of alkali metals and alkaline-earth metals (K, Li, Rb, Sr, Ba). However, in saline samples from the confined aquifer, mixing with a seawater end member is likely to be the most important control. Concentrations of K and Li increase in the saline part of the confined aquifer. This may be partly related to ion exchange involving clay minerals but may be controlled by mixing with seawater (with higher K and Li concentration; about 390 mg l^{-1} and 170 µg l^{-1} respectively in modern seawater; Hem, 1992). Molar K/Cl and Li/Cl ratios are roughly comparable with those of modern seawater in many of the saline groundwaters and suggest that reaction of these alkali metals from the rock matrix has been relatively minor.

Groundwater residence times have been the subject of few comprehensive studies in the Yorkshire Chalk aquifer. The saline component in the confined parts of the aquifer could represent connate water or a fossil Quaternary water trapped at some time of previous higher sea level, or

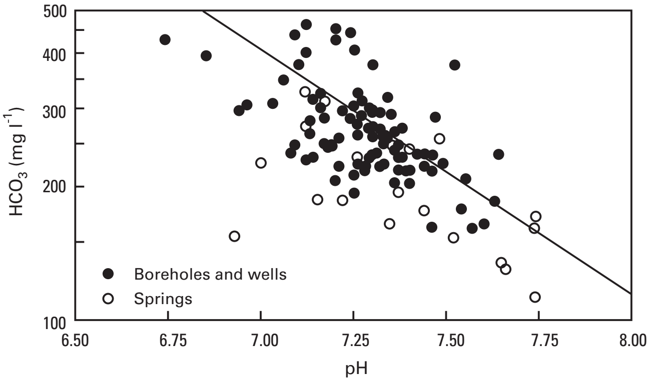


Figure 4.3 Variation of pH against HCO_3 for the Chalk groundwaters together with the curve for calcite saturation (^{12}C).

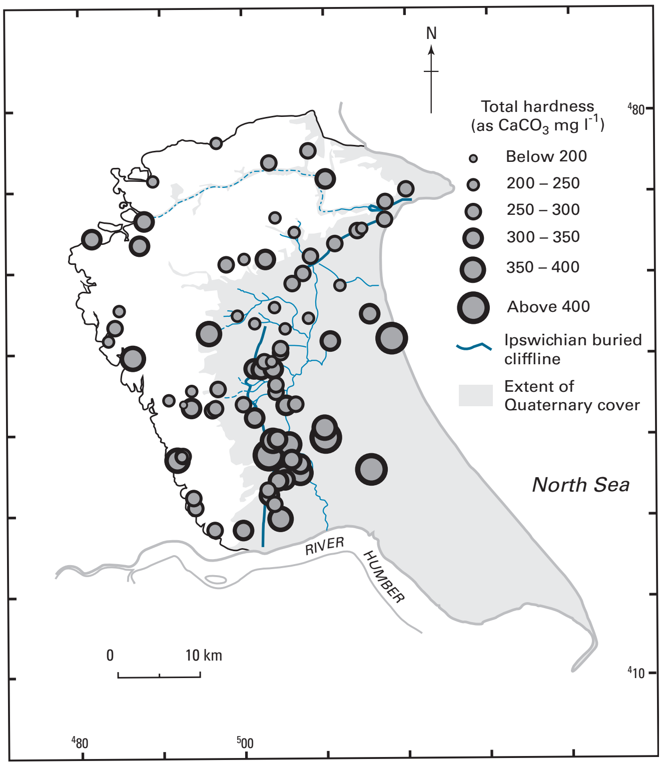


Figure 4.4 Regional variation in total hardness in groundwater from the Chalk aquifer.

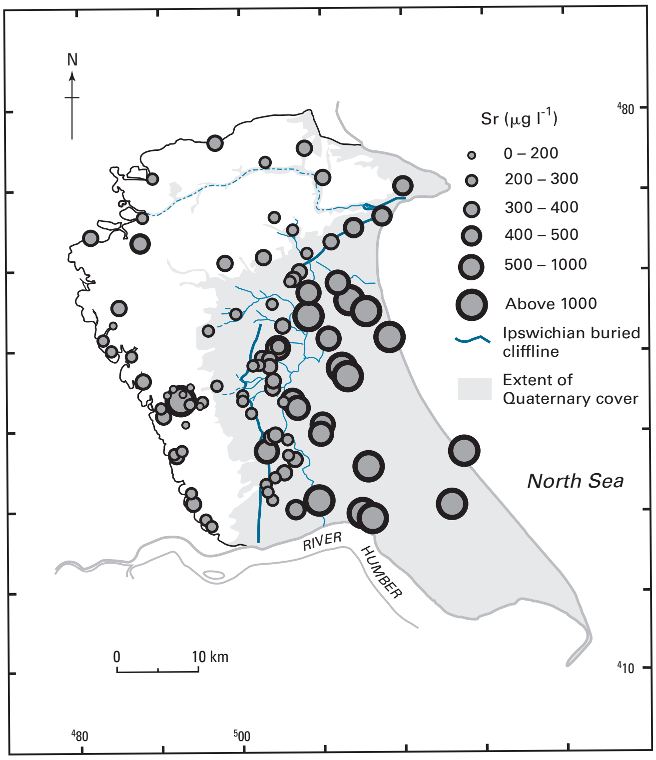


Figure 4.5 Regional variation in Sr in groundwater from the Chalk aquifer.

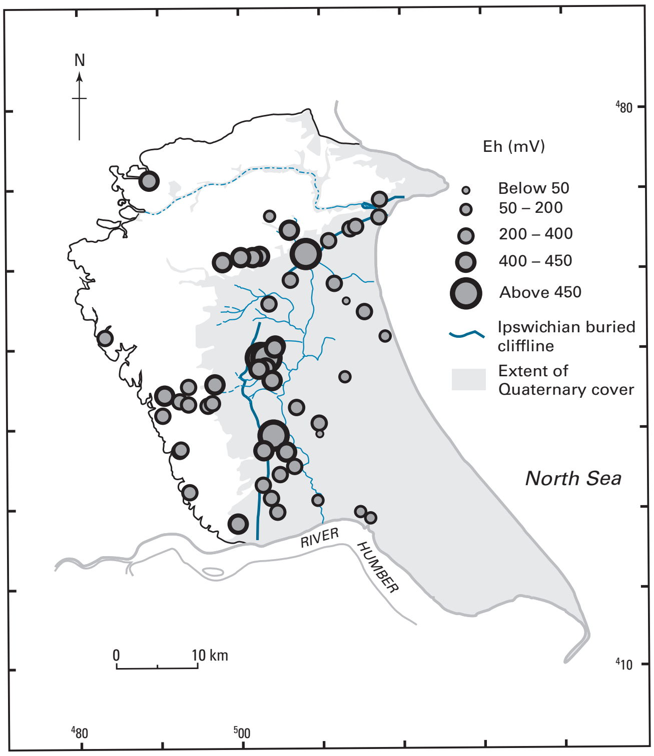


Figure 4.6 Regional variation in Eh in groundwater from the Chalk aquifer.

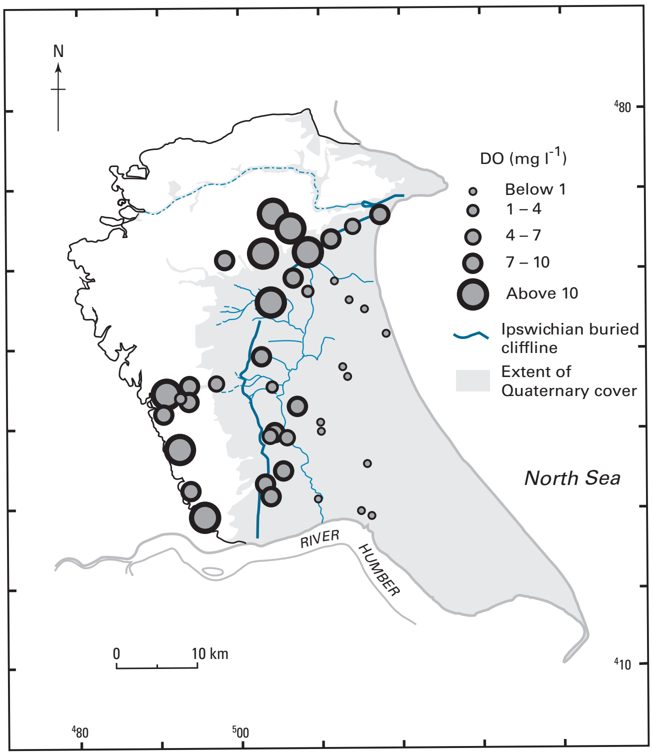


Figure 4.7 Regional variation in DO (dissolved oxygen) in groundwater from the Chalk aquifer.

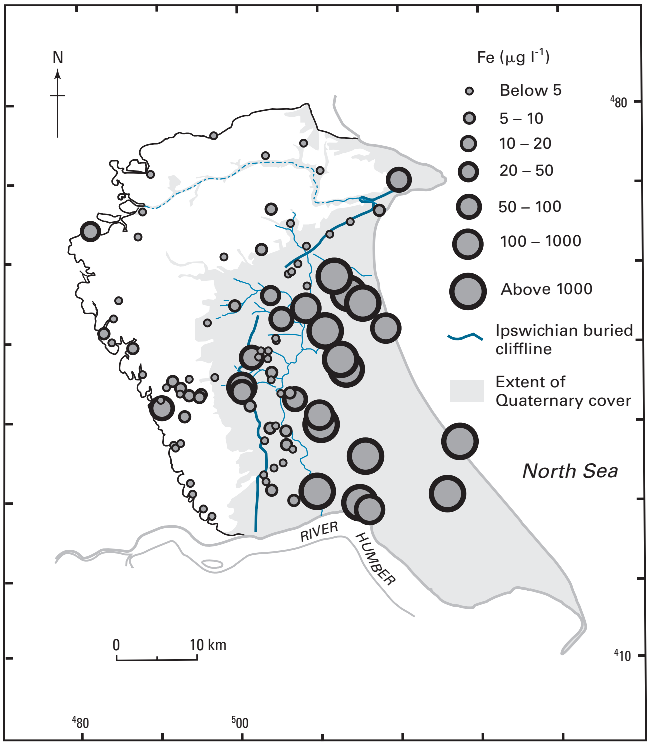


Figure 4.8 Regional variation in Fe in groundwater from the Chalk aquifer.

modern seawater. Distinction between these is not possible on available evidence and data. The age of the fresh groundwater end member is also difficult to determine.

Some studies argue, on the basis of elevated Sr and I concentrations, that groundwaters from the Holderness area include trapped seawater from the Ipswichian Interglacial (e.g. Pitman, 1986). Elliot et al., (2001) argue for emplacement of some saline water bodies related to a middle/late Holocene marine transgression. Other water bodies are considered to have been emplaced more than 19 000 yrs BP as they underlie Devensian tills. Studies of the groundwaters in the Hull area suggest that intrusion of relatively recent seawater from the Humber Estuary is occurring as a result of overabstraction of groundwater (Foster et. al., 1976). This is supported by evidence of increasing Cl concentrations in pumped groundwaters from this area over the last few decades. The seawater component cannot, however, be strictly modern as tritium concentrations of most groundwater samples investigated in the 1970s were low (mostly <2 TU, Foster et. al., 1976). A period of residence in the aquifer is necessary to reduce dissolved oxygen concentrations from saturated values to the low values observed in the confined aquifer of the Hull area.

Ratios of δ^{18}O of 49 samples analysed range between -8.4‰ and -7.0‰ and δ^{2}H between -59‰ and -47‰. Groundwater samples from the shallow spring sources cover almost the whole compositional range (δ^{18}O -8.3 to -7.3 ‰). This may reflect the range of composition of local modern recharge. The most depleted isotopic signature observed is from the Holderness part of the confined aquifer (Manor Farm B [TA 1540 3538] δ^{18}O -8.4‰, δ^{2}H-59‰). This groundwater has a Cl concentration of 1300 mg l^{-1} and represents a mixture between freshwater and a minor proportion of seawater. The fresh end member is likely to have had an even lighter δ^{18}O composition since seawater has a δ^{18}O composition at, or close to zero. The fresh end member may, therefore, represent relatively old water having recharged under an earlier, cooler climate than present climatic conditions would generate.

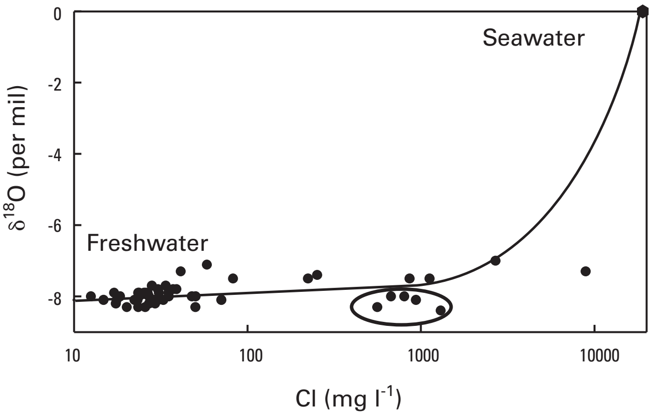


Figure 4.9 Variation of δ^{18}O with Cl in Chalk groundwaters.

Limited radiocarbon data support the suggestion that groundwater in the Holderness area is palaeowater. Chalk groundwater from the Aldbrough area on the coastal margin has a ^{14}C composition of 3 pmc, suggesting that it is of Pleistocene age (PALAEAUX, 1999).

Figure 4.9 shows the variation of δ^{18}O with Cl in the Chalk groundwaters. A theoretical mixing line between fresh groundwater and modern seawater is given for reference. Most of the groundwater samples fall close to this theoretical curve, including brackish samples from the Hull area, north of the Humber Estuary. Most sample compositions can, therefore, be explained by mixing between relatively recent recharge and modern seawater, although this conclusion would be strengthened with isotopic dating evidence.

A few saline groundwaters from the confined aquifer have isotopic compositions which are slightly more depleted than the seawater mixing line. The most depleted sample from Manor Farm B (sample 372) is included in the outlined ellipse (Figure 4.9), along with other samples from the eastern part of the confined aquifer (Holderness and Brandesburton areas). A saline sample (Cl 8900 mg l^{-1}, Manor Farm A) from further south in the Holderness area is also more depleted than the theoretical curve. These groundwaters probably represent mixtures between slightly more depleted (older) recharge water and seawater and hence fall on a more depleted mixing line than that shown in Figure 4.9.

Chalk groundwaters from the Yorkshire and Humberside area do not share the isotopic depletions characteristic of the Triassic Sandstone aquifer further west in Nottinghamshire and south Yorkshire, where δ^{18}O compositions more negative than -9‰ have been reported (e.g. Edmunds et al., 1982; Smedley et al., 1993). The Chalk groundwaters, therefore, do not show such clear evidence of the significant presence of a palaeowater component. This perhaps relates to the nature of groundwater flow in the Chalk: flow is more strongly controlled by fissures than that in the Sherwood Sandstone, where matrix flow has much greater importance. Groundwater in the British Chalk is known to represent a much poorer record of palaeo-environmental conditions during the Quaternary than the sandstones because of the relative importance of rapid by-pass flow and consequent obliteration of evidence for pre-existing palaeowaters (Darling et al., 1997).

The research borehole drilled to a depth of 100 m at Carnaby Moor [TA 1505 6486], 3 km to the south-west of Bridlington, provides some evidence of water of pre-industrial age. The temperature (10.3°C), conductivity (370 µS cm^{-1}) and Cl (20–30 mg l^{-1}) profiles in the borehole indicate present day groundwater movement. However, there are indications of older interstitial water between 85 and 95 m depth. It was found that F, I and SO_4 increase whilst NO_3 decreases to background levels. The $\delta^{18}O$ (-7.8 ‰) and the $\delta^{2}H$ (-50 ‰) values are almost constant. A ^{14}C of 68 pmc was measured in a sample bailed from 96 m. These results probably indicate that modern (high nitrate) water is flowing at selected horizons to depths of at least 100 m but below 80 m may contain water of pre-industrial age (PALAEAUX, 1999).

4.2 NITRATE AND OTHER INORGANIC POLLUTANTS

Nitrate concentrations in the unconfined Chalk aquifer of northern England have been rising steadily over the last few decades. The onset of the nitrate problem was first identified and investigated in the Yorkshire Chalk (Foster and Crease, 1974). Many springs and pumped groundwaters have nitrate concentrations in excess of the EC MAC for NO_3-N in drinking water of 11.3 mg l^{-1}. As a result, nitrate-vulnerable zones (NVZs) have been established around public-supply sources at Market Weighton (Springwells), North Newbald and Kilham. The Kilham public-supply source is also in a nitrate-sensitive area (NSA).

Studies of nitrate in pore waters in the unsaturated zone indicate that they are often notably higher (e.g. 2 to 4 times higher; Lawrence et al., 1983) than groundwater concentrations. Future groundwater quality with respect to nitrate in the Chalk aquifer may deteriorate still further over the coming years, despite changed agricultural practise, as the nitrate moves down into the saturated zone.

Nitrate is an indicator of pollution from agricultural activities and/or domestic (septic tank, soakaway, sewage) sources and may signal the deterioration of groundwater quality with respect to a range of other pollutants, most notably Cl, SO_4, NH_4, K, P, B and organic compounds (e.g. pesticides, chlorinated solvents. See Section 4.3).

Some groundwater sources from the unconfined Chalk aquifer have shown distinct seasonal variations in nitrate concentration, with peaks corresponding to highest groundwater levels during spring (March–April), and hence flushing of the unsaturated zone within the zone of fluctuation. The following description is based on the results of the regional survey carried out during April 1996, at a time when concentrations of dissolved nitrate and other pollutants may be expected to be at their highest following winter recharge and rising groundwater levels. The results are discussed in the context of the most important natural geochemical processes affecting the groundwater chemistry.

Detailed descriptions of changes in agricultural practices, fertiliser and pesticide use and application rates are beyond the scope of this report. However, the dominant fertilisers in use over the Chalk aquifer over the last decade comprise NH_4, NO_3 and urea. Overall fertiliser use on the whole Yorkshire Chalk area is 151 kg ha^{-1} on tillage (i.e. everything except grasses), of which 130 kg ha^{-1} is applied as these compounds. The remainder comprises mixed NPK fertilisers (British Survey of Fertiliser Practice, 1995). Foster and Crease (1974) noted a progressive replacement of $(NH_4)_2$ SO_4-based fertilisers by NH_4 NO_3-based fertilisers in the Etton, Cherry Burton and Goodmanham catchment areas during the 1970s. Application rates of nitrogenous fertiliser were noted to increase from an estimated <10 kg N ha^{-1} yr^{-1} in the 1940s to around 95 kg N ha^{-1} yr^{-1} in 1971.

Over the subsequent 30 years, agricultural practices changed considerably. Improved agricultural practices, such as autumn rather than spring planting, aimed at reducing nitrogen leaching, have been more than offset by the steadily increasing application of fertiliser (Chilton et al., 1997). Cereals, potatoes and oil-seed rape, the latter crops being fertilised at rates from 120 to over 200 kg N ha^{-1} yr^{-1}, have replaced low-intensity grazing. Leaching losses are estimated to be in the range of 45–55 kg N ha^{-1} yr^{-1}; i.e. 35% of applied nitrogen. These losses are reflected in the unsaturated zone porewater profiles as described in Section 4.2.2.

Sulphate-based fertilisers are applied to oilseed rape crops and some other cereals, but not to sugar beet or potatoes. Salt (NaCl) is also applied to sugar beet in the area at a rate of 400 kg ha^{-1} (British Survey of Fertiliser Practice, 1995). Ranked in order of weight, the most important compound used in northern Britain in 1995 was sulphuric acid (594 t, over 5 kha). This is used in spray form to kill potato haulms and as a desiccant for onion and linseed crops. Elemental sulphur is also applied to sugar beet as a fungicide.

4.2.1 Temporal trends in nitrate concentration

Concentrations of nitrate in many of the groundwaters from the unconfined Chalk aquifer of Yorkshire have been rising steadily since the 1970s. Predictions made by Lawrence et al. (1983) that concentrations at some sites would exceed the EC MAC of 11.3 mg l^{-1} during the 1990s have in some cases been realised. Market Weighton (Springwells) pumping station is currently inoperable for this reason. The dominant source of the nitrate is intensive agricultural practices including the application of fertiliser. Pig, poultry and cattle farming is also common on the Chalk outcrop and this constitutes a likely additional diffuse source of nitrate.

Lawrence et al. (1983) observed from groundwater-quality monitoring during the 1970s that nitrate concentrations varied between pumping sites in dip-slope and escarpment locations. The Market Weighton (Springwells) site on the Chalk escarpment was reported to show elevated nitrate as well as Cl and SO_4 concentrations throughout the year, with peak concentrations generally in April–May and not coincident with the peak groundwater level. Lawrence et al. (1983) also found no obvious correlation between nitrate and rainfall intensity and observed frequent nitrate lows during mid-winter, perhaps due to dilution after the major autumn leaching episode. It was suggested that this relates to increased influence of rapid by-pass flow through the unsaturated zone. Pumped groundwater from the site had higher tritium concentrations than the Etton dip-slope site, suggesting rapid flow of recent water to the water table.

Nitrate (and chloride) concentrations in groundwaters from a typical dip-slope site at Etton were noted by Lawrence et al. (1983) to increase with rising groundwater levels during the early part of the winter and to peak simultaneously (to within a few days) with high groundwater level. They also found that the magnitude of the nitrate increase was directly proportional to the water-level rise. This was confirmed by Chilton et al. (1997), even through the drought period, 1988–92 (Figure 4.10).

There is not such a good correlation between groundwater levels and NO_3-N concentrations at the Millington Springs and North Newbald sites (Chilton et al., 1997). This is consistent with the earlier observations of

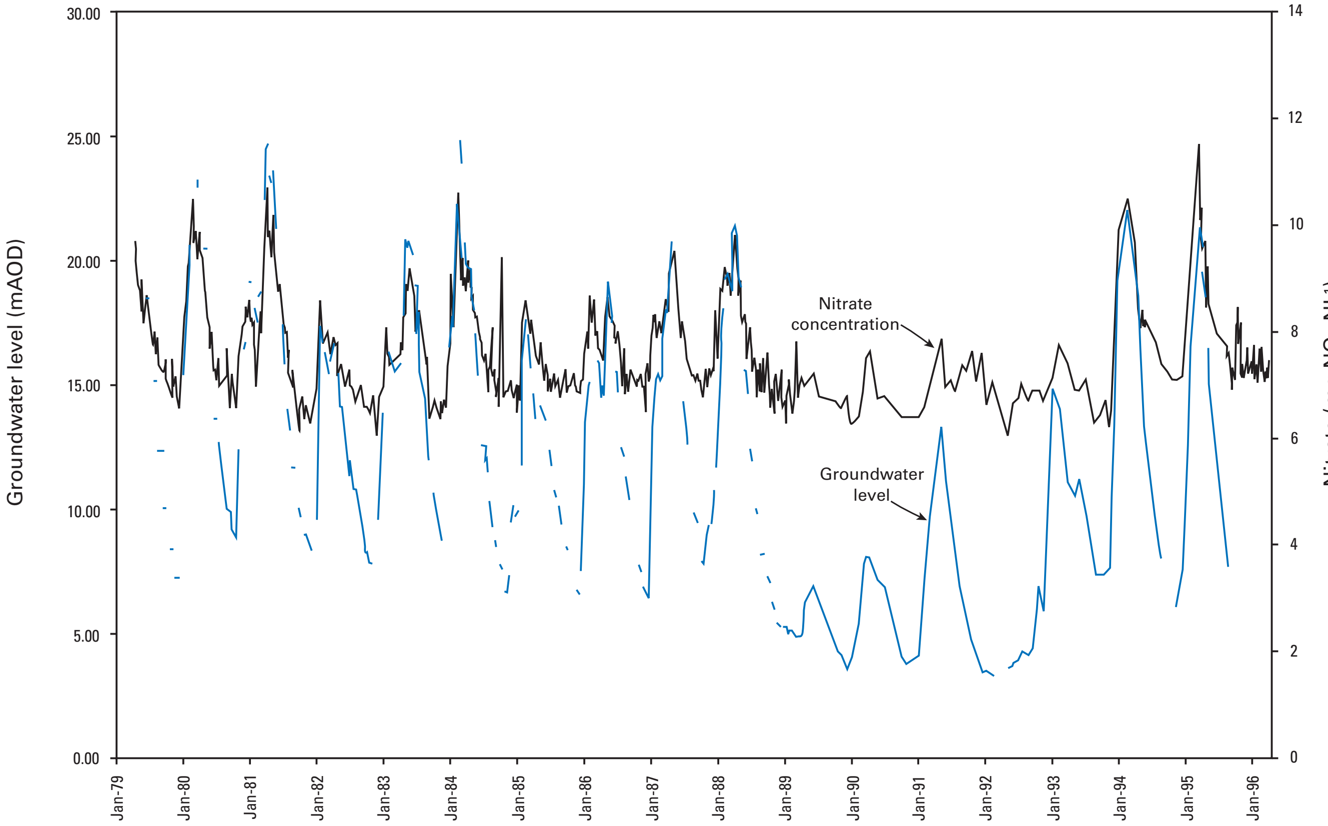


Figure 4.10 The relationship between nitrate concentrations and groundwater levels at Etton, 1979 to 1996.

Lawrence et al. (1983). It is also less clear whether seasonal variations are occurring at Millington Springs as sampling intervals have been greater than at North Newbald and Etton and resolution is, therefore, poorer. For the Etton site in particular, and probably other dip-slope sites in general, sampling during spring, when groundwater levels are at a maximum following winter recharge, is likely to have given an indication of the regional quality of the aquifer at its worst with respect to nitrate and other pollutants.

Figure 4.11 displays trends in NO_3-N concentrations since the early 1960s at Springwells, Kilham and Etton public water supply (PWS) pumping stations. The first site is an escarpment site and the others are located on the dip slope.

At Etton, data from Lawrence et al. (1983) indicate that NO_3-N concentrations increased steadily during the 1970s. Concentrations during 1970 were around 3 mg l^{-1} but by 1980 had risen to 8 mg l^{-1}. Trends since 1980 (Figure 4.11) do not appear to show any increase. Concentrations have varied between about 6.5 mg l^{-1} and 11 mg l^{-1} between 1980 and 1996 but average annual concentrations are apparently little different today from their values during the 1980s. More detailed investigations of the relationships between groundwater levels and NO_3-N concentrations at Etton (Chilton et al., 1997) suggest that there has still been a slight increase in concentrations since 1980, but that this is only around 0.05 mg l^{-1} per year and much lower than at the escarpment sites. This is thought to be due to increased abstraction resulting in increased drawdown and a longer delay time in the unsaturated zone.

4.2.2 Depth variations

In the unsaturated zone of the unconfined Chalk, Lawrence et al. (1983) found that concentrations of NO_3-N as well as SO_4 and Cl reached much higher values than those in the saturated zone. Peak NO_3-N concentrations in the range 20–40 mg l^{-1} were observed in unsaturated zone porewaters from the Etton catchment area. Concentrations in the zone of water-level fluctuation were in the range 5–15 mg l^{-1}.

Sampling was repeated 18 years on at the same sites in the Etton catchment (Chilton et al., 1997). The results showed that NO_3-N, Cl and SO_4 concentrations still peak in the top 10 m of Chalk, reaching up to 47 mg l^{-1}, 50 mg l^{-1} and 60 mg l^{-1} respectively in porewaters from three cored boreholes. Figure 4.12 shows the results from one of these

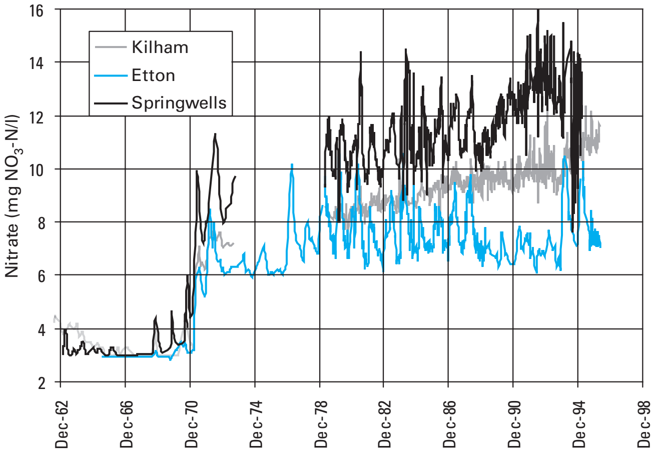


Figure 4.11 Concentrations of nitrate in groundwater at Springwells, Kilham and Etton water supply sources, 1962 to 1995.

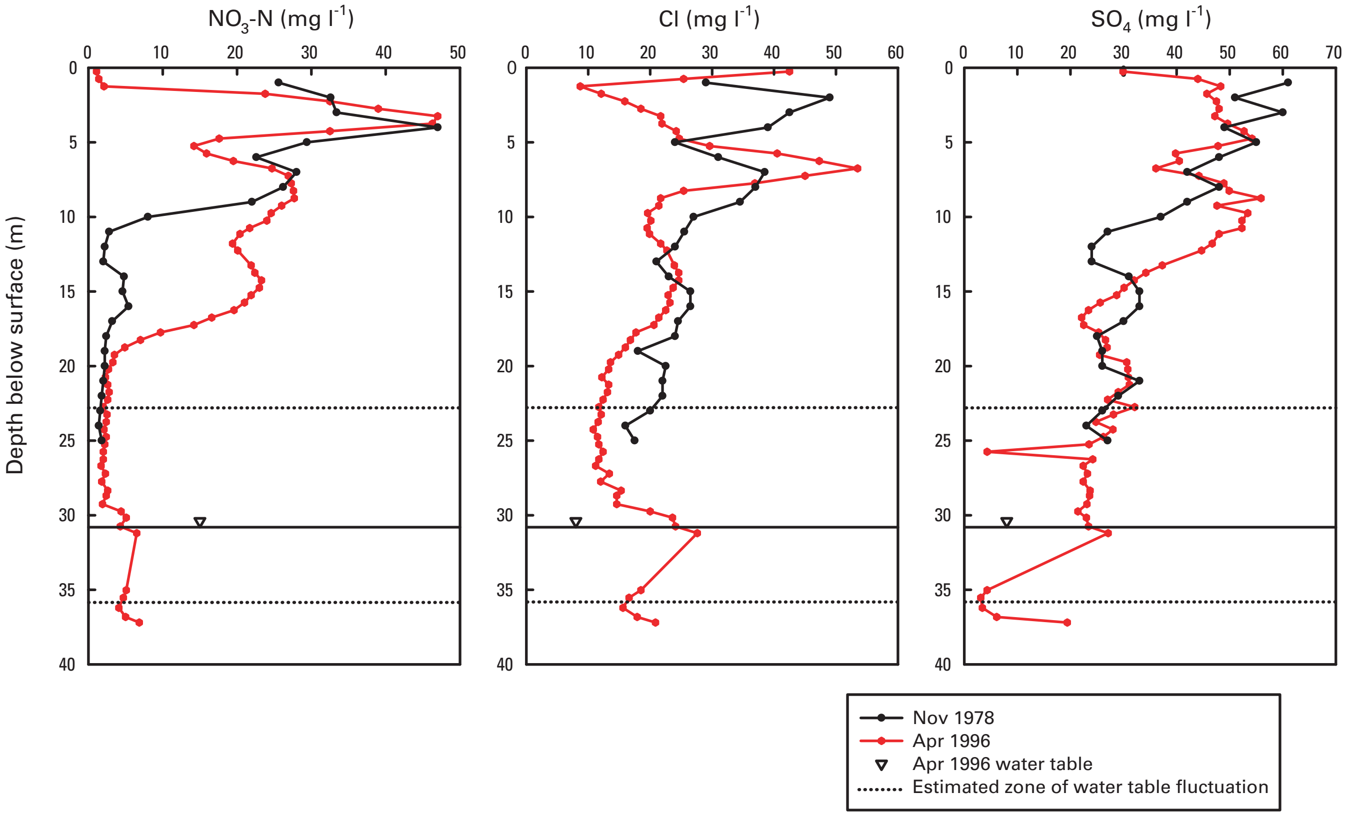


Figure 4.12 Comparative pore-water profiles of nitrate, chloride and sulphate in 1978 and 1996 at a selected research site (NH03) in the Etton catchment.

boreholes. In the zone of water-table fluctuation, concentrations were much lower at about 15 mg l^{-1}, 20 mg l^{-1} and 23 mg l^{-1} respectively, most likely as a result of dilution by deeper groundwater of better inorganic quality. The implication of the recent unsaturated zone study by Chilton et al. (1997) is that concentrations of NO_3-N, Cl and SO_4 at least have not yet reached a peak and groundwater quality is likely to deteriorate still further as the poor-quality porewater infiltrates downwards towards the water table.

Depth samples from the shallow part of the saturated zone at Etton pumping station (Etton 2, 4 and Etton C observation borehole, Figure 4.13) indicate that concentrations of NO_3-N, Cl and SO_4 also diminish with depth below the water table. This is interpreted as a result of dilution of solute loads picked up from the unsaturated zone by groundwater of better quality. Highest concentrations of these determinands were present in the samples from Etton C observation borehole. Heat-pulse flow logging of Etton C whilst pumping Etton 4 indicated that groundwater flows downwards in the borehole from the water table to about 38 m depth and upwards from 72 m depth towards 38 m depth (Chilton et al., 1997). Groundwater close to the water table is, therefore, of poorer inorganic quality than that deeper in the unconfined aquifer.

4.2.3 Regional variations

Regional variation in NO_3-N concentrations in the Chalk aquifer is shown in Figure 4.14. Data are sparse in part of the Yorkshire Wolds due to lack of licenced abstraction sites in this area. Coverage in the confined aquifer of Holderness is also poor due to paucity of available boreholes for sampling. Many groundwater abstraction sites in this area have been abandoned due to high salinity and poor yield. Better coverage has been achieved over the rest of the aquifer.

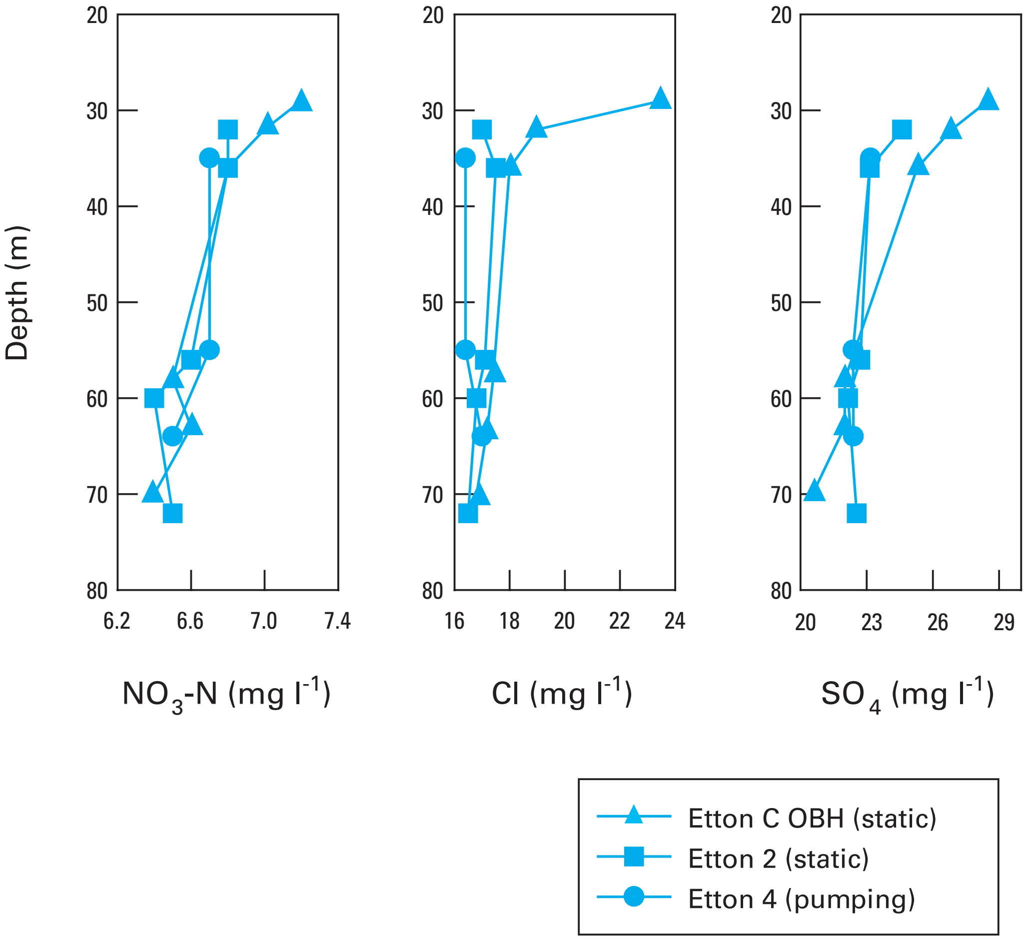
Nitrate concentrations are higher in groundwaters from the escarpment sites at Millington Springs and North Newbald than at the Etton dip-slope site. Figure 4.14 shows that this trend is apparent on a much larger scale: groundwaters from the westerly edge of the Chalk, notably the shallow springs, have higher concentrations than unconfined dip-slope groundwaters further east. Highest observed groundwater concentrations are about 20 mg NO_3-N l^{-1}.

In the Beverley–Driffield area, where Quaternary cover is largely arenaceous and the groundwaters are oxidising, NO_3-N concentrations are generally in the range 2–10 mg l^{-1}. These are still relatively high, but much lower than the escarpment spring sites, and below the EC maximum admissible concentration (MAC).

Groundwaters from the confined aquifer further east have low NO_3-N concentrations, usually <0.2 mg l^{-1}. One sample from the Holderness area (Manor Farm A) has an apparently high concentration of 9.5 mg l^{-1} (TON, though the NO_2 contribution is minor). This value is anomalous and appears to show persistence of nitrate at least in part of the confined aquifer. A repeat chemical analysis of the sample confirmed the value.

It is unclear whether the low NO_3-N concentrations in the confined aquifer relate to their age (i.e. pre-pollution recharge) or to denitrification under reducing conditions, but both are likely to have played a role. Pre-pollution inputs would be low, though still detectable NO_3-N concentrations, as N would be derived from atmospheric inputs and natural microbiological processes in the soil (concentrations probably <5 mg l^{-1}). Indeed, NO_3-N concentrations in the unconfined Chalk groundwaters during the 1960s were relatively constant and in the range 3 to 4 mg l^{-1} (Foster and

Figure 4.13 Variation of NO_3-N, Cl and SO_4 with depth in groundwaters from Etton.



Crease, 1974). From this assumption, concentrations of <0.2 mg l^{-1} imply that some denitrification must have occurred during the history of downgradient groundwater flow, just as dissolved oxygen concentrations have diminished from near-saturation values around 10 mg l^{-1} at outcrop to <0.1 mg l^{-1} in the reducing confined aquifer.

Concentrations of organic carbon are around 0.5–3 mg l^{-1} in the aerobic groundwaters from the Chalk. The concentration of organic matter in the solid chalk ranges from 0.1% to about 1% (Pacey, 1989), although this is not likely to be entirely labile. Such sources of organic carbon are potentially important in supporting microbial populations, which catalyse the denitrification process. Ferrous Fe and rare, though present, sulphide minerals (pyrite, marcasite), constitute potential additional electron donors to drive the denitrification reaction.

Other inorganic pollutants of interest include Cl; the regional distribution of which is given in Figure 4.15. As with nitrate, relatively high concentrations are found in groundwaters from the escarpment springs. These are believed to result largely from pollution (animal wastes and inputs from salt used for sugar-beet crops and road salting). Some extra Cl is derived from atmospheric inputs. Chloride concentrations are lowest in the area covered by Quaternary deposits but west of the buried cliffline (i.e. the Beverley–Driffield area). Baseline concentrations appear to be about 20 mg l^{-1} or less. Concentrations of Cl are much higher in the low-lying confined aquifer as a result of mixing with seawater, though this is not considered to be modern seawater (see discussion in Section 4.1.3 on saline intrusion and residence time).

Regional trends in SO_4 concentrations are very similar to those of Cl. Lowest values are found in groundwaters from the Beverley–Driffield area (west of the buried cliffline); slightly higher values are present in spring sites located along the westerly Chalk escarpment. The highest values occur in the easterly, low-lying confined aquifer.

Pitman (1986) claimed that SO_4 reduction is important in the confined aquifer, although this was based on analysis of only one sample. No analysis was carried out of sulphide in the groundwaters in this study. A few sites from the confined aquifer in the Holderness and Hull areas have a detectable H_2S smell, but this does not necessarily mean that concentrations of sulphide are high. Also, redox conditions in the aquifer are insufficiently low for sulphate reduction to be an important process. Concentrations of SO_4 generally increase in the confined aquifer, rather than decrease, such that any SO_4-reduction effect is insignificant compared with saline mixing.

In the aerobic groundwaters, there is a good positive correlation between Cl concentrations and those of NO_3-N and SO_4 (Figure 4.16). This suggests that both Cl and sulphate are derived from the same pollutant sources as the nitrate. These are likely to be agricultural activities including fertiliser application, effluent from pig, poultry and cattle farming. Application of sulphuric acid to potato crops may be an additional localised SO_4 source. In the groundwaters as a whole, correlations between Cl and SO_4 appear to fall on two distinct slopes (Figure 4.16). A steeper slope dominated by the spring sites is considered to be pollution-controlled. A less steep slope, but ranging to much higher concentrations is related to mixing with seawater. In the diagram of NO_3-N versus Cl (Figure 4.16), the pollution-influenced waters have a positive slope. The reducing, confined groundwaters,

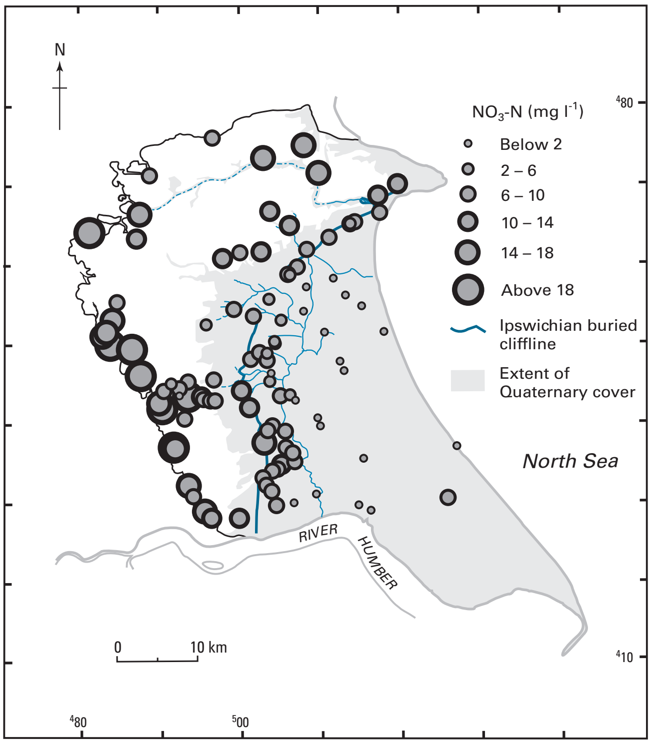


Figure 4.14 Regional variation in NO_3-N concentrations in the Chalk aquifer.

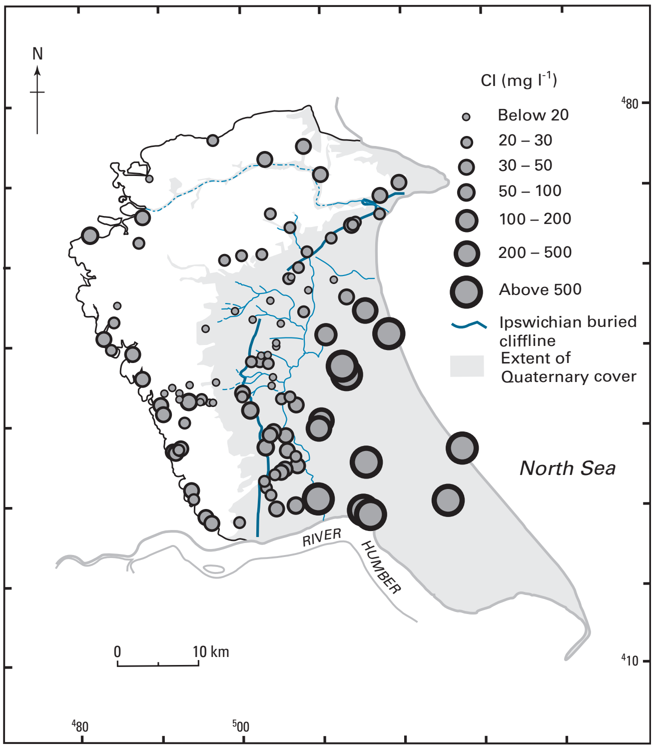


Figure 4.15 Regional variation in Cl in groundwater from the Chalk aquifer.

influenced by mixing with seawater, have low NO_3 concentrations.

Variations of K and total P concentrations are also shown against Cl in Figure 4.16. Trends in K show some distinct scatter in the low-Cl samples. The reasons for this are not clear, but are likely to result from, not only addition of K in fertiliser, but also from ion-exchange reactions involving clay minerals in the chalk. Springs show a particularly large scatter. Influence of interaction with clays at the top of the underlying Jurassic strata cannot be ruled out for these samples, although this effect is considered to be minor.

Groundwaters from the confined aquifer have the highest concentrations of K, reaching in excess of 100 mg l^{-1}. The concentrations correlate closely with groundwater salinity (Figure 4.16). This trend is believed to relate mainly to mixing with a seawater component, although as discussed in Section 4.1.3, clay-surface exchange reactions are also of importance during saline intrusion as K and other cations on the clay surfaces are exchanged with Na, the dominant cation in the saline end member.

Only two groundwater samples from the unconfined aquifer have high total P concentrations (Kilham 2 and Westfield Spring). This may relate to interaction with localised phosphorite horizons in the Chalk. However, since these appear to be distinct anomalies, it is perhaps more likely that the origin is related to localised pollution effects from NPK fertilisers. The majority of groundwaters from the unconfined Chalk, including the springs, do not have high P concentrations. This is likely to relate to uptake by vegetation and the high tendency for sorption onto chalk surfaces resulting in the formation of Ca phosphate. Figure 4.16 also demonstrates the dominant influence of rock reactions in the generation of high P concentrations in the confined aquifer. The concentration of P in seawater is only around 0.09 mg l^{-1}. The high concentrations in the saline groundwaters must, therefore, be derived from reaction with rock material, notably phosphorite-rich horizons in the Chalk and possibly desorption from iron oxide over relatively long residence times.

Regional variation in NH_4-N concentration in the Chalk groundwaters can reflect application of ammonium-based fertilisers and are known to be a potentially important component of manure from local animal farming. Small amounts of NH_4-N are also derived from atmospheric deposition. Despite this, the concentrations of NH_4-N in groundwaters from the unconfined aquifer are low and usually below detection limits. Escarpment-spring sources with the highest pollution component, evidenced by high NO_3, Cl and SO_4 concentrations, also have low NH_4-N concentrations. It is considered that any excess NH_4 leaching from the soil zone is oxidised rapidly to NO_3 in the aerobic aquifer.

Further down gradient in the confined aquifer, NH_4 concentrations are much higher, reaching up to 11 mg l^{-1}. Concentrations correlate well with groundwater salinity. The NH_4 cannot be derived from seawater as concentrations in seawater are relatively low. Ammonium ions are known to sorb readily to clay-mineral surfaces (e.g. Appelo and Postma, 1993). Other cations, having increased activity in the saline waters (high ionic strength), may be responsible for the high dissolved concentrations of NH_4, due to increased competition for binding sites on clay surfaces. The NH_4 in the confined, saline groundwaters is not taken to be pollution-derived, but the source of the N must ultimately have been from the soil zone and from atmospheric-N fixation.

4.3 ORGANIC COMPOUNDS

Pesticides and non-aqueous phase liquids (NAPLs) are the two main groups of organic compounds that can potentially contaminate groundwater. Samples of groundwater are

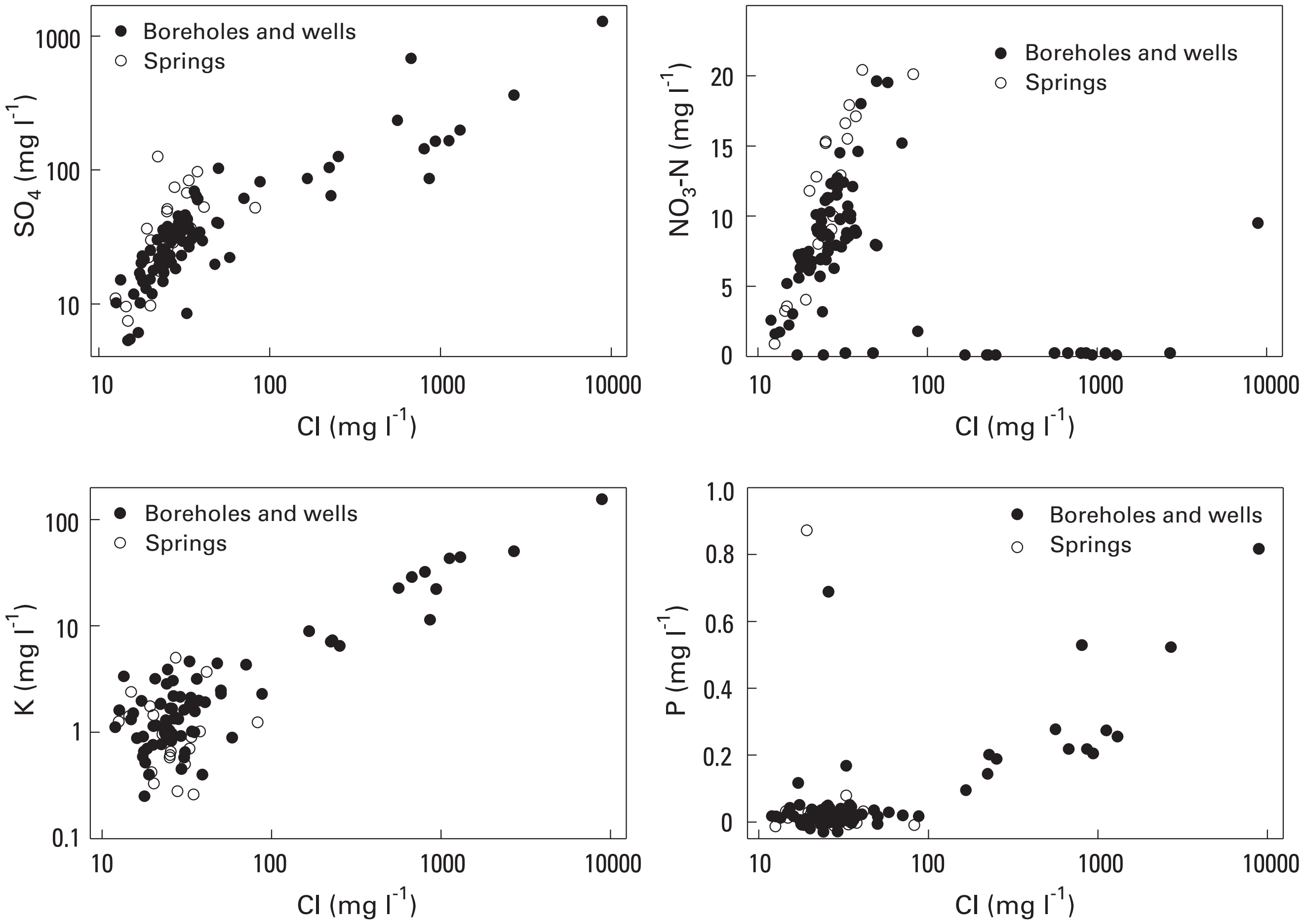


Figure 4.16 Variation of SO_4, NO_3-N, K and P with Cl concentration in groundwaters from the Chalk aquifer.

monitored for a broad range of compounds in order to ensure that the results of pollution incidents are detected and managed effectively.

A regional survey was carried out in order to obtain a synoptic view of the occurrence of organic compounds in Chalk groundwaters (Smedley et al., 1996). The movement and degradation of organic compounds in the unsaturated and saturated zones of aquifers is poorly understood. Results of analyses from a site can vary considerably depending on time and depth of sampling. A series of samples need to be taken over a representative time in order to make a defensible assessment of concentrations of organic compounds. Pesticide results of the survey are summarised in Table 4.2.

Most of the organic compounds analysed for the Chalk groundwaters were below detection limit. Of the detectable compounds, only atrazine, dichloromethane (DCM) and some of the trihalomethanes (THM) were present at concentrations above EC guideline values. It is notable however, that many of the detectable compounds are present in raw water from the pumping stations. In many cases this relates to the vulnerability of the sites on the unconfined Chalk to both point source and diffuse source pollutants.

4.3.1 Pesticides

All pesticide compounds pose a significant environmental-health hazard since they are designed to be toxic. The stringent EC Drinking Water Directive has a maximum allowable concentration of 0.1 µg l^{-1} for any one pesticide and 0.5 µg l^{-1} for the total pesticide concentration. Pesticide

Table 4.2 Summary of results of analysis for pesticides in groundwater (Smedley et al., 1996).

Pesticide	Number of samples analysed	Number of samples in which pesticides were detected	Number of samples exceeding EC MAC
Isoproturon	50	2	0
Atrazine	50	4	2
Simazine	50	2	0
Terbutryn	50	2	0
Triazophos	50	2	0
Ethyl parathion	50	1	0

compounds encompass herbicides, insecticides, fungicides, growth regulators and desiccants. Pesticide and herbicide use in northern Britain in 1995, ranked by area, was dominated by isoproturon (408 t, over 414 kha), chlormequat (448 t, over 377 kha) and fenpropimorph (66 t, over 260 kha). Mecoprop usage amounted to 162 t over 100 kha and simazine to 39 t over 14 kha.

BOX 4 PESTICIDES — THEIR PROPERTIES AND POTENTIAL IMPACT ON GROUNDWATER

Ureas

Isoproturon, also known as IPU and ipuron, is the leading cereal herbicide (Chilton et al., 1995). It is a selective systemic herbicide, sorbed by roots and leaves with translocation. It is used for the pre- and post-emergence control of annual grasses and many broad-leaved weeds in spring- and winter-wheat, spring- and winter-barley, winter-rye and triticale. It is toxic to birds, rats and fish, and has a water solubility of 65 mg l^{-1}. Its half-life in soil is 6–28 days (Tomlin, 1994). Sorption in the saturated and unsaturated zones of the Chalk beneath soil cover is negligible, due to the lack of clay and organic carbon (Chilton et al., 1995).

Triazines

The triazine pesticides, atrazine and simazine, were heavily used in non-agricultural situations, particularly for weed control, until their use was banned in August 1992. Weed control, outside agriculture is undertaken largely by public bodies for clearance of paved areas, highways, airfields, railway embankments and car parks. In 1989, atrazine was used for 25%, and simazine for 14%, of all non-agricultural weed control.

Atrazine is also known as Atratol and Aatrex. It was in regular use for non-agricultural weed control before 1992 and is still the dominant herbicide used on maize crops. It is also used on sorghum, turf and rangeland. It is available as a wettable powder, a dispersible liquid and as granules. It can be applied to the soil surface and as a weed foliar spray. It has a water solubility of 33 mg l^{-1} and a field half-life in the soil of 60 days (Ware et al., 1992). Degradation rates in the subsurface are 10% of those in the surface soil. Half-lives in aquifers have been estimated at 105–200 days, depending on the system and environment (Helweg, 1992).

Simazine has the trade names Aquazine and Princep. It is used on corn, fruit crops and turf and for the control of aquatic weeds. Until 1992, it was also used for non-agricultural weed control. It is applied directly to pond surfaces and as a soil-surface spray. It has a water solubility of 6.2 mg l^{-1} and a degradation half-life in the soil of 60 days (Ware et al., 1992). In the saturated zone, the degradation half-life is 80 to 110 days. A dealkylated metabolite is produced (Helweg, 1992).

Terbutryn, or Igran, is used as a herbicide on wheat and barley and also on non-cropland. It has a field half-life of 42 days and a water solubility of 22 mg l^{-1}. It is available in powder, liquid and granule form and is applied as a soil-surface spray or target weed foliar spray (Ware et al., 1992).

Organophosphorus pesticides

Triazophos is an organophosphorus broad-spectrum insecticide, acaricide and nematicide. It is used for insect control on fruit trees, oil-seed rape, cereals, sugar beet, maize and forestry. It is also toxic to birds, fish and bees and has a water solubility of 30–40 mg l^{-1} (Tomlin, 1994).

Ethyl Parathion or *Parathion*, otherwise known as Aqua 8 parathion or Phoskil is an insecticide used on field crops, fruit, vegetables and ornamental plants. It is applied as a foliar spray and is available as an emulsifiable concentrate and as a wettable powder. It has a water solubility of 24 mg l^{-1} and a soil half-life of 14 days (Ware et al., 1992). Its half-life in the unsaturated zone is estimated at 200–400 days (Helweg, 1992).

Pesticides and their daughter products can reach groundwater by different pollution and transport mechanisms. Pollution can occur by leaching after field treatments, spillage, and from the disposal of pesticide containers. Pesticide usage has increased considerably since the 1960s and 1970s and total use continues to grow. In the UK, the most rapid growth has been associated with the increasing use of herbicides and fungicides in the cultivation of autumn-sown cereals. There has also been increasing non-agricultural use, particularly of the triazine herbicides, for defoliation (Chilton et al., 1993).

A study of agricultural pesticide in an unconfined chalk aquifer (Chilton et al., 1995) concluded that two main factors influence the transport and fate of pesticide: depth of soil cover and the potential for preferential flow. The soil zone is the most important zone for degradation and sorption of pesticides. Maximum sorption and degradation is possible when the majority of the water moves through the soil matrix rather than finding by-pass routes. Therefore, chalk sites with a thin soil cover, shallow unsaturated zone and large amount of preferential flow are more likely to have a groundwater-pesticide pollution problem. Laboratory experiments showed that there was little or no sorptive capacity for the herbicide isoproturon in the Chalk due to the lack of organic carbon and clay minerals present. Below the soil zone, there is unlikely to be significant further sorption of most pesticides.

Rates of degradation of pesticides in the soil zone are controlled by temperature, water content, soil pH, soil-organic-matter, clay and sand content, oxygen availability and microbial activity. Organic matter influences adsorption and transport processes. Soil pH affects sorption and hydrolysis rates (e.g. Helweg, 1992).

4.3.2 Non-aqueous phase liquids

The EC has set a guideline value for NAPLs at 1 μg l^{-1} for individual compounds in this category, but only three compounds, tetrachloromethane (3 μg l^{-1}), trichloroethene (30 μg l^{-1}) and tetrachloroethene (10 μg l^{-1}), have EC MAC values. The EC guideline values are an order of magnitude higher than the recommended limits for pesticides.

4.3.2.1 CHLORINATED SOLVENTS

Chlorinated solvents have a low solubility in water and are significantly denser and less viscous. They are, therefore, categorised as dense non-aqueous-phase liquids, or DNAPLs. The combination of these properties means that rapid and deep penetration into aquifers can be expected (Chilton et al., 1989). When spilt, they percolate downwards through the unsaturated zone by the most permeable route once the residual saturation has been exceeded. Lateral spreading in response to capillary forces also occurs. Migration through the saturated zone is also gravity-driven, as a result of density contrasts. DNAPLs migrate quickly via fissures but may be retarded by non-fractured or clay-rich layers. Solvent pools may form at the base of the aquifer. The subsequent slow dissolution into groundwater can persist for decades.

The chlorinated solvents investigated by Smedley et al. (1996) were tetrachloroethene (also known as perchloroethene, PCE), trichloromethane (or chloroform, TCM) and dichloromethane (DCM), which is used as a paint stripper and aerosol repellent. The degradation products 1,2-dichloroethane (DCA) and *t*-1,2-dichloroethene were also analysed. DCA is a breakdown product of 1,1,1,2-tetrachloroethane and 1,1,2,2-tetrachloroethane, which in turn are degradation products of pentachloroethane and

BOX 5 SOURCES AND IMPACTS OF LNAPLS IN GROUNDWATER

Toluene (or methylbenzene) is a component of petrol. It is quite soluble and can easily contaminate waste water. Point-source pollution can occur from leaking petrol storage tanks in garages and from fuel spills.

Methyl-t-butylether (MTBE) is the most common additive in unleaded petrol and can constitute up to 10% of the fuel. It is emitted from car exhausts and is found in runoff from roads. Point-source pollution from leaking petrol tanks and fuel spills can also occur.

MTBE has a low toxicity, but its low odour- and taste-threshold make it a problem at concentrations above 2 to 3 µg l^{-1} in water. It is highly soluble in water (50 g l^{-1} at 10°C) and over ten times as soluble as the BTEX components of fuel (benzene, toluene, ethylbenzene and xylene). Retardation by sorption onto organic carbon is negligible and the additive is reported to be non-biodegradable (Symington et al., 1993). These physical properties indicate that once MTBE has entered the groundwater system, it will be a persistent and mobile contaminant.

hexachloroethane. The compound *t*-1,2-dichloroethene (DCE) is an anaerobic breakdown product of trichloroethene (TCE), itself a breakdown product of tetrachloroethene (PCE) (Vogel et al., 1987).

Tetrachloroethene (PCE) was detected in two out of thirty four boreholes, i.e. 6% of the sites sampled but both concentrations were below the EC drinking-water guideline limit of 1 µg l^{-1}.

Chloroform (TCM) was detected at four sites at concentrations of 0.1 µg l^{-1} to 0.7 µg l^{-1}, again at concentrations below EC limits. Dichloromethane (DCM) was found in five out of fifty samples, two of which were taken from springs. The concentrations ranged from 1.7 to 3.9 µg l^{-1}, and were not determined in any of the samples from pumping stations.

The compound DCA was found at low concentrations of 0.12 µg l^{-1} in groundwaters at two sites. Higher concentrations of DCE were found, at between 0.1 and 0.3 µg l^{-1} in 28 out of 74 sites. Only one of these was from a water pumping station.

4.3.2.2 HALOMETHANES

Di- and trihalomethanes are commonly by-products of water chlorination and enter the groundwater system from leaking water mains. They result from competitive bromine substitution on chlorinated hydrocarbon compounds. The brominated dihalomethane, bromochloromethane, and the trihalomethanes, bromo-dichloromethane, dibromochloromethane and bromoform were also investigated. They were only found at four sites, all of which are pumping stations. The latter two compounds exceeded 1 µg l^{-1} at one site, but were well below the EC limit for THMs. Detection of these compounds close to the pumping stations may result from localised leakage of water mains in the raw-water supplies or to disinfection activities at the pumping stations. Bromobenzene was also tested for but was not found in any of the samples.

4.3.2.3 LNAPLS — FUEL COMPONENTS AND ADDITIVES

Light non-aqueous-phase liquids (LNAPLs) are less dense than water. They float on top of the groundwater and, unlike DNAPLs, their flow direction is dictated by the hydraulic gradient. Toluene and MTBE were sampled for. Toluene was detected at two sites at concentrations of 0.18 µg l^{-1} and 0.17 µg l^{-1} respectively. MTBE was found at concentrations in excess of 0.1 µg l^{-1} at six sites, all of which are pumping stations. None of the samples exceeded 1 µg l^{-1}.

5 Groundwater management

5.1 ABSTRACTION MANAGEMENT

Management of water resources in East Yorkshire commenced with the Water Resources Act, 1963 and the formation of river authorities with a duty to license abstractions. Historic abstractions were granted 'licences of right' even though over-abstraction might be taking place.

The nature of the Chalk, with groundwater flow concentrated in fairly thin zones of the aquifer, tends to make it self-limiting in terms of abstraction. This was highlighted in the drought of 1976, when the limiting output of the pumping stations was recognised. Yorkshire Water Authority subsequently developed a system of active management of the aquifer resources based on modelling studies undertaken by the University of Birmingham (see Chapter 3).

Present-day abstraction from the chalk aquifer in Yorkshire is equivalent to only 14% of total recharge, implying that there is a large resource yet to be exploited. However, the aquifer shows signs of stress during periods of low recharge, with pollution from agricultural sources and saline water ingress into boreholes (Elliot et al., 1998).

The Water Resources Act of 1963 determines that all water abstractions, except small domestic supplies, are authorised by an abstraction licence granted at that time by the river authorities. Responsibility for abstraction licensing passed to the Yorkshire Water Authority and then the National Rivers Authority and subsequently the Environment Agency. Further Water Resources acts were implemented in 1973 and 1991.

Following privatisation of the water industry in 1989, operational responsibility for providing public water supply fell to Yorkshire Water plc whilst regulatory authority fell to the National Rivers Authority (NRA)–Yorkshire Region. In 1992, Yorkshire and Northumbrian NRA regions merged to form the North-East Region. The Environment Agency was formed in April 1996, by combining the National Rivers Authority, Her Majesty's Inspectorate of Pollution and the Waste Regulation Authorities.

Abstraction management is based on surface water catchments rather than groundwater units. For groundwater management purposes the Chalk aquifer may be divided into four areas:

1. Wold Valley: few public water supply (PWS) abstractions
2. Driffield area: mostly isolated rural PWS abstractions and private boreholes (Plate 2)
3. Hull area (up to northing 40): extensively exploited for public water supply (Plate 3)
4. Holderness: the Chalk aquifer is overlain by thick drift deposits and has poor quality water.

The supply zone boundaries used by Yorkshire Water plc., cut across these areas (Figure 5.1).

Most of the major abstractions are located just off outcrop or in the confined Chalk, although a scattered network of boreholes in the Wolds (Area 1) supplies the rural population. The largest abstractions are taken from the Chalk around Kingston upon Hull where shaft and adit systems are used. The Cottingham pumping station, for example, comprises two pumping shafts, 17 other shafts and 1000 m of operational adit (typically 1.8 m high and 1.2 m wide), and has a licensed abstraction of about 68 000 and a mean actual abstraction of 24 000 $m^3 d^{-1}$ (Zang and Lerner, 2002). Estimated total actual abstraction from the Yorkshire Chalk aquifer is 105 Ml d^{-1} (Aspinwall et al., 1995a) although total licensed abstraction approaches 300 Ml d^{-1}. Major abstractions from the Chalk aquifer in Yorkshire are shown in Table 5.1 and the locations of the public water supply boreholes in Figure 5.1.

In Area 2, groundwater abstractions are relatively low and spring flow from the Chalk aquifer contributes 85% of the baseflow of the River Hull. Spring flows are dependent

Plate 2 The rural setting of the Elmswell borehole source.

on the previous winter's recharge and the low recharge in several winters in the drought period of the early 1990s resulted in very low flows in the river.

The Hull area derives it's water supply from the boreholes noted in Area 3, but also from an abstraction from the River Hull at it's tidal limit, approximately 15 km north of the city, together with a link from the Yorkshire Water regional grid system.

In the Hull area (3) the groundwater levels are controlled by the abstraction; areas that were once artesian have not been so for many decades. Abstraction in the Hull area has resulted in saline intrusion from the Humber Estuary, which is controlled by management of groundwater abstraction together with a decline in industrial abstraction (see Figure 3.12).

Area 3 is over-licensed and Yorkshire Water undertakes abstraction management, based on the groundwater storage available. The aquifer is viewed as a reservoir; the area below the 1976 minimum level is considered 'dead storage' and the available groundwater is calculated from the difference between the current level and the minimum level. The abstraction management plan is, therefore, based on observed groundwater levels and produces an average abstraction of around 65 Ml d^{-1}.

The Environment Agency has a network of observation boreholes throughout the Chalk aquifer (Figure 5.2), which are monitored for both groundwater level and quality on a regular basis. Seasonal head variations in the confined aquifer are low, but in the unconfined aquifer can be as much as 30 m.

An initial estimate of the Groundwater Resources of the Chalk aquifer was made by YOHRA (1969) as a requirement of Section 14 of the Water Resources Act, 1963. This estimate, with later revision, provided data for subsequent abstraction licensing decisions.

The complexities of groundwater behaviour and resource estimation outlined in Chapter 3 and the dynamic behaviour of the aquifer have meant that the most successful method of studying the aquifer is through the use of groundwater models.

A modelling study was initiated because Kingston-upon-Hull, the principal consumer of groundwater from the Chalk aquifer, has suffered water shortages at various times, since the 1940s. Forecasts suggested that new supply capacity would have to be built into the system by the year 2000 if frequent drought restrictions were to be avoided (University of Birmingham, 1985). Various options making use of spare capacity in the northern part of the aquifer were modelled, including a proposed river augmentation scheme, though this has not been implemented.

Details of the models developed to help manage the northern part of the aquifer are given in Chapter 3. In summary, for the period modelled (1975–1984; including the 1975/76 drought), although total licensed abstraction from the Chalk in the area was 64 Ml d^{-1}, actual abstraction was only 23 Ml d^{-1}. In terms of the aquifer's water balance these figures are quite low. Spring flow accounts for 89% of the recharge, abstraction 6%, and flows to sea 3%, the change in storage totalling only 2%. The system was determined to be in long-term equilibrium for the period modelled.

This model was incorporated into a model of the whole aquifer in which spring flows account for 55% of recharge, abstraction 14%, and flow to the sea to maintain a stable saline/freshwater interface, 31% of recharge. The model is used in a predictive mode to manage the water resources of the Yorkshire Chalk aquifer and has been used by Yorkshire Water to revise the 'control curves' for regulating abstraction around Hull. Information from the model has also been used to delineate groundwater protection zones for the major groundwater abstractions.

Plate 3 Converging adits in the Cottingham shaft and adit source (Courtesy of Yorkshire Water Services plc).

Younger et al. (1997), assessed the impacts of climate change on the groundwater resources of the Yorkshire Chalk aquifer. Predictions indicate that there will be a slight increase in both winter and summer recharge in the area over the next 50 years. This suggests increased security of the resource but predictions for global temperature rises beyond 2045 may increase evapotranspiration in excess of the increase in rainfall.

5.2 GROUNDWATER PROTECTION

5.2.1 The evolution of groundwater protection in the region

Immediately prior to the privatisation of the water industry of England and Wales in 1989, the separate Regional Water Authorities (RWAs) were responsible for groundwater resource management, including groundwater quality protection. In 1988, the Yorkshire Water Authority produced aquifer protection documents as a response to the distinct change in the perception of groundwater as a well-protected resource. More sensitive analytical techniques capable of detecting low concentrations of substances hitherto undetected (e.g. a wide range of pesticides and hydrocarbons) had been developed in response to new European legislation on water quality. Increasing costs of treatment were expected to occur due to a range of pollutants, especially the rising nitrate concentrations. In general there was an increasing awareness of the vulnerability of groundwater to pollution from a variety of contaminants, including persistent chemicals which can readily be transported by groundwater.

In recognition of this vulnerability of groundwater to pollution, a European review had been commissioned; the review for the UK being contracted to the Institute of Geological Sciences (renamed the British Geological Survey on 1 January 1984). Although the work was never published, it remains as an open file report with eight manuscript maps at a scale 1:500 000 (Monkhouse, 1983).

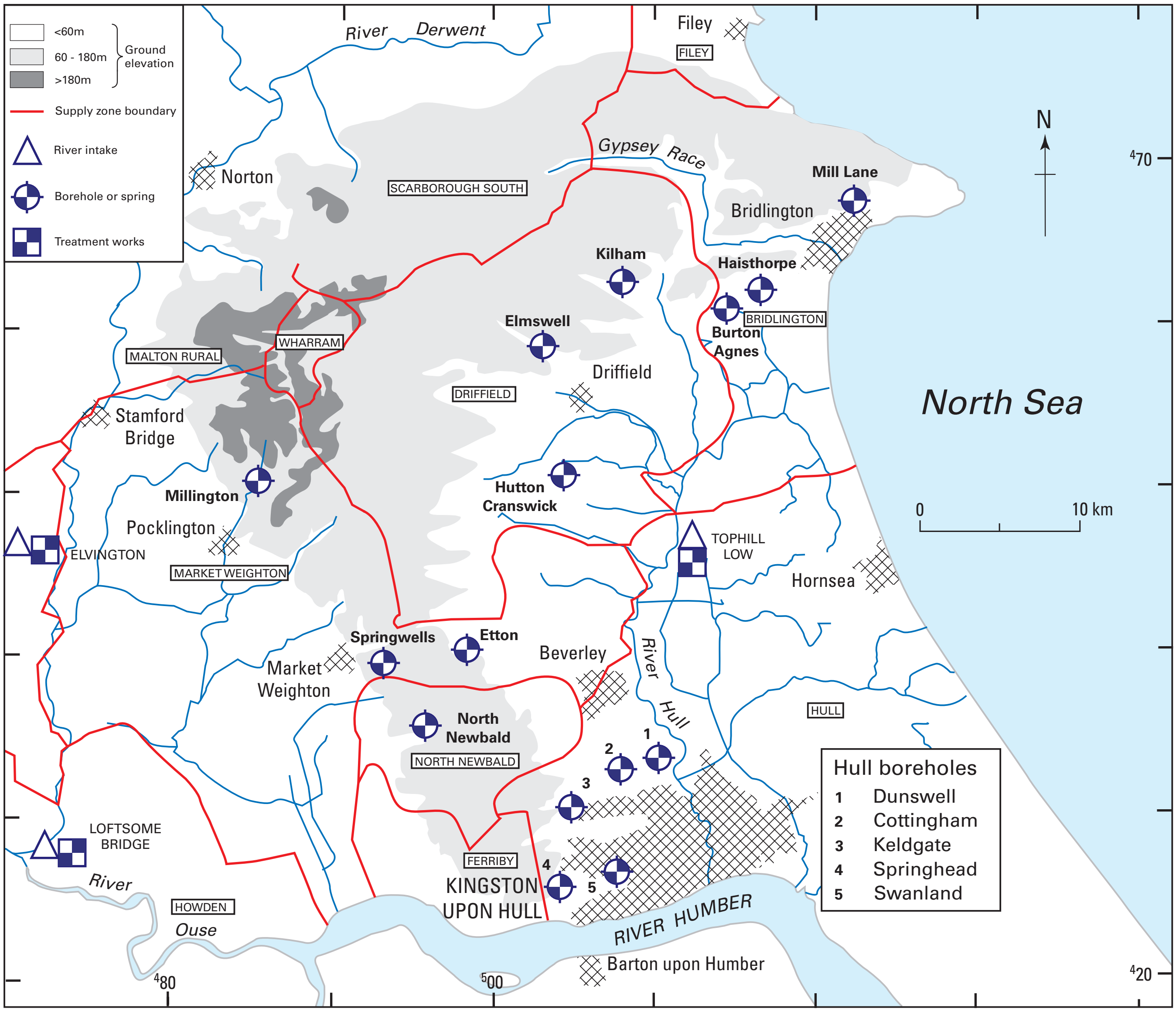


Figure 5.1 Location of water supply zones and major water sources in the Yorkshire Wolds (after Yorkshire Water).

Zones of vulnerability were based on the time a pollutant would take to move vertically from the ground surface to the water table, i.e. the residence time in the unsaturated zone (Box 6).

The need was recognised for a uniform approach from different centres within the region in setting standards of pollution control and in responding to proposals and inquiries. To some extent the aquifer protection documents produced in 1988 drew upon previous practices and guidelines (e.g. the Code of Practice for Utilisation of Sewage Sludge as a Fertiliser, 1986, and the Groundwater Protection Policy, 1982 of Yorkshire Water Authority), and the Aquifer Vulnerability to Pollution maps produced by BGS in 1983 and 1985.

At this time a significant body of national and international experience of contaminated groundwater had shown that 'clean-up' was at best difficult and always expensive. Thus it was generally accepted that it was better to prevent or reduce the risk of groundwater contamination, rather than to deal with its consequences. Additionally, the Control of Pollution Act of 1974 had provided legislative powers to permit the control of discharges to land and underground water from prescribed activities liable to cause groundwater pollution in designated areas. The aquifer protection policies provided a means for such control by restricting the activities permitted within the defined zones.

The National Rivers Authority was formed in 1989 and carried forward the aquifer protection policies in Yorkshire with no change. Table 5.2 shows the essentials of the zones defined by the various policy statements. It was recognised that whilst the zones for protection against pathogens (Zone 1) should be calculated individually, the number of boreholes involved made this impractical. Thus a small number of standard areas were drawn up which related to the majority of abstraction rates and aquifer properties. These protection areas were either circular or elongated depending initially on the size of the abstraction. Circular protection areas with radii of 100 m and 300 m were calculated for abstractions of $0–20 \times 10^3$ m^3 a^{-1} and $0–200 \times 10^3$ m^3 a^{-1}, respectively. For abstractions of over 200×10^3 m^3 a^{-1} a water balance was calculated using conservative estimates of specific yield and saturated thickness to derive upstream and

Table 5.1 Major abstractions from the Chalk aquifer in Yorkshire. (>1.2 Ml d^{-1}).

Location	**National Grid Reference**	**Daily licensed abstraction (Ml d^{-1})***
Public water supply		
Cottingham	TA 0470 3420	68.2
Springhead	TA 0410 2950	45.5
Dunswell	TA 0680 3510	45.5
Keldgate	TA 0270 3300	15.9
Etton	SE 9590 4280	15.0
Haisthorpe	TA 1360 6490	15.0
Mill Lane	TA1720 6860	9.8
Elmswell Wold	SE 9987 6136	6.8
Kilham	TA 0600 6480	5.5
North Newbald	SE 9240 3730	3.6
W W Gatenby	TA 0970 6970	3.2
Millington Springs	SE 8400 5300	2.7
Market Weighton (Springwells)	SE 8990 4250	2.7
Burton Agnes	TA 1100 6350	2.7
Northend	TA 0220 5830	2.6
Hutton Cranswick	TA 0130 5340	2.2
Sherburn	SE 9640 7580	1.3
Total		**248**
Private abstractions		
British Gas	TA 1787 5153	9.6
British Railways	TA 0260 2550	8.6
Munton & Fison plc	TA 1960 7020	4.5
Needlers plc	TA 0940 3100	3.0
Barff Farming Co	SE 8930 6700	2.7
Wansford Trout Farm	TA 0587 5558	1.9
Rhone-Poulenc Chemicals	TA 0400 3940	1.8
BTP Cocker Chemicals Ltd	TA 0390 3930	1.8
Seven Seas Ltd	TA 1480 2940	1.8
Tarmac Roadstone Ltd	TA 0980 4380	1.8
C K Soanes	TA 0100 4130	1.7
Sandsfield Gravel Co Ltd	TA 1320 4650	1.6
North Humberside	SE 9090 6110	1.5
T H Harrison	SE 0980 7160	1.4
Monroe Europe (UK) Ltd	TA 0520 4010	1.3
Total		**45**

* Due to licensed over-abstraction of the aquifer, restrictions may prevent the full licensed abstraction from being taken from the aquifer.

BOX 6 1983 EC/BGS VULNERABILITY CLASSIFICATION

Vulnerability zones were defined according to the time a conservative pollutant would take to move vertically from the ground surface to the water table, i.e. the residence time in the unsaturated zone. Residence time was determined subjectively based on knowledge of local conditions. The zones comprise:-

Zone 1	Residence time in the unsaturated zone longer than 20 years
Zone 2	Residence time in the unsaturated zone generally 1–20 years
Zone 3	Residence time in the unsaturated zone generally 1 week to 1 year
Zone 4	Residence time in the unsaturated zone generally less than one week
Zone 5	Zones varying rapidly over short distances and which cannot be clearly differentiated — the range of zones is indicated.

At the 1:125 000 scale used it was not possible to define Zone 2 and so is included in Zone 5.

downstream distances. The smallest viable standard area (A to H, Table 5.3) was then applied. Account was taken of confining zones, geological boundaries, combined protection zones for two or more boreholes and spring sources.

The National River Authority's Groundwater Protection Policy superseded this policy in 1992. The NRA's policy document specified a series of policies for all activities that could give rise to groundwater pollution, and defined the measures that the NRA would adopt in applying them. The policies were drawn from the many statutory duties, powers and regulations that the NRA had available to it, although in themselves they did not constitute legal powers. They are largely consultative in nature and advise developers, local authorities and others of the response that they can expect to receive from the NRA to proposals that they put forward which might have an impact on groundwater.
The policy was based on two independent elements:

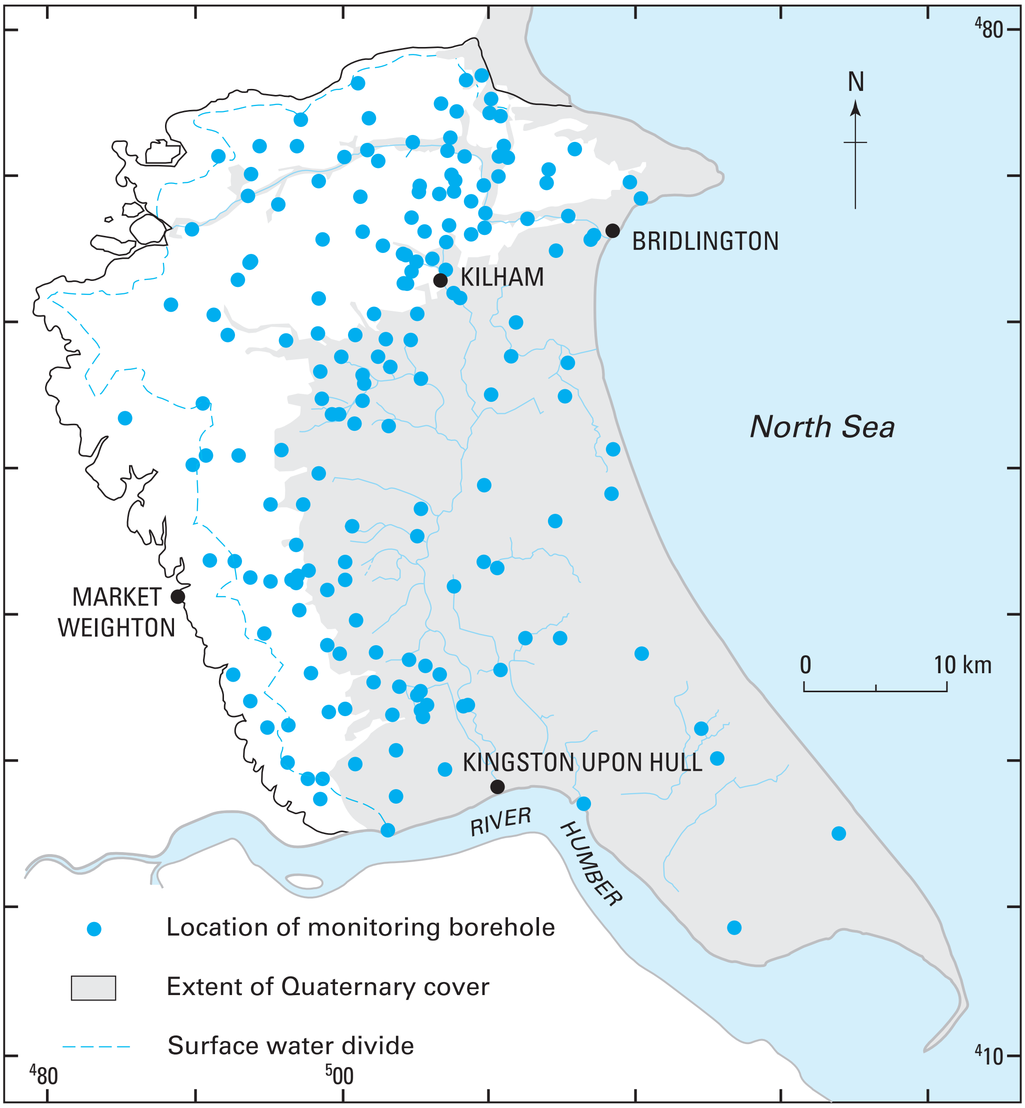
- aquifer vulnerability: division of the land surface on the basis of aquifer pollution vulnerability
- source protection: special protection areas for individual sources, in which, various potentially polluting activities are either prohibited or strictly controlled.

In the Chalk aquifer of Yorkshire, the groundwater protection zones were defined using the particle-tracking module of GPTRAC, a model developed by the US Environmental Protection Agency.

Table 5.2 Groundwater protection policy in Yorkshire at the time of privatisation of the water industry in 1989.

Zone 1	Area adjacent to any groundwater source $>365 \times 10^3$ m^{3}a^{-1}, (100 days horizontal travel time — min. radius of 100 m) to permit dispersion and dilution of chemical pollutants and elimination of pathogens.
Zone 2	Major aquifers where the seasonal water table is <5 m below ground level (bgl).
Zone 3	All exposed aquifers where the seasonal water table is <15 m bgl — excluding the drift where it is a separate aquifer.
Zone 4	All remaining aquifers — i.e. where the water table is >15 m bgl or has >5 m confining layer.
Zone 5	All aquicludes.

Figure 5.2 Locations of observation boreholes in the Environment Agency groundwater monitoring network.



5.2.2 Aquifer vulnerability

In developing the hydrogeological basis for the national groundwater protection policy, Adams and Foster (1992) defined aquifer vulnerability to pollution as a function of:

- the inaccessibility of the saturated zone, in a hydraulic sense, to the penetration of pollutants
- the attenuation capacity of the strata overlying the saturated zone as a result of physicochemical retention or reaction of pollutants.

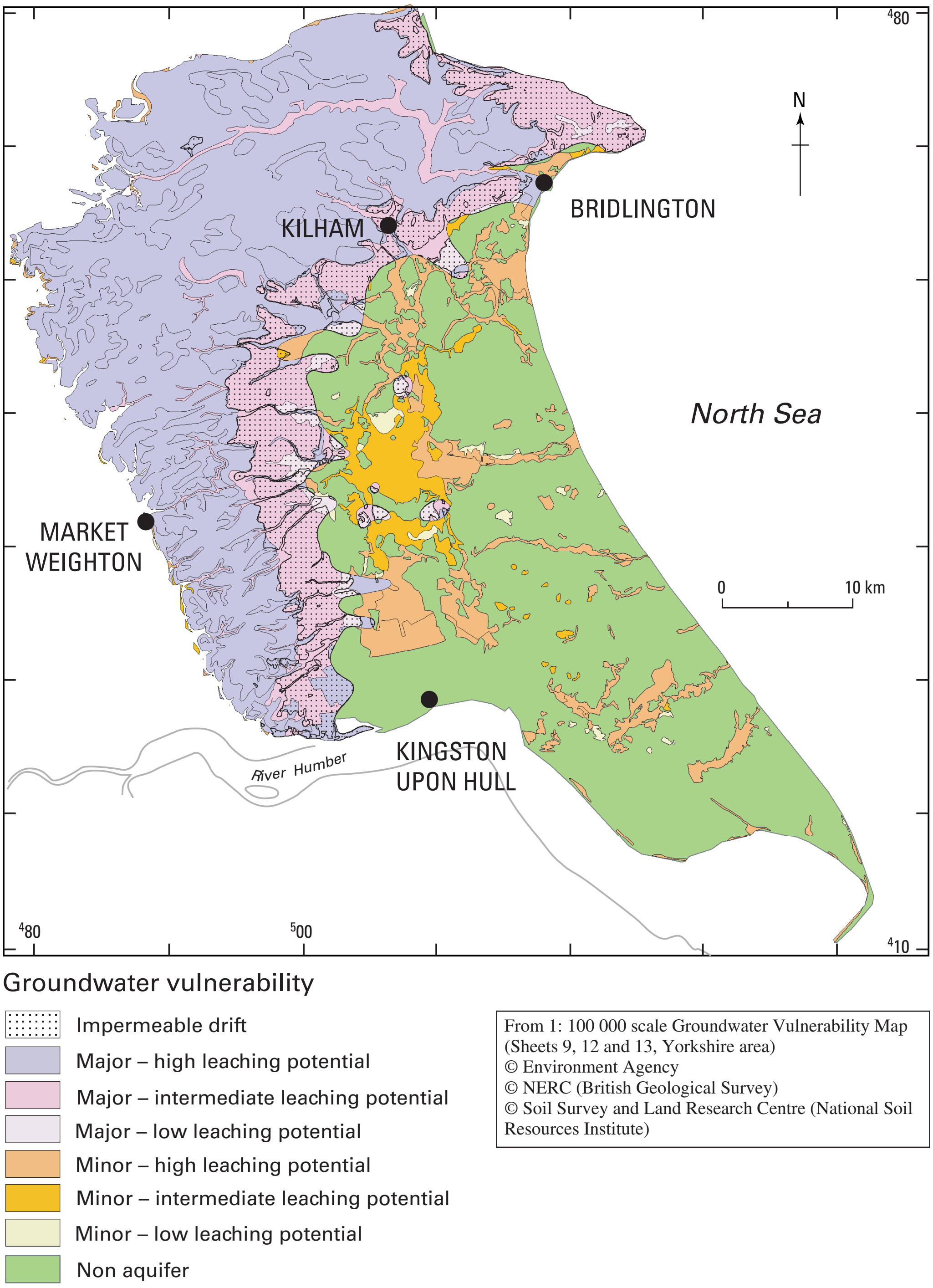
The factors that together define the vulnerability of groundwater resources to a given pollutant or activity, are: the presence and nature of the overlying soil; the presence and nature of drift; the nature of the unsaturated strata; and the depth of the unsaturated zone. It has been recognised that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

However, even if the required data were available, an atlas of maps would be required for any particular region, and the issues would be too complex for general land-use planning purposes. Thus the NRA (1992) adopted a more pragmatic approach based on available soil and geological information. They produced a nationally reliable map at the most detailed scale currently possible (1:100 000), whilst providing sufficient detail for strategic land-use planning purposes. It was still recognised that there may be a requirement for specific pollutant vulnerability maps in certain circumstances (e.g. nitrate vulnerability maps).

Table 5.3 Descriptions of standard Zone-1 protection areas (Yorkshire Water, 1988).

Area	Description
A	Circular, r = 100 m
B	Circular, r = 300 m
C	Circular, r = 500 m
D	Circular, r = 1000 m
E	Circular, r = 1500 m
F	Elongated, up = 1000 m, down = 500 m
G	Elongated, up = 2000 m, down = 1000 m
H	Non-standard
J	Semi-circular, r = 300 m
K	Semi-circular, r = 500 m
L	Semi-circular, r = 1000 m

Figure 5.3 Groundwater vulnerability map for the Chalk aquifer.



From 1: 100 000 scale Groundwater Vulnerability Map (Sheets 9, 12 and 13, Yorkshire area)
© Environment Agency
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© Soil Survey and Land Research Centre (National Soil Resources Institute)

Three hydrogeological types (major, minor and non-aquifers) were recognised and for the major and minor aquifer groups, three classes of soil were identified (high, intermediate and low leaching susceptibility).

Quaternary deposits forming aquifers are included in the 'minor aquifer' group, except where they are in hydraulic contact with 'major aquifers' when they are then classified as 'major aquifers' themselves. Superficial deposits with low permeability (e.g. till, soliflucted material, peat, lacustrine deposits, clay-with-flints and brickearth) are identified by a distinctive stipple overlay. Such deposits may effectively protect underlying aquifers (where they contain more than 5 m of clay) but their integrity and effective thickness are not adequately understood and site-specific evaluation is, therefore, essential. In all cases only the uppermost superficial deposits are classified.

A series of 53 regional maps, each covering an area of 60 × 60 km^2, was produced by the BGS and SSLRC for the National Rivers Authority between 1994 and 1998. A guide to groundwater vulnerability in England and Wales has been published (Palmer et al., 1995). Sheet numbers 9, 12 and 13, cover the Chalk of the Yorkshire, area. These maps are at a scale of 1:100 000 and a composite map is shown in Figure 5.3. As would be expected the Chalk outcrop is highly vulnerable where it is overlain by less than 5 m Quaternary cover. There are higher vulnerability areas where the deposits are thin or sandy in nature on the western margins of the cover, and around Kingston-upon-Hull.

5.2.3 Source protection

The NRA policy provided for three protection zones around all private and public groundwater sources of

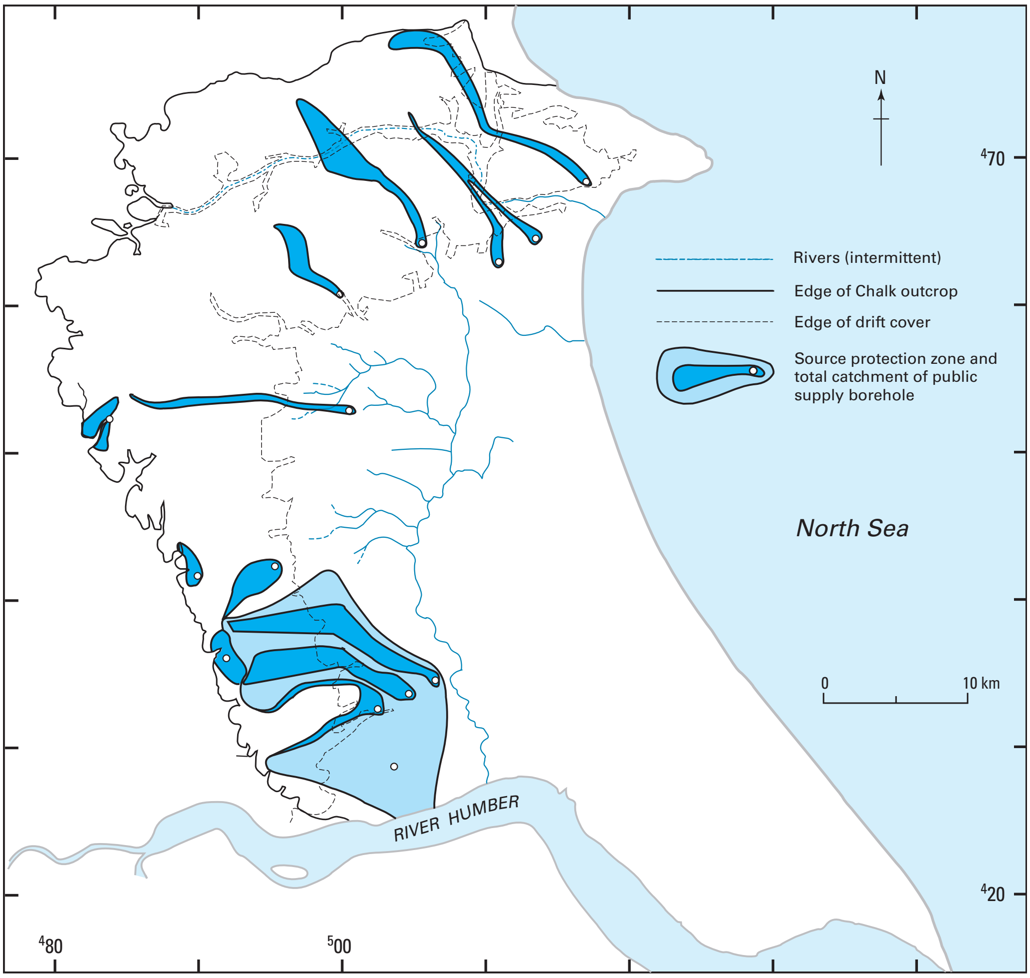


Figure 5.4 Steady-state protection zones, summer 1992 (after Salmon et al., 1996).

potable water; that is inner and outer protection zones. These are defined by 50 and 400 days time of travel through the saturated zone respectively, and the whole catchment. The objective of the inner protection zone is to protect against the effects of pathogenic pollution, the 50-day travel time being based on the time it takes for biological contaminants to decay. The outer protection zone is based upon the time necessary to provide delay and/or attenuation of slowly degrading pollutants.

The methodology developed to define these source protection zones (SPZs) used steady-state groundwater models. Zones were defined and made public using the best available data, and represent the 'first pass'. A general introduction to the zone delineation process has now been published (Keating and Packman, 1995) as well as a more detailed manual of zone delineation methodologies. The NRA also recognises that consideration may need to be given to the redefinition of zone boundaries in the light of additional investigations carried out prior to particular developments, or due to land-use changes. Source protection zones are, therefore, rarely regarded as definitive, being subject to regular reappraisal in the light of new data or changed circumstances (NRA, 1992).

Examples of source protection zones developed using a regional groundwater model (Salmon et al., 1996) are shown in Figures 5.4 and 5.5. The figures show capture zones for a number of Chalk boreholes in summer and winter 1992. The different sizes and shapes of the individual zones for the two seasons reflect the differences in recharge and direction of hydraulic gradient.

Subsequent national harmonisation and improved modelling of protection zones has resulted in the zones in Figure 5.6. The considerable differences in the areas covered by the zones reflect the difficulty in modelling these zones in the fracture-dominated flow system in the Chalk aquifer.

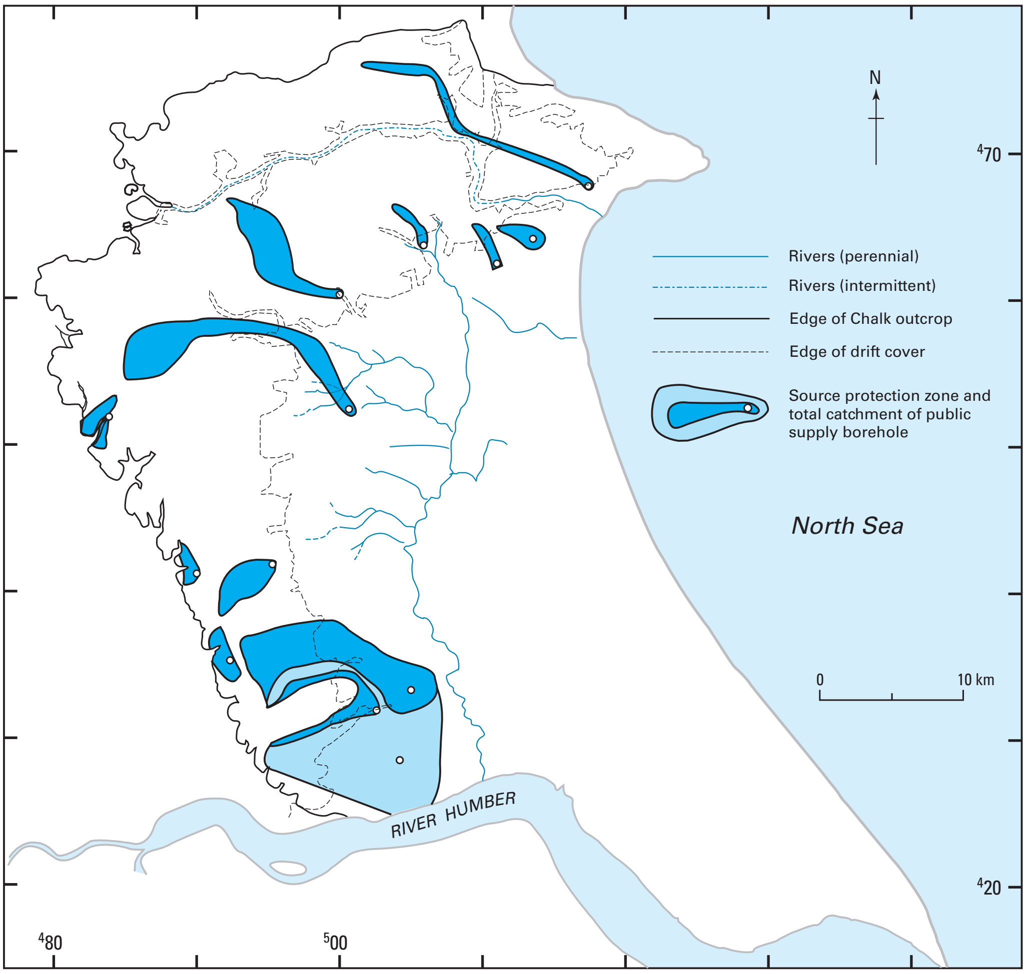
A series of special protection areas exist for individual sources, in which various potentially polluting activities are either prohibited or strictly controlled. Such activities include:

- control of groundwater abstractions
- physical disturbance of aquifers/groundwater flow
- waste disposal to land
- contaminated land
- disposal of liquid effluents, sludges, slurries to land
- discharges to underground strata
- diffuse pollution of groundwater
- additional activities or developments which pose a threat to groundwater quality.

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

The competing pressures of urban development and groundwater protection are exemplified in the westward expansion of Kingston-upon-Hull (Aldrick et al., 1999). The city (population of about 260 000) has developed using adited groundwater sources from the Chalk aquifer

Figure 5.5 Steady-state protection zones, winter 1992 (after Salmon et al., 1996).



since the mid-1800s. The four major sources; Springhead, Keldgate, Cottingham and Dunswell are located in the outskirts of the city, to the west and north-west, and provide just under half of the demand for water, the balance coming from the River Hull. Superficial deposits at the sources are about 10 m thick but the protecting clay component can be as little as half that thickness. Protection zones around the sources merge at the Zone 2 level and Zone 3 extends to the drift-free catchment boundary. The sources are currently threatened from pollution from (a) intensive market gardening (fertilisers, pesticides and fumigants), (b) semi-urban development with no mains sewers; septic tank/soakaway systems into the drift deposits (Kirk and Chadha, 1992) and (c) urban development may breach the protective clay layer where thin (Aldrick et al., 1999). Implementation of the Environment Agency groundwater protection policy requires cooperation with the local planning authorities to combine the requirements for urban growth effectively with the protection of the urban groundwater resource.

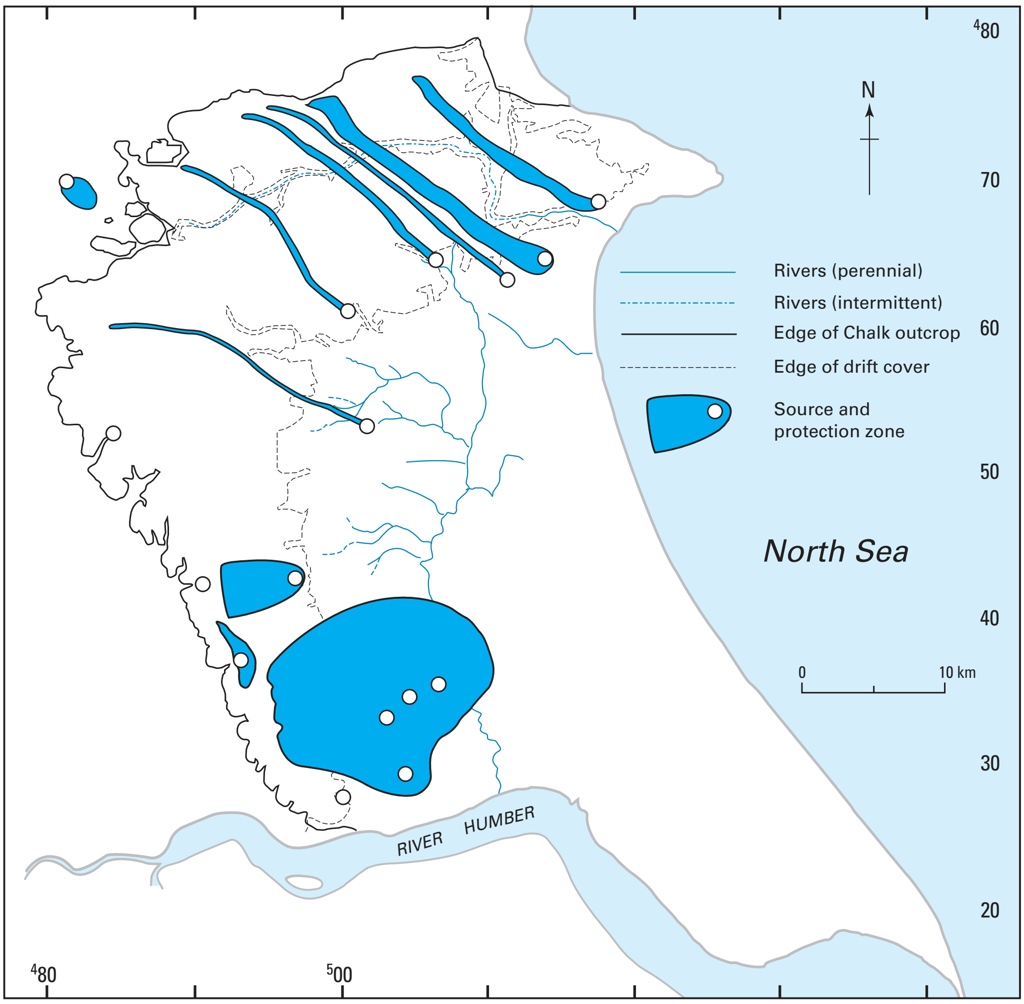
5.3 CURRENT AND FUTURE ISSUES

Although the abstraction from the Chalk aquifer in Yorkshire is currently only about 14% of annual recharge, the availability of additional resources is restricted due to the environmental demands for baseflow to the tributaries of the River Hull and to wetlands, as well as the need to maintain a barrier against saline intrusion in the vicinity of Kingston-upon-Hull. The induced saline intrusion and the related decline in demand from industry in the Hull area has led to an abstraction management plan in the area in order to stop any further ingress of saline water and ensure the resource is developed in a sustainable manner.

Increased utilisation of the groundwater resources in the Chalk aquifer in the headwaters of the Hull has been proposed at various times but the latest study (Halcrow, 1998) concludes that only changes that ameliorate man-induced effects should be considered. Several scenarios to modify groundwater abstraction were modelled including relocation of public water supply (PWS) boreholes and abstraction quantities, as well as artificial recharge of the aquifer. However, because spring discharge and available groundwater resources are so closely linked to the duration and intensity of recharge to the aquifer, modification to the regime is only likely to produce marginal impacts.

The quality of the groundwater in the aquifer has deteriorated over the last three decades through the impacts of both agricultural and point source pollution incidents. The diffuse pollution is the cause of most concern as, increasingly; control on potentially polluting activities in the source protection zones becomes increasingly effective. The legacy from agricultural activities over the last few decades will continue to be inherited for some years, even decades to come. Due to the long transit times and lack of natural degradation, nitrate levels exceeding guide levels will continue to be of

Figure 5.6
Environment Agency protection zones, 2000.



concern. Understanding the processes controlling the transport of pollutants and predictive modelling of the concentrations at individual sources will assist in developing management and treatment strategies that make best use of resources.

Although pesticides and their daughter products have been found in Chalk groundwater in Yorkshire, their occurrence is low in number and at concentrations close to detection limits. The results of a survey by Smedley et al., (1996) found only atrazine in concentrations in excess of EC guide limits in a few borehole samples. Other organic compounds that were detected included chlorinated solvents, although only DCM exceeded the EC guide limits. Awareness of the toxic nature of these compounds has been enforced through the implementation of demanding standards. However, residual contamination in both the unsaturated and the saturated zone of the aquifer has to work its way through the system. The manner in which it does this will determine how the problem is managed.

Bacterial contamination (*Guardia*, *Cryptosporidium* etc.) of groundwater sources is an area of concern in this highly vulnerable aquifer, particularly where large urban groundwater sources are extensively adited, thus increasing the highly vulnerable area.

The impacts of climate change have been assessed but the results are ambiguous as the predicted slight increase in recharge may be offset by increased evapotranspiration. As predictions from climate models improve, the impacts on water resources and the potential for improved management techniques will need to be reassessed.

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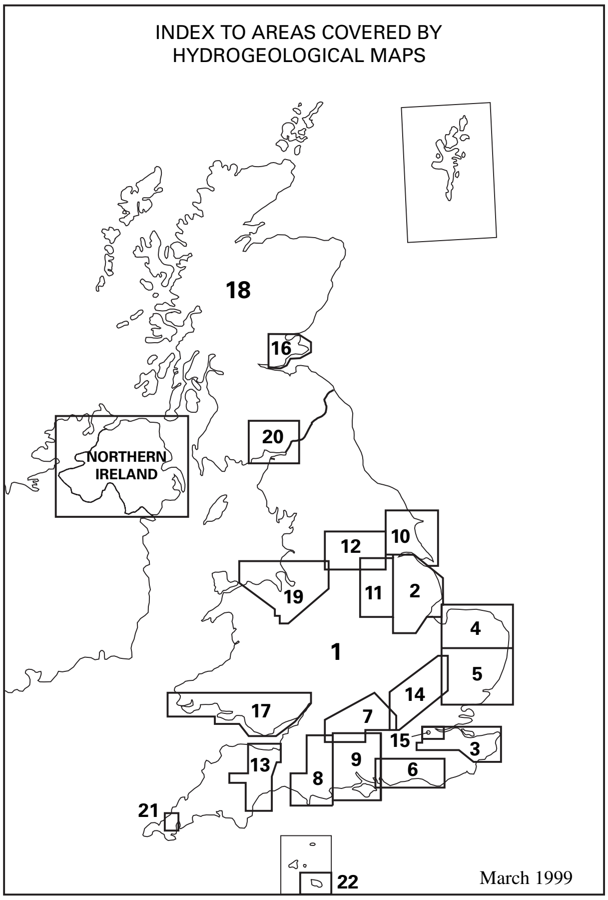

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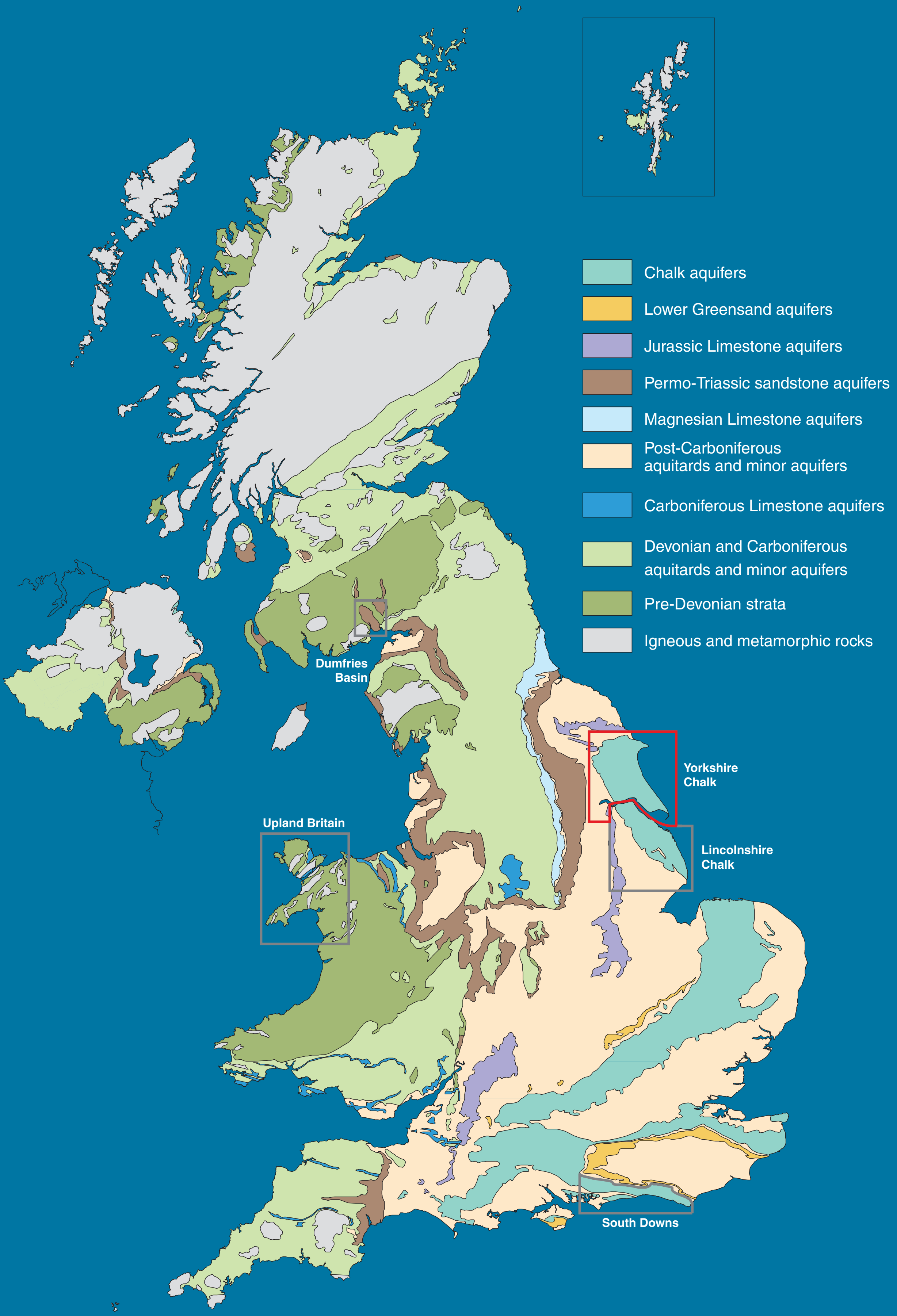

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