British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Recharge to the Chalk Aquifer Beneath Thick Till Deposits in East Anglia

Groundwater Systems and Water Quality Programme

Internal Report IR/04/007

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/04/007

Recharge to the Chalk Aquifer Beneath Thick Till Deposits in East Anglia

R J Marks, A R Lawrence, E J Whitehead, J E Cobbing, W G Darling and A G Hughes

Contributor/editor

D C Entwisle

Key words

Groundwater recharge; till; Chalk; nitrate; East Anglia.

Front cover

Sampling borehole CLR1.

Bibliographical reference

R J MARKS; A R LAWRENCE; E J WHITEHEAD; J E COBBING; W G DARLING AND A G HUGHES. 2004. Recharge to the Chalk Aquifer Beneath Thick Till Deposits in East Anglia. *British Geological Survey Internal Report*, IR/04/007. 58pp.

Keyworth, Nottingham British Geological Survey 2004

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham and Edinburgh; see contact details below or shop online at www.thebgs.co.uk

The London Information Office maintains a reference collection of BGS publications including maps for consultation.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.thebgs.co.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE

☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS

☎ 028-9066 6595 Fax 028-9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Acknowledgements

A number of staff in the British Geological Survey (BGS), Anglian Water Services (AWS) and the Environment Agency (EA) (Anglian Region) have contributed to the project. In addition to the collection of data, many staff have freely given their advice, and provided local knowledge and helped to review draft chapters of this report. Of the many individuals who have contributed to the project we would particularly like to thank the following:

Mr S Eyre and Mr M Cook of AWS

Mr M Grout and Mr J Fairbairn of the EA (Anglian Region)

Dr K M Hiscock of University of East Anglia (UEA)

Mr T Marsh of the Centre for Ecology and Hydrology

and the following staff in the British Geological Survey:

Mr M J Bird, Mr P Williams, Miss D Allen, Mrs S Hannay, Dr C Jackson and Dr M Mansour.

The authors would also like to thank Mr A J Kiddy and Mr D Midwood for allowing the construction and monitoring of investigation boreholes on their land.

Contents

FIGURES

TABLES

Executive Summary

This report describes the results of a project to investigate the Chalk-till groundwater system in East Anglia and to estimate rates of recharge through thick till (boulder clay) deposits. The project has involved drilling two cored boreholes, monitoring groundwater levels, sampling Chalk and till groundwaters and porewaters, and development of a conceptual model of Chalk-till groundwater hydrogeology.

The main findings of the report have been:

- the till has a significant impact on recharge quantity and distribution. Beneath the interfluves recharge appears to be lower than previously estimated (Klink et al. 1996, Soley and Heathcote 1998), probably <20 mm/a and possibly as low as 5 mm/a. Recharge to the Chalk aquifer is enhanced at the edge of the till sheet because of runoff from the till;
- the Chalk groundwater beneath the interfluves is old (probably a minimum of several hundreds of years) and has negligible nitrate concentrations. This groundwater makes only a relatively small contribution to the active circulation system in the valleys, which is normally characterised by modern (post-1960s), high-nitrate waters;
- the Chalk-till groundwater system and the spatial distribution of recharge to the Chalk aquifer determine the shape and dimensions of the catchment areas of abstraction boreholes. This in turn controls the proportion of modern water pumped by abstraction boreholes, which has implications for the concentration of nitrate in pumped water. One consequence is that boreholes close to the edge of the till are likely to pump a greater proportion of modern recharge than previously believed, probably with higher nitrate concentrations.

1 Introduction

In April 2000, the British Geological Survey (BGS) funded, as part of its core science programme, a 3 year research project to investigate and quantify recharge to the Chalk aquifer beneath thick till (boulder clay) deposits in East Anglia. This project met the criteria for core funding in that the research was of national/strategic value given (a) the importance of the Chalk aquifer to the UK water industry, (b) the sizeable area of Chalk outcrop in East Anglia that is overlain by thick till deposits and (c) the considerable uncertainty whether any significant recharge does occur through the till and, if it does, the recharge mechanism.

In addition to the funding under the BGS core programme, Anglian Water Services (AWS) contributed financially to the project, and were interested in this research for two principal reasons:

- an understanding of recharge to the Chalk, through till deposits, should allow a better delineation of the catchment areas for abstraction boreholes (at least in areas where till cover is significant). This, in turn, should help with modelling groundwater flow to abstraction boreholes, which is an essential first step when attempting to predict future groundwater nitrate concentrations;
- the research may indicate whether a useful resource of low nitrate groundwater exists in the Chalk aquifer beneath the till which might be suitable for blending.

This report was prepared for AWS and is an initial assessment of the research to date. A full Summary Report will be prepared by April 2004.

2 Background

2.1 THE CHALK AQUIFER

The Chalk, which is a major aquifer of the UK providing a significant proportion of the public water supply outcrops over large areas of East Anglia (Figure 2.1). Where the Chalk is exposed at the surface the soils are usually thin and very permeable, permitting maximum infiltration. However, there are large areas of East Anglia where the Chalk is overlain by glacial deposits, some of low permeability. In these areas the soils are thicker, less permeable and natural drainage is poor. Key questions directly relevant to the quantification of available resources include the amount of recharge that infiltrates through these till deposits, its spatial distribution and the mechanisms by which it occurs.

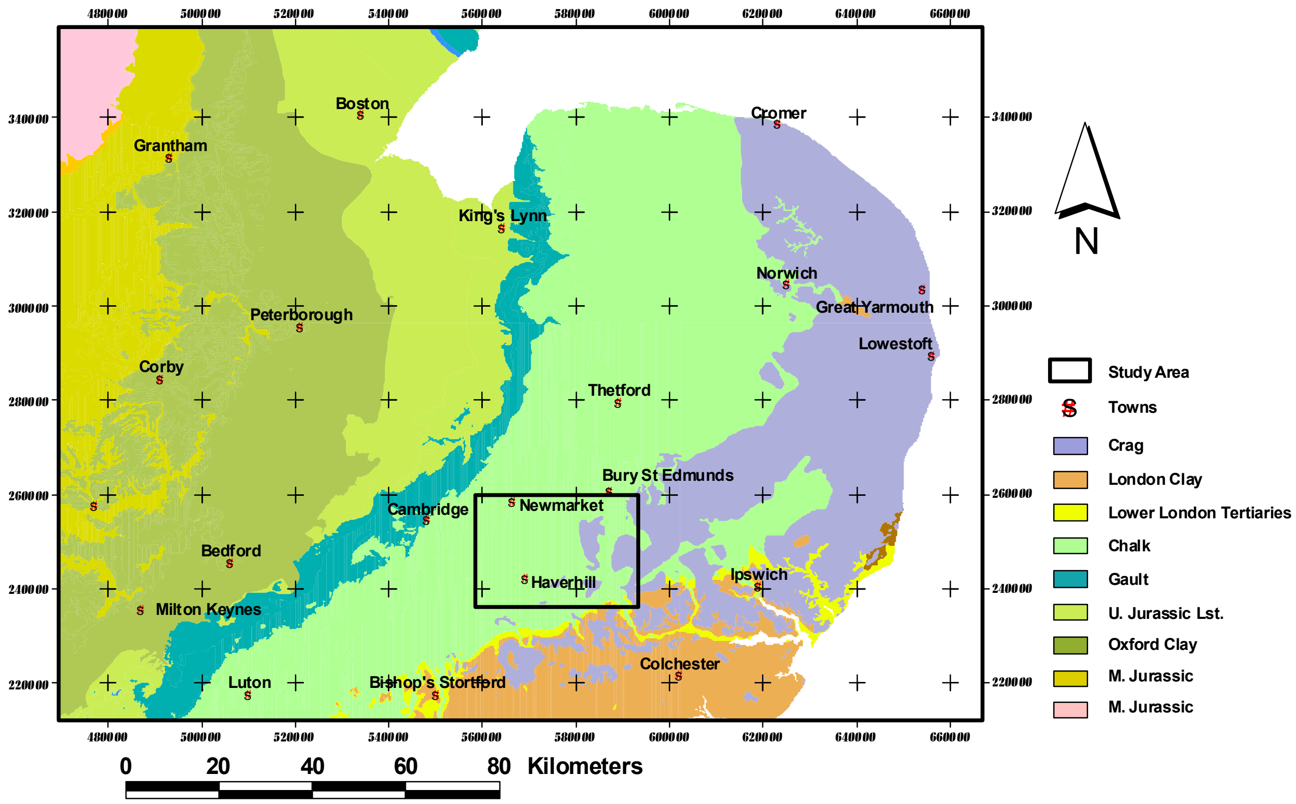


Figure 2.1 Chalk outcrop in East Anglia and location of study area

Water quality, especially the rising nitrate concentrations observed in many Chalk groundwaters, is a major concern. Since the 1960s intensive cereal cropping, supported by high applications of nitrogen fertilisers, has been widely practised on the Chalk outcrop in East Anglia. One consequence is that groundwater nitrate concentrations have increased and concentrations in excess of 20 mg/l N are widely observed. Many public supply sources now require action to reduce nitrate concentrations in supply water (e.g. blending or treating) or are likely to in the near future. However, Chalk groundwater beneath glacial deposits generally has low nitrate concentrations. This has been attributed both to longer residence times (Lloyd et al. 1981) and to bacterial denitrification (Parker and James 1985). Such low-nitrate groundwaters may provide a valuable resource for blending with higher nitrate groundwater to produce an acceptable quality for supply.

The Chalk is a fine-grained marine limestone, composed of debris from calcareous algae in the form of plate-like crystals (Duff & Smith 1992). The matrix of the Chalk is porous (porosity is usually in the range 25 – 45%) but has only low permeability because of the small pore throat diameters (typically 1 – 2 µm). The Chalk only forms an aquifer because it is fractured. The spacing, and more importantly the aperture, of the joints and fractures can vary widely, and as a consequence there is a large range in transmissivity. A fuller description of the hydrogeology of the Chalk aquifer is given by Price et al. (1993), Woodland (1946) and Ineson (1962) who were the first to observe that Chalk transmissivity was greatest in the valleys and much lower beneath the interfluves. Chalk transmissivity in valley/valley-side environments is usually in excess of 250 m^2/d and can be more than 2000 m^2/d. Enlargement of joints and fractures by carbonate dissolution is considered to be responsible for these high values. Beneath the interfluves, the confined Chalk transmissivity is usually less than 50 m^2/d and can be less than 10 m^2/d. The latter figure is believed to represent the permeability of the primary joint and fracture pattern (Lloyd et al. 1981).

Groundwater abstraction is largely concentrated in the valleys where aquifer transmissivity, and, therefore, borehole yield is higher. Perennial streams are generally restricted to the lower reaches of the valley floor (in exposed Chalk) and are groundwater-fed. Intermittent streams flow at higher elevations in the valleys in response to seasonal rises in the Chalk water table. The valleys thus represent discharge areas for the Chalk aquifer. Recharge occurs over the whole of the Chalk outcrop and groundwater flows towards the valleys (Figure 2.2). However, the picture is complicated where thick till deposits cover the interfluves and restrict recharge to the underlying Chalk. Under these circumstances, the valley and valley sides represent both the main recharge and discharge areas (Figure 2.3). Nevertheless some recharge through the till must occur because:

(i) groundwater levels in the Chalk aquifer beneath the till-covered interfluves are higher than in the valleys confirming that some vertical flow through the till must occur;

(ii) the till matrix is not completely impermeable and so some downward infiltration to the Chalk is possible. Furthermore, fractures in glacial tills have been widely reported (Horberg 1952, Williams and Farvolden 1969, Grisak and Cherry 1975, Grisak et al. 1976, Hendry 1982) and these could increase infiltration rates significantly.

2.2 HYDROGEOLOGICAL SIGNIFICANCE OF TILLS

The significance of tills to hydrogeology has been widely recognised in recent years, especially in North America. This is partly in response to concern about the vulnerability of the underlying aquifer to pollution where tills have been used for waste disposal and partly to considerations of groundwater resources in the underlying aquifers.

It is generally recognised that tills possess low matrix permeability typically in the range 10^{-10} – 10^{-11} m/s (Hossain 1992) and infiltration rates based on these permeability values are estimated to be as little as 0.3–3.0 mm/a which suggests that travel times through the till are likely to be many hundreds if not thousands of years, assuming a till matrix porosity of 0.2.

However, there is evidence that some tills are fractured and that this can increase the overall vertical (and horizontal) permeability of the till considerably. Furthermore, where solutes migrate via fractures there may be insufficient time for significant diffusion/exchange with till porewaters to occur, and as a consequence solute retardation could be limited and fast travel times are possible. This has implications both for water resources and for aquifer vulnerability. Evidence for fracturing includes direct field observation at recently exposed cuttings, relatively high permeability as determined by hydraulic tests, and the presence of tritium and other indicators of modern water at depth within or beneath the till (Hendry 1982, Van der Kamp 2001, Gerber et al. 2001).

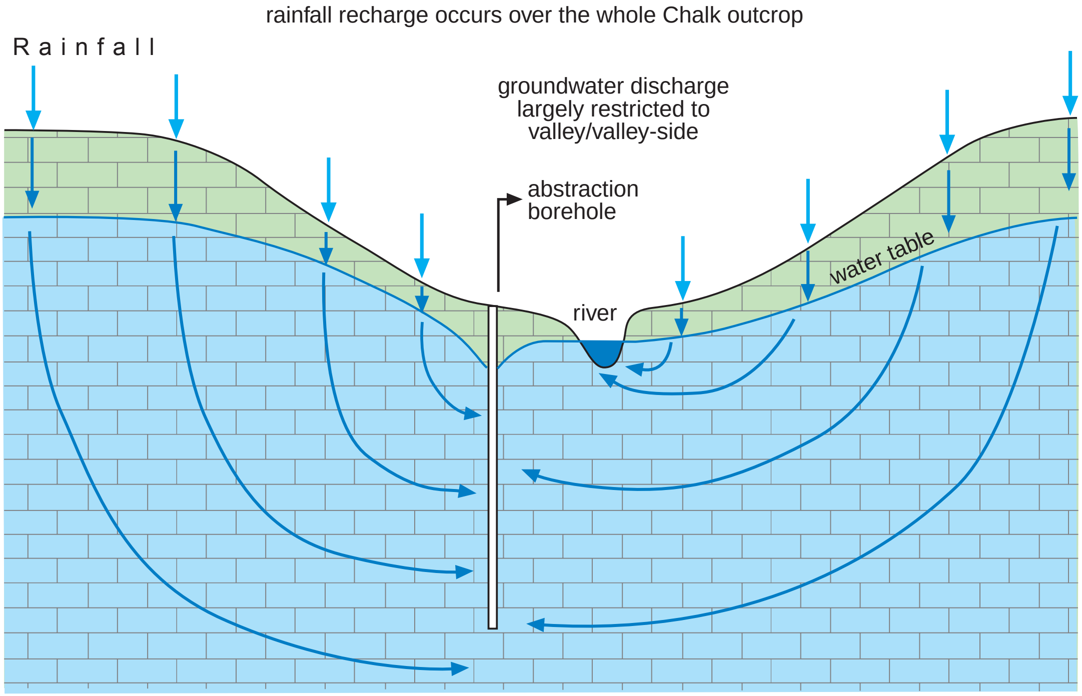


Figure 2.2 Groundwater flow system, unconfined Chalk

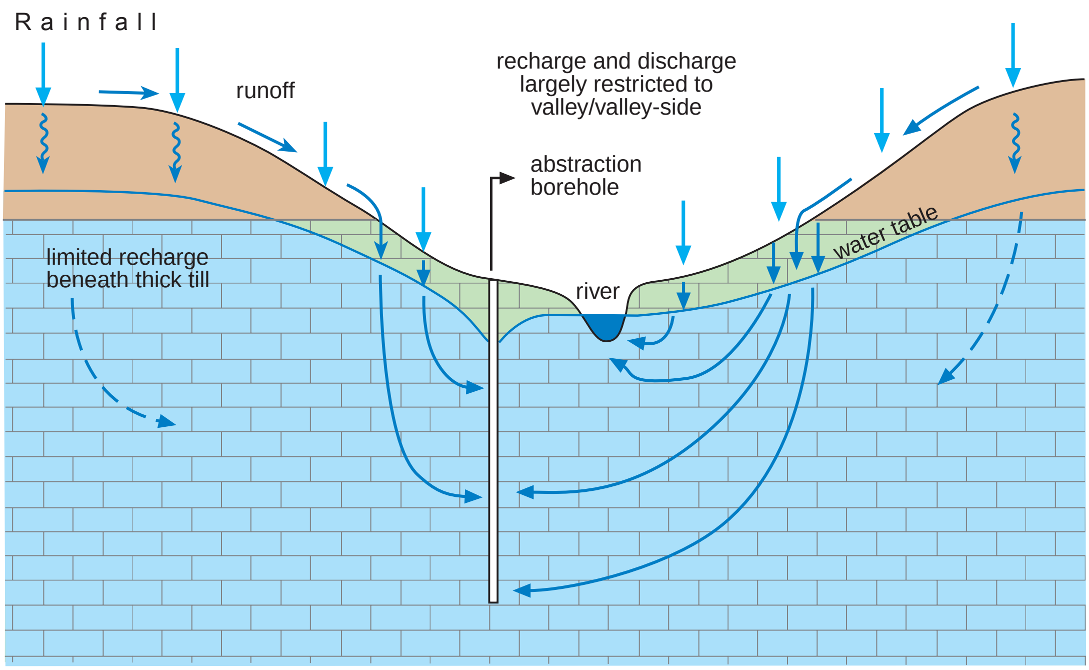


Figure 2.3 Groundwater flow system, confined Chalk

Research has suggested that some UK tills are also fractured (Rowe 1972, Vines 1984, Klinck et al. 1996). Infiltration rates through till deposits as high as 20–40 mm/a were estimated for both the Chalk aquifer in East Anglia (Klink et al. 1996) and for the Permo-Triassic sandstone (Vines 1984). The latter estimate was based on a water balance approach.

Tills can vary considerably in terms of thickness and lithology over short distances, however, the chalky boulder clay of East Anglia, which is a lodgement till deposited during the Anglian glaciation, is generally more uniform and consists predominantly of clay with subordinate lenses of sand and gravel, and contains pebbles of chalk and flint. It can be divided into an upper weathered, oxidised, zone (generally more permeable), and a lower un-weathered, un-oxidised, clay.

3 Description of Case Study Area

3.1 LOCATION

The area selected for detailed research lies between the River Stour and its tributaries, which drains to the south and east, and the Rivers Granta and Kennet, tributaries of the River Cam, which drain from the study area to the northwest (Figure 2.1 and Figure 3.1). The land is characterised by gentle slopes and differences in elevation between interfluves and valley floors are typically 50 to 70 m.

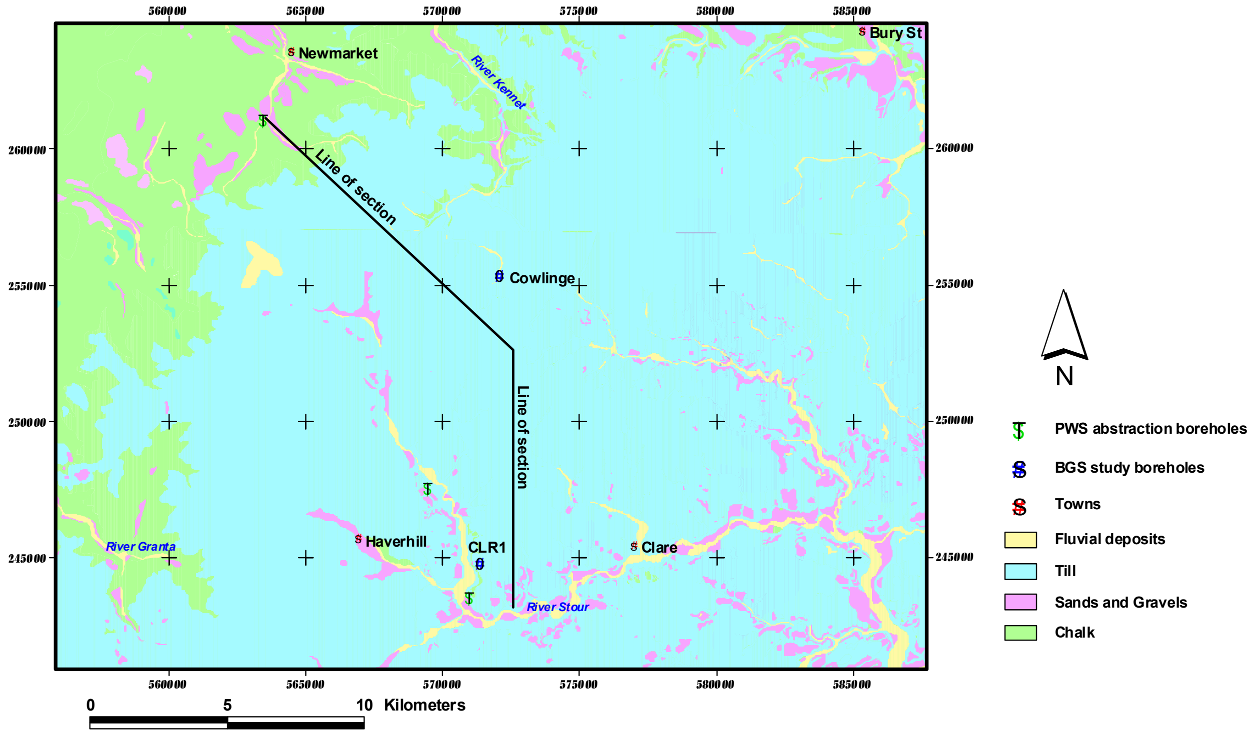


Figure 3.1 Geology of study area, showing main towns and rivers

The region is mainly rural and arable cultivation accounts for more than 80% of the land area. Soils on the interfluves are clayey and require land drains to prevent waterlogging and to make cereal cropping possible. These land drains discharge significant quantities of water into surface watercourses. In the valleys, where Chalk and sands and gravels are exposed, the soils are more permeable.

The 1960–1990 annual average rainfall for the area is 593 mm and the Penman evapotranspiration is about 524 mm/a. Actual evapotranspiration of 438 mm/a has been estimated using the Low Flow Study procedure (T Marsh, pers. commun.). On this basis excess rainfall is close to 150 mm/a making it one of the drier areas of the UK.

The River Stour is perennial in the main valley, although there is a transfer of water into the upper reaches above Great Wratting that is used to augments flow. A number of streams that flow off the till sheet to the northwest disappear on reaching the exposed Chalk outcrop.

3.2 GEOLOGY AND HYDROGEOLOGY

The Chalk formations dip to the southeast and over most of the study area the upper Chalk subcrops beneath the till which can exceed 30 m in places (Figure 3.2). However, the till is absent from the main river valleys and here the Chalk is either exposed or covered by permeable fluvial deposits. Occasional sand and gravel lenses occur within the till but these are not extensive, the exception being a basal sand and gravel layer (about 2 m thick on average), which is widely developed.

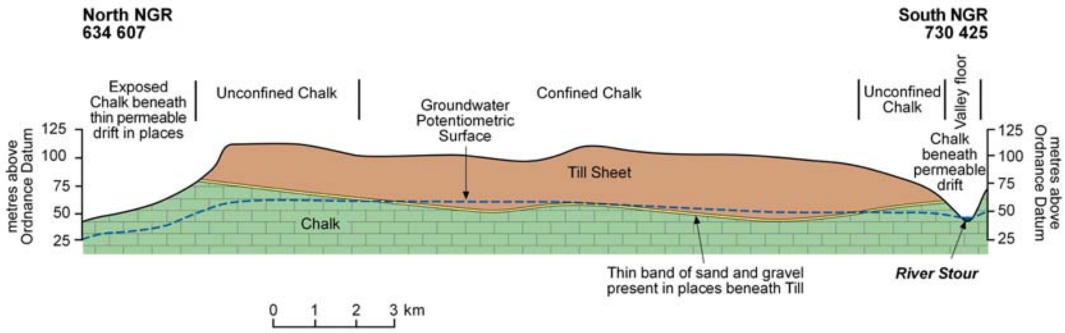


Figure 3.2 Geological cross-section (line of section shown on Figure 3.1)

The Chalk is the major aquifer in the area and is very permeable, at least in the valleys where yields of 6 Ml/d can be maintained for drawdowns of 8 m. Large quantities are abstracted from Chalk sources in the Stour Valley (e.g. Great Wratting and Wixoe) and from the exposed Chalk outcrop to the northwest of the till sheet (e.g. Lower Links). In the Stour Valley Chalk transmissivity is typically in the range 250–2000 m^2/d (Allen et al. 1997), but is much lower beneath the interfluves where Chalk transmissivity is typically in the range 2–30 m^2/d (Figure 3.3). The higher transmissivities occupy a relatively narrow zone within the valley of the Stour, probably less than 1–2 km in width. The transition to the lower transmissivities beneath the interfluve appears to be sharp, although pumping test data from beneath the interfluves is sparse. Intermediate Chalk transmissivities of 50–120 m^2/d are occasionally observed in the Chalk aquifer beneath the interfluves and usually close to minor streams flowing over the till sheet (e.g. Hundon, NGR TL 733 486).

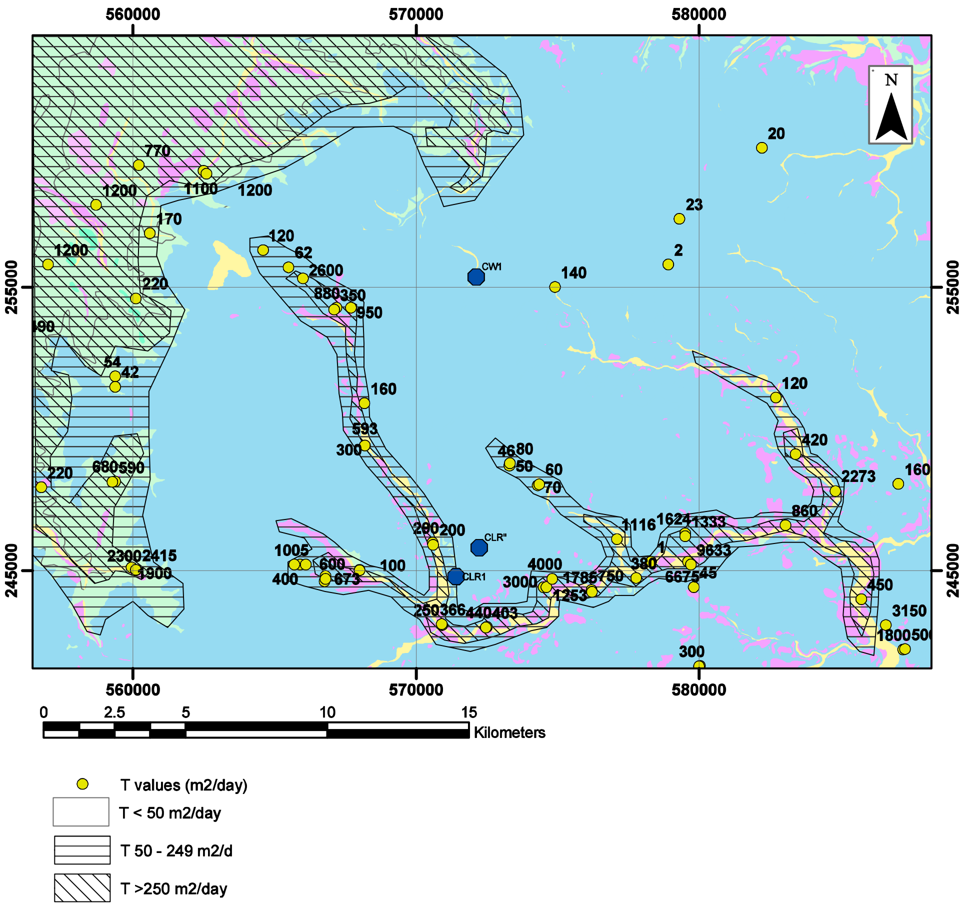


Figure 3.3 Plot of transmissivity distribution across study area

Data on Chalk storativity are rather sparse; for the confined aquifer storativity is probably in the range $10^{-3} - 10^{-4}$ and for the unconfined aquifer closer to $10^{-3} - 7 \times 10^{-2}$ (Allen et al. 1997). The higher storativity (or specific yield) values for the unconfined Chalk may be a consequence of the Chalk water table fluctuating within the more porous sands and gravels that commonly overlie the Chalk in the valleys. Chalk specific yield may be higher than some pumping test results suggest because of delayed drainage effects (Lewis et al. 1993). In a study to evaluate the volumes of water stored in the Chalk aquifer it was observed that the volumes of water leaving two Chalk catchments as baseflow during long recessions was much greater than the estimated changes in groundwater storage in the catchments during the same periods. Lewis et al. concluded that the most likely source of water was slow drainage from the unsaturated zone, a process they termed 'delayed recharge'. Price et al. (2000) attributed the effect to the draining of irregularities on the fracture walls.

Chalk groundwater levels reach a maximum beneath the interfluves and are lowest within the river valleys (Figure 3.4 and Figure 3.5), indicating that groundwater flows from the interfluves towards the valleys. The gradient of the water table is steeper along the northwest edge of the till sheet (Figure 3.4) and this feature coincided with increasing chalk transmissivity. This presumably reflects greater lateral flow within the aquifer and suggests that recharge along the edge of the till sheet is enhanced.

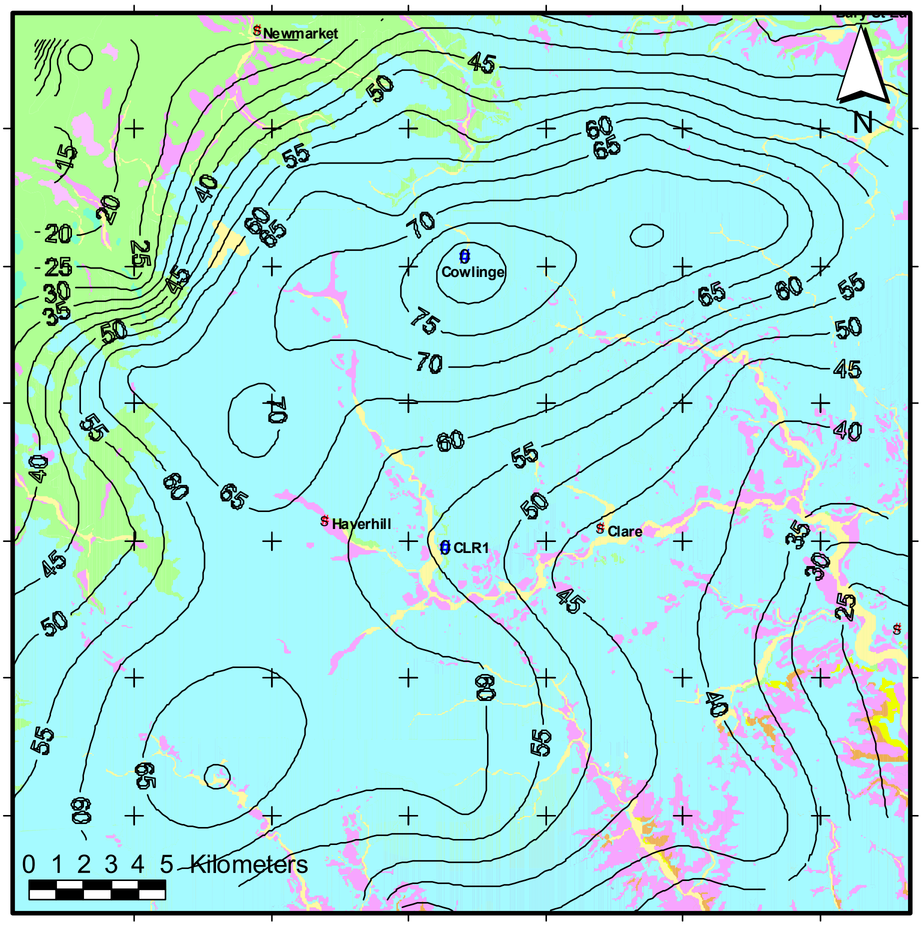
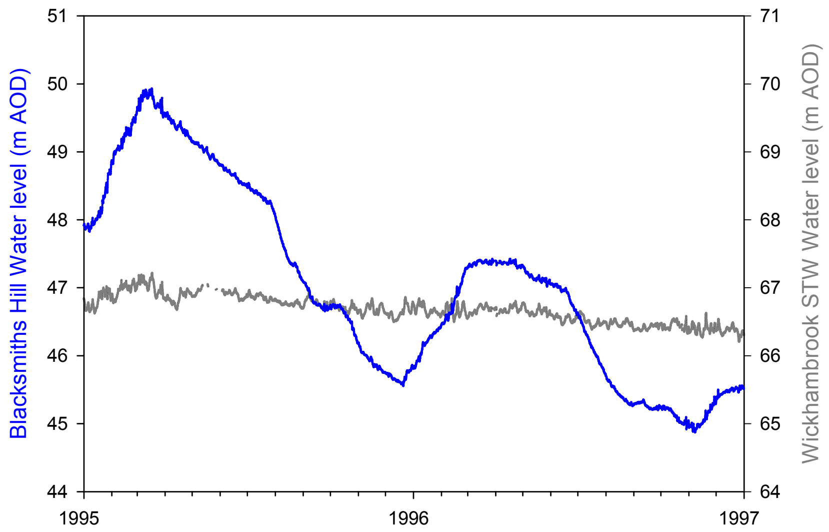


Figure 3.4 Contours of Chalk rest water level, March 1999 (mAOD)

Chalk groundwater level fluctuations beneath the interfluve are relatively subdued and where the till confines the Chalk a seasonal fluctuation of about 0.3 m is typical. This compares with a seasonal fluctuation of 2–4 m where the Chalk is unconfined in the valley sides (Figure 3.5).



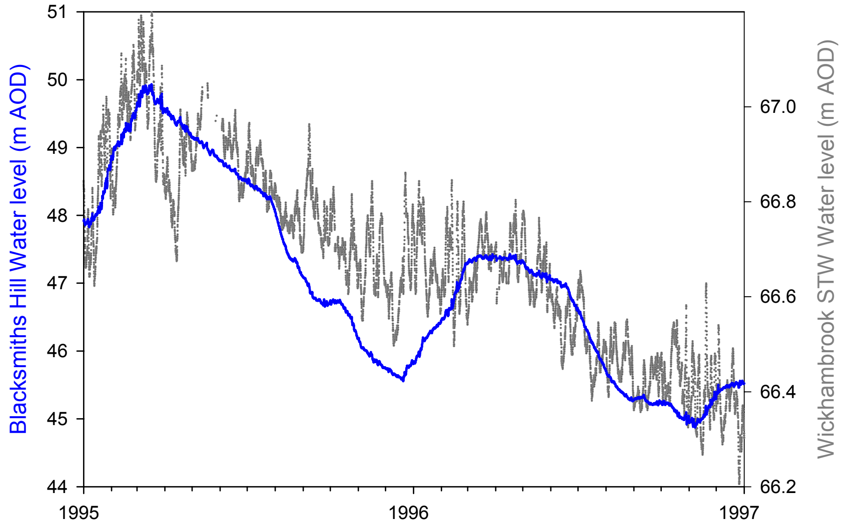


Figure 3.5 Groundwater hydrographs: Blacksmith's Hill borehole is located in a valley edge setting, Wickhambrook STW borehole in an interfluve environment

4 Methodology

The limited resources available precluded a comprehensive investigation; instead the approach adopted by the project was to:

1. Drill investigation boreholes (one partly and one fully cored) near the centre and at the edge of the till sheet to (a) identify the main geological units within the Chalk-till sequence and their likely hydrogeological significance, (b) determine the porewater chemistry of the till and the Chalk (including residence-time indicators) and assess what interaction occurs between groundwater within the till and Chalk (i.e. is there evidence for modern recharge moving through the till to the Chalk?).
2. Determine regional water quality variations by sampling existing boreholes (EA monitoring boreholes, AWS abstraction boreholes) to set the data obtained from the research boreholes into a regional context.
3. Monitor water level response within Chalk and till groundwaters to rainfall infiltration.
4. Attempt to quantify recharge rates to the Chalk aquifer through till.
5. Develop a conceptual model of the Chalk-till groundwater system, which identifies the recharge components of the groundwater system and the flow pathways. It was the intention for the conceptual model to include semi-quantified estimates of recharge rates.

5 Work Programme and Methods

5.1 CLR1 CORED BOREHOLE

A borehole (CLR1) was drilled northwest of Boyton End on an agricultural track between arable fields in November 2000 (NGR TL 7142 4477) in a till edge domain (Figure 5.1). It was drilled by a light percussion-drilling rig commencing at 260 mm diameter and telescoping down to 150 mm diameter at the base. The ground level at the site is about 80 mAOD and the borehole was fully cored by driving U4 tubes to a total depth of 31 m (Figure 5.1), through 21.4 m of drift and into the unsaturated and saturated Chalk. Most of the drift was unoxidised till, but it also included a sequence of sandy gravel and saturated silt between 2.0 and 5.30 mbgl. Temporary casing was used to seal the wet silt seam and also to support the Chalk.

The core was logged and porewaters were extracted for analysis. Porewater was obtained by centrifugation for the Chalk core and by squeezing in a triaxial cell for the till. Porewater samples were analysed for major ion concentrations, stable isotopes and tritium.

The borehole was constructed with two groundwater piezometers and seven gas piezometers. The groundwater piezometers are constructed from 52 mm ID HDPE shoulder-less pipe and are fitted with caps at the base and surface. A 4 m slotted screen piezometer was positioned in the base of the borehole to enable groundwater sampling of the Chalk and monitoring of Chalk groundwater levels. Groundwater levels were unconfined at 26.8 mbgl in November 2000, approximately coincident with the top of the slotted screen, and test bailing of this installation did not significantly affect groundwater levels. A second groundwater piezometer with a slotted geotextile wrap screen was installed against the wet silt band for the collection of groundwater samples and monitoring of perched water levels. The piezometric level was 4.5 mbgl in November 2000, showing the seam to be confined. Test bailing showed that the piezometer could be pumped dry after drawing 11 litres, although it took 24 hr to recover which indicated the low permeability of the silt.

The gas piezometers are 0.3 m long and fabricated from perforated PVC pipe capped at each end and filled with glass wool. They are connected to the ground surface with quarter-inch OD nylon tubing with taps fitted at the surface to isolate each installation from atmospheric contamination. Two gas piezometers are installed within the unsaturated Chalk (Figure 5.1 and a further three piezometers are installed within the unoxidised till beneath the silt seam. A sixth gas piezometer has been placed within the sandy gravel seam and a seventh positioned within the oxidised till above. All piezometer installations are enclosed by a 2–4 mm grade sand pack, which extends to just above and below the open zone of the piezometer and effectively limits the sampling depths. The piezometer zones were mainly isolated by intervening bentonite pellet seals, although the zone between 14.8 and 17.8 mbgl is filled with spoil material.

All the surrounding fields have a system of piped land-drains, which were flowing in November 2000, and these are overlain by a system of mole drains. This network catches a proportion of the infiltrating water and transfers it into the ditch system. Thus some of the water that infiltrates the soil migrates laterally through field drains and then into surface watercourses.

The sequence between the base of the till, the underlying sand and gravel and the Chalk is fairly well exposed in a ditch lower down the valley side and gives an approximate elevation of the top of the Chalk of 63 mAOD, which is supported by the mapped line for the top of

Chalk. This compares to an approximate elevation of 59 mAOD in the borehole. In the ditch the intervening sand and gravel has a thickness of about 1–2 m.

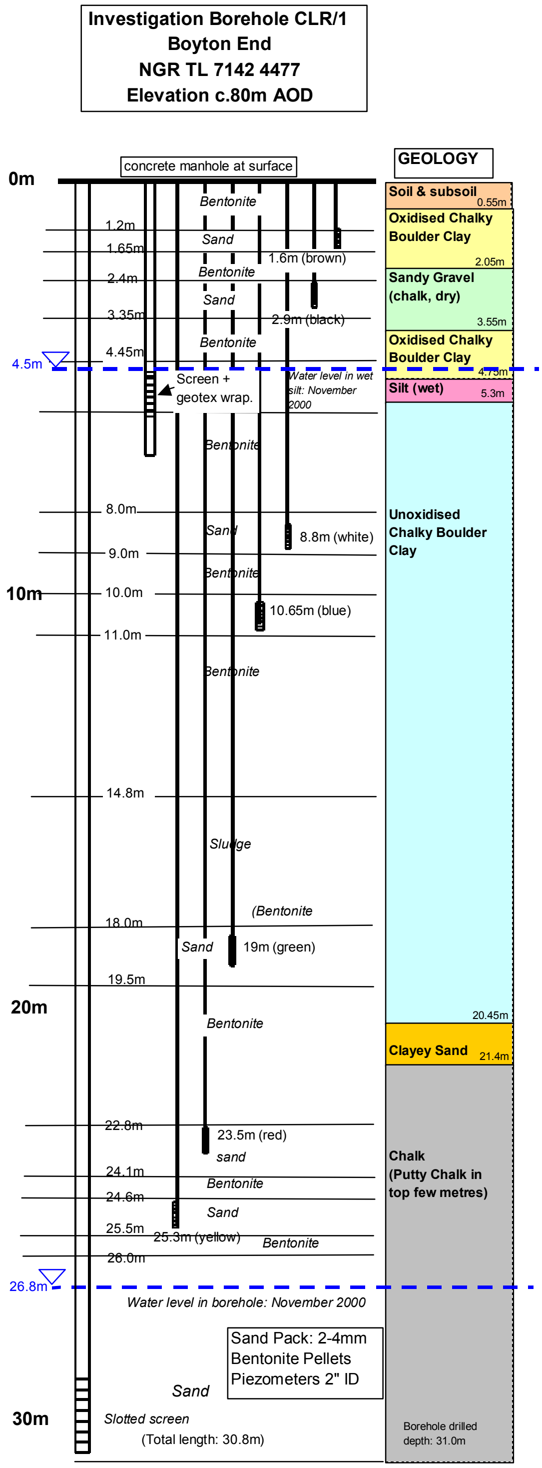


Figure 5.1 Geology and construction logs CLRl

5.2 CW1 PART-CORED BOREHOLE

A borehole (CW1) was drilled by the percussion method to a total depth of approximately 80 m, near Cowlinge (NGR TL 571 254) in February 2003. Representative core samples from both the till and Chalk formations were obtained by driving U-4 tubes, though only about a quarter of the total drilled depth was cored owing to budgetary constraints.

The core was logged on site. Samples of the till (in U-4 tubes) were sent to the University of East Anglia (UEA) to support a research project and on completion of this the till porewater chemistry will be forwarded to BGS. The Chalk porewaters were extracted by centrifugation and were analysed at the BGS Wallingford laboratories.

On completion of drilling the borehole was hydrogeophysically logged prior to packer testing. The purpose of packer testing was to obtain:

(i) hydraulic conductivity data for the Chalk;

(ii) head data for discrete intervals within the Chalk;

(iii) water samples from discrete intervals within the Chalk.

Unfortunately, the packer equipment became lodged in the borehole and the packers parted from the pump and rising main. The packers were retrieved at a later date but no testing of the borehole proved possible.

A short pumping test was carried out, the interval being from 40–80 m in the Chalk. The borehole was completed with three monitoring piezometers, one in the till at 12.9 mbgl, and two in the Chalk (49 and 74 mbgl).

5.3 CLR1 BOREHOLE GROUNDWATER LEVEL AND CHEMISTRY MONITORING

Water level data were collected at 6 hourly intervals by loggers and the data downloaded at each visit for each of the two piezometers in the borehole. Groundwater chemistry monitoring was (initially) halted by the Foot and Mouth epidemic of 2001. Later, water samples were collected by pump and bailer from the two piezometers. These were analysed for major ions, O and H stable isotopes, $\delta^{13}C$ and tritium and CFCs to characterise the aquifers, monitor seasonal variations (and attribute to recharge) and for dating the water, but major chemical changes were not anticipated. Pumped samples for dissolved gas analysis to assess the N systematics were also collected to determine if denitrification is occurring. There are seven colour-coded gas piezometers and these were sampled in the unsaturated zone in both the till and Chalk.

5.3.1 CFC groundwater dating

Concentrations of the CFCs (chlorofluorocarbons) have been increasing in the atmosphere at known rates since they began to be used industrially (CFC-12 in the 1930s, CFC-11 in the 1950s) (Plummer and Busenberg, 1999). Recharging rainfall contains CFCs dissolved in proportion to the atmospheric concentrations at the time of the event. In general the CFCs behave in a conservative way during travel in the subsurface. They therefore have the potential to act as indicators of the time elapsed since recharge, in other words the groundwater ‘age’.

CFC results can be interpreted in two main ways: either as a bulk age, which assumes that groundwater moves by piston flow, or in terms of mixing. In the latter case a simple mixing between ‘dead’ groundwater (<50 yrs) and ‘modern’ recharge (within the past few years) is often assumed for simplicity. This interpretation is usually preferred for fractured aquifers as they are considered more likely to promote mixing than simple intergranular flow.

5.4 REGIONAL WATER CHEMISTRY MONITORING

To set the data collected from the two-cored boreholes in a broader context, water samples were collected from existing EA monitoring boreholes and from AWS abstraction boreholes. These boreholes were located in a variety of settings including interfluves, valley side and valley floor sites (Figure 5.2). In addition some surface water samples were also collected.

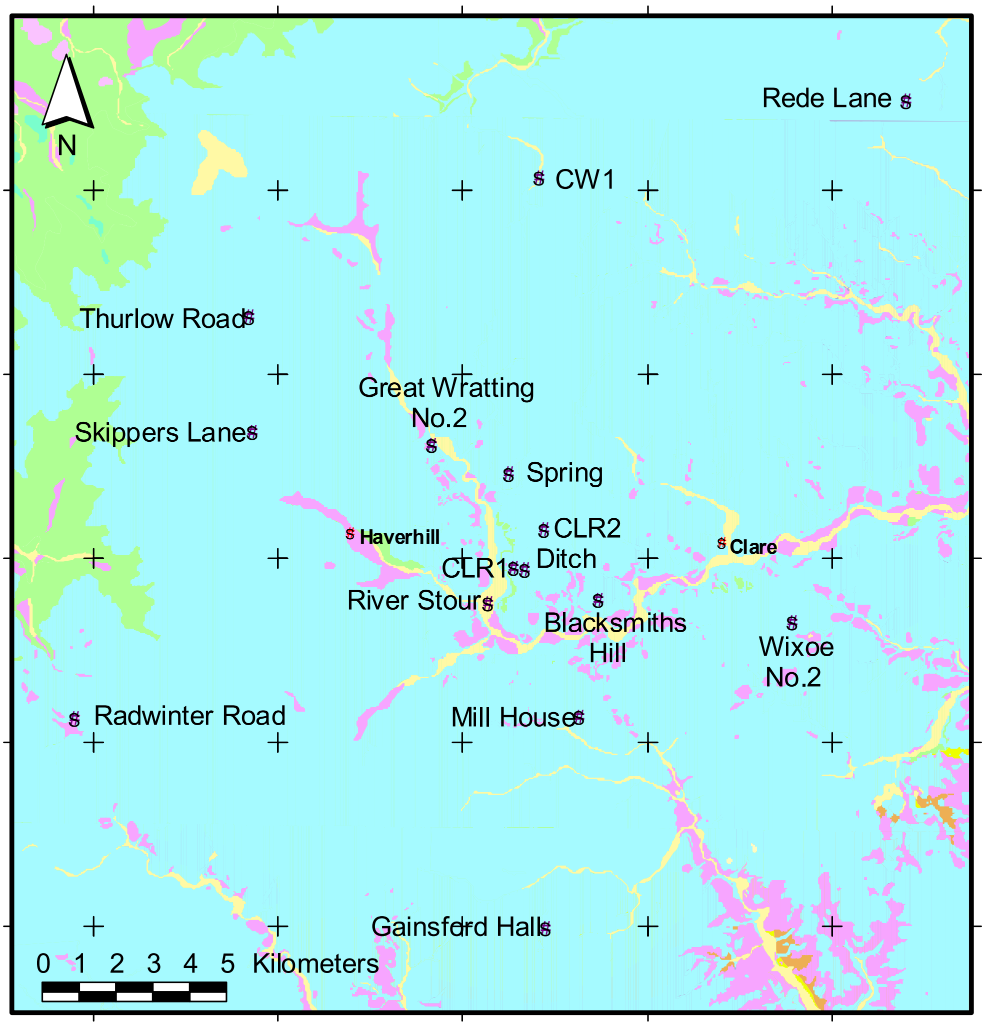


Figure 5.2 Locations of sampling points

6 Results

6.1 DRILLING RESULTS: CLR1

The till in borehole CLR1 can be subdivided into 3 layers (Table 6.1):

- an upper weathered, oxidised zone (that extends from the surface to a depth of about 5 m) which includes till, clayey sand and silt;
- an un-oxidised grey till which extends from 5 – 20 m; and
- a basal clayey sand some 1 m thick.

Table 6.1 Sub-division of till and Chalk at CLR1

Depth (mbgl)	Geology	Hydrogeological significance
0 to 5.3 m	Upper weathered, oxidised till zone, with bands of silt, sand and gravel	The intergranular permeability of the till has been measured by triaxial cell at BGS and a value of 1.8×10^{-10} m/d obtained. The overall permeability of the till may be higher where fractures are present. The sand and gravel band (which was dry when drilled) is likely to have a relatively high permeability and the silt band (which was saturated during drilling) is likely to have a modest permeability. This near surface zone is likely to become partially dry in the summer and become saturated or partially saturated during the winter/spring. Land drainage will route some infiltration to surface watercourses.
5.3 to 20.4 m	Unoxidised till zone	This zone accounts for the bulk of the till thickness. An intergranular permeability of 1.1 to 1.2×10^{-10} m/d was determined at BGS which is likely to restrict recharge. However, if fractures are present they could significantly increase recharge. No sand lenses were observed in this borehole although such lenses are known to occur within the till elsewhere.
20.4 to 21.4 m	Basal clayey sand	This thin sequence is likely to have a higher permeability than the overlying till.
21.4 to 31.0 m	Upper Chalk	The Chalk is unconfined and consists of a putty chalk in the upper part, which may limit downward water movement to the underlying more permeable zones in the Chalk.

The upper weathered, oxidised zone at this site is likely to be of higher permeability than the underlying un-oxidised till because (a) the weathered zone includes silt and clayey sands which can be assumed to be more permeable than till and (b) it is not uncommon for oxidised tills to be fractured (Hendry 1982). One consequence of the higher permeability developed in this layer is that some lateral flow within the weathered zone can be anticipated.

The underlying zone of un-oxidised till is a relatively uniform and dry chalky till. The oxidised/unoxidised boundary is defined here by the colour change from brown to grey.

The permeability of the till matrix is low (Table 6.2) and confirms that water movement through the till matrix is limited. Therefore, for significant quantities of water to be transferred from the near surface to the Chalk aquifer would require fractures to provide a pathway. The basal clayey sand layer is likely to have higher permeability but is unlikely to transmit much water at this site.

Table 6.2 Triaxial constant flow hydraulic conductivity results of glacial till samples from borehole CLR1

Geological description	Initial moisture content %	Bulk density Mg/m^3	Dry density Mg/m^3	Mean effective stress kPa	Flow rate mm^3/hr	Pressure difference kPa	Hydraulic conductivity m/s
Oxidised till	17.3	2.189	1.866	20	60	8.2	1.8×10^{-10}
Unoxidised till	14.8	2.174	1.893	74	30	9.9	1.2×10^{-10}
Unoxidised till	18.3	2.18	1.843	186	20	7.1	1.1×10^{-10}

Indeed most of the till appears to be unsaturated other than for the interval 4–11 mbgl. There was little evidence of water entry into the borehole during drilling and, following completion of the borehole; most of the gas sampling cells were dry.

6.2 DRILLING RESULTS: CW1

In borehole CW1, at Cowlinge, the weathered zone is much thinner (only 2 m) and no sand or silt is present. The underlying unoxidised till (again defined by the colour change from brown to grey) extends from 2 – 34 m (Table 6.3) and contains two thin sand seams at 8 and 28 m (Figure 6.1). The till appeared to be saturated and, during drilling, water entered the borehole overnight, even when temporary casing had been pushed to total depth.

Table 6.3 Subdivision of till (and Chalk) for CW1

Depth (mbgl)	**Geology**	**Hydrogeological significance**
0 to 2.0 m	Upper weathered, oxidised till zone	The intergranular permeability of the weathered till is likely to be similar to that measured in borehole CLR1 (1.8×10^{-10} m/d). This near-surface zone is likely to become partially dry in the summer and become saturated or partially saturated during the winter and spring. Land drains are likely to route some infiltration laterally to surface watercourses.
2.0 to 34.2 m	Unoxidised till with thin sandy seams at 8 and 28 m	This thick zone is likely to be saturated at all times and the intergranular permeability is likely to be low, similar to that measured in CLR1 (1.1 to 1.2×10^{-10} m/d) although if fractures are present they could have a significant effect on recharge. The sandy bands at 8 m and 28 m appeared saturated during drilling and limited lateral groundwater flow within these beds is possible.
34.2 to 35.8 m	Basal gravel	This thin sequence is likely to have a relatively high permeability and could transfer groundwater laterally.
35.8 to 80.0m	Upper and Middle Chalk	The Chalk is confined with a piezometric surface at 24 mbgl. The putty Chalk in the upper part can act to limit groundwater movement.

The basal gravels were relatively “clean” (containing a relatively low proportion of fine-grained material) and, therefore, likely to be of moderate or high permeability. The gravels appeared to be in hydraulic continuity with the underlying Chalk, and should be considered as part of the Chalk aquifer system. The transmissivity of the Chalk-gravel aquifer was estimated to be about 12 m^2/d from the short-term (6.5 hours) pumping test.

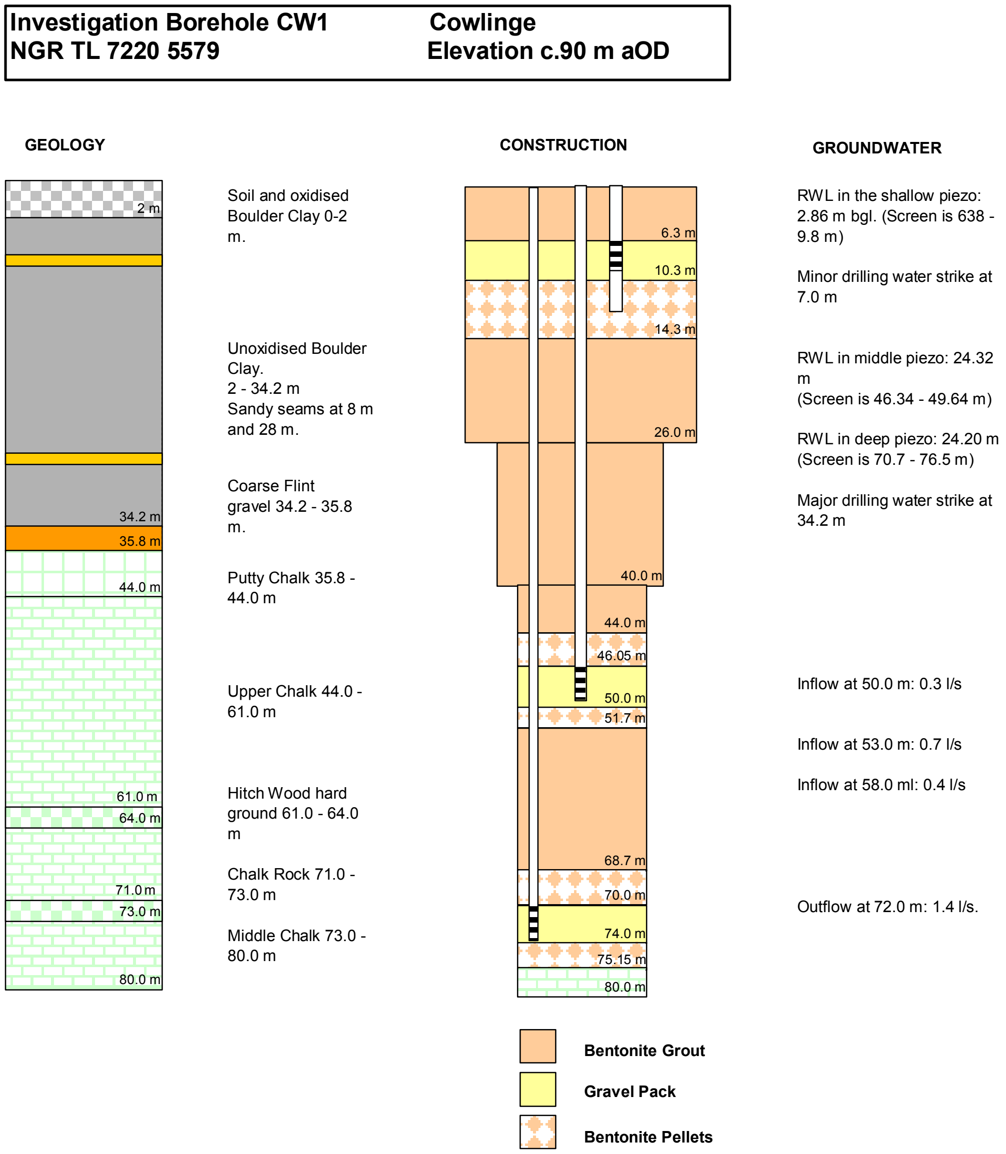


Figure 6.1 Geology and construction logs CW1

6.3 WATER CHEMISTRY RESULTS: CLR1

Major ion, stable isotope, CFC and N2/Ar results from CLR1 and other sampling locations are given in Appendix 2.

6.3.1 Till porewaters

The chemistry of the till porewaters in borehole CLR1 shows considerable variability which can be summarised as follows:

(i) porewaters in the upper 8 m are modern (tritium activity is ~15 TU), have high nitrate concentrations (up to 50 mg/l N), and bicarbonate usually accounts for less than half of the total anions (Figure 6.2). Chloride concentrations are relatively high (50–450 mg/l). Groundwater sampled from the shallow piezometer, which is screened against the silt and the oxidised till layer, is of similar chemistry to the oxidised till porewaters. The nitrate and chloride (and possibly some of the sulphate) in the oxidised till is likely to be of anthropogenic origin;

(ii) the porewaters in the unoxidised till are relatively old (^{3}H ~1 TU) suggesting pre 1960 water), and nitrate concentrations are below 0.5 mg/l N. Chloride concentrations are mostly below 50 mg/l. Calcium accounts for between 70 and 90% of the total captions. These porewaters trend along a line from bicarbonate- to sulphate-dominated, with chloride accounting for less than 10% of the total anions (Figure 6.3). This suggests that sulphate dissolution is the major control on water chemistry. Porewater concentrations of SO_4, Ca, Mg, K and NH_4 in the un-oxidised till are highest in the depth interval 8 – 15 m. Below 15 m the till porewaters are of the Ca-HCO_3 type. High sulphate concentrations in till porewaters are not unexpected: the clay often contains disseminated pyrite, the oxidation of which releases sulphate ions.

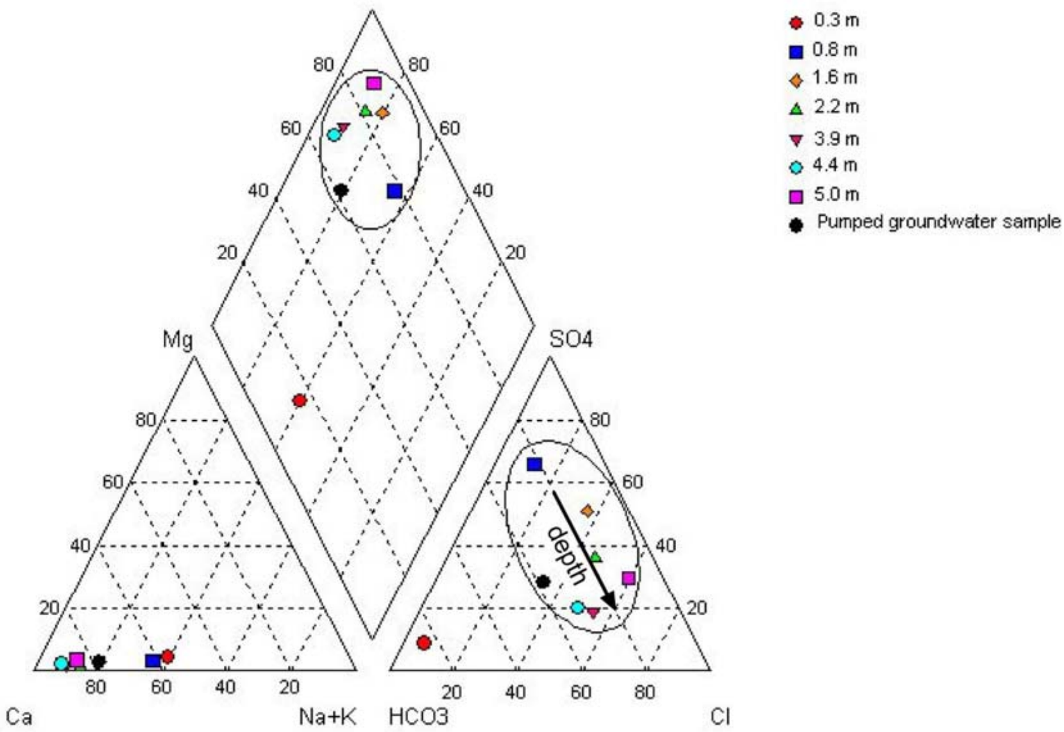


Figure 6.2 Piper diagram, CLR1 oxidised till porewaters

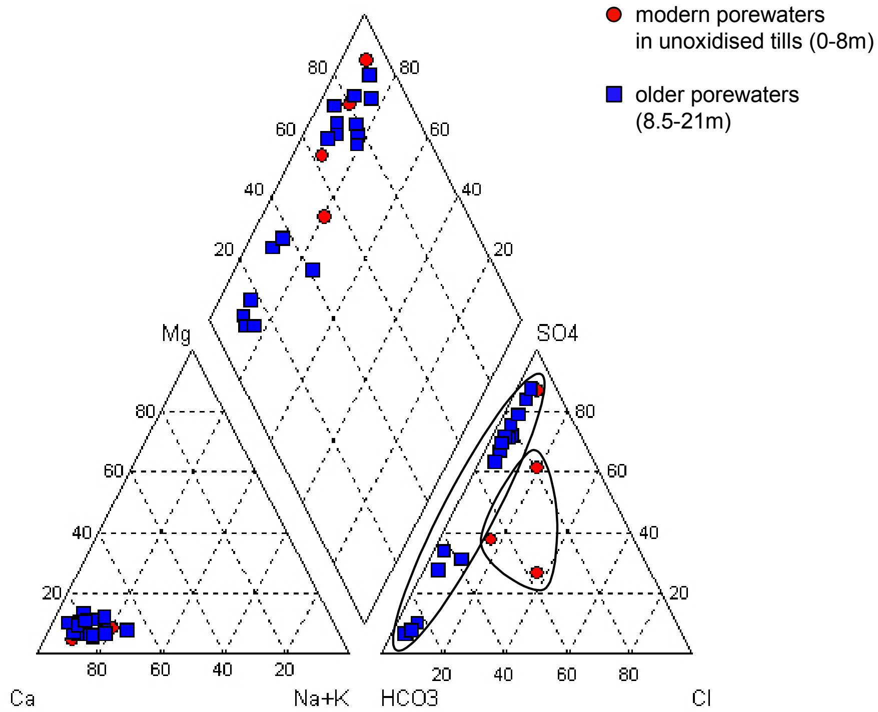


Figure 6.3 Piper diagram, CLR1 unoxidised till porewaters

6.3.2 Chalk porewaters

The underlying Chalk porewaters are mostly of the Ca-HCO_3 type but show a trend of increasing sulphate concentrations with depth (Figure 6.4 and Figure 6.5). These porewaters are relatively old, pre-1960 (^3H <1 TU) and have low nitrate concentration (<2 mg/l N).

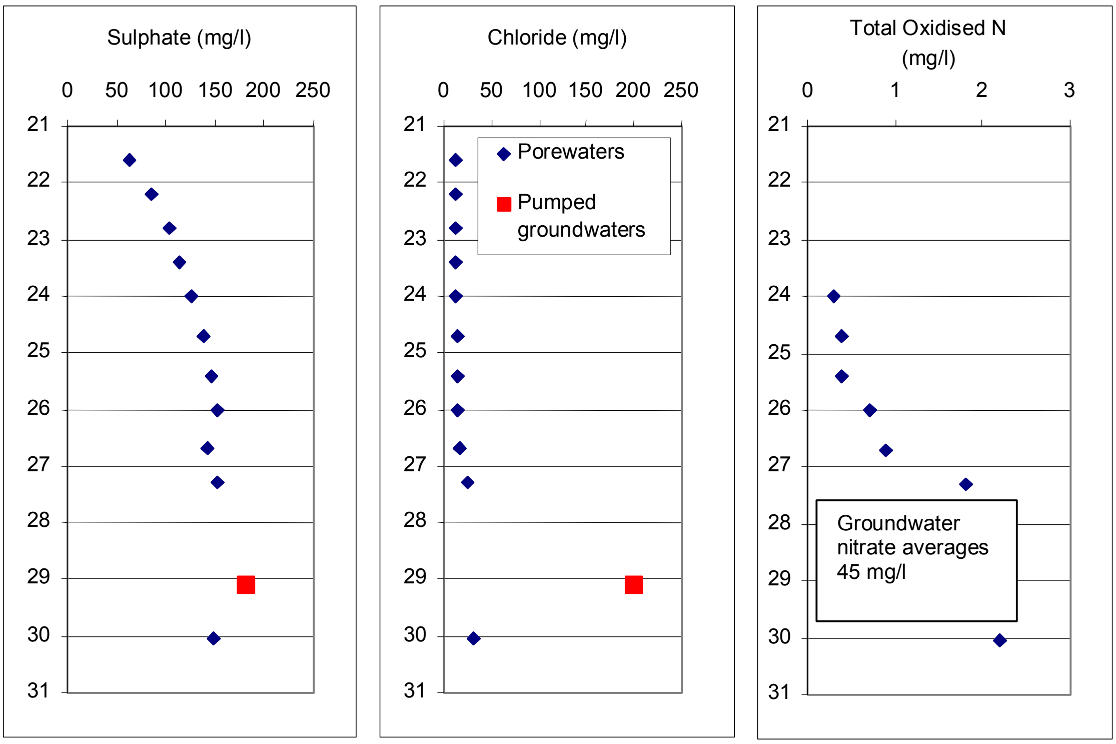


Figure 6.4 Porewater profiles and groundwater concentrations (CLR1) SO_4, NO_3, Cl^-

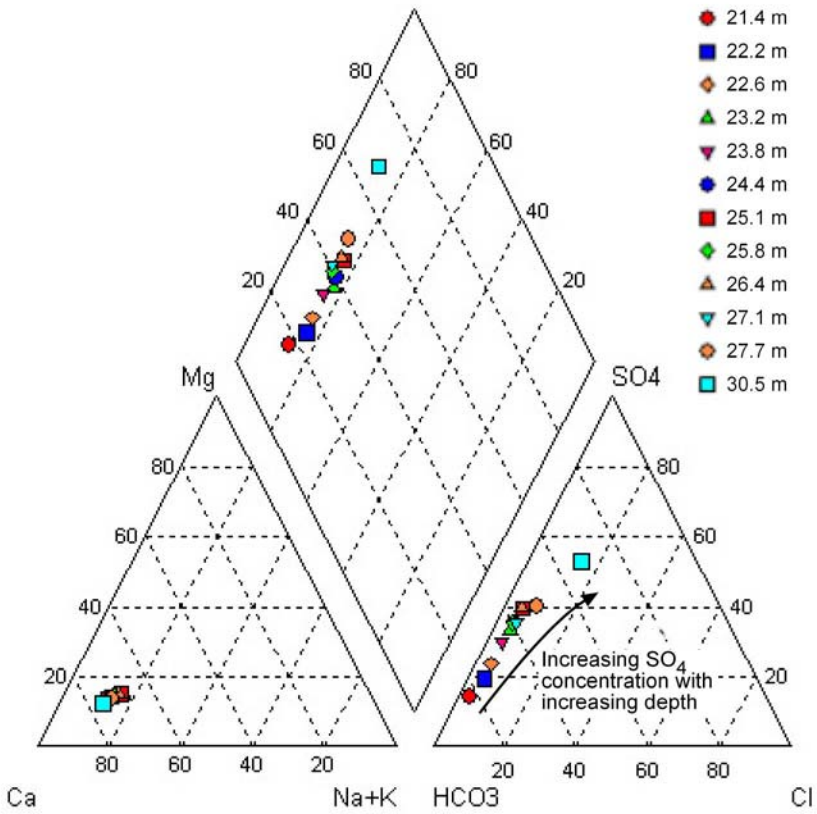


Figure 6.5 Piper diagram, CLR1 Chalk porewaters

The Borehole CLR1 penetrated the unsaturated zone and the upper part of the zone of water table fluctuation. As a consequence only the lower sequence contacts groundwater and then only on a seasonal basis during periods of high groundwater levels. The Chalk groundwaters are different to the porewaters; they are modern (^{3}H ~25 TU), have high nitrate concentrations (up to 40 mg/l N), and chloride and sulphate concentrations are also relatively high (Table 6.4). Clearly, these groundwaters have not been derived by slow leakage from the overlying till. Instead recharge to the Chalk must migrate rapidly from the ground surface and by-pass the till matrix.

Table 6.4 Summary of porewater and groundwater chemistry for borehole CLR1

Depth	Geology	Porewater chemistry	Groundwater chemistry
0 m	Weathered, oxidised till	Modern water: Cl 50-450 mg/l NO_3-N 50-100 mg/l SO_4 70-850 mg/l Tritium >15 TU	Modern water: Cl 200-300 mg/l NO_3-N 50-60 mg/l SO_4 200-300 mg/l Tritium ~26 TU
5.3 m	Unoxidised till with basal clayey sand	Modern water penetrates upper part of unoxidised zone	
8.0 m		Old water: Cl 10-50 mg/l NO_3-N <1 mg/l SO_4 20-3000 mg/l Tritium ~1 TU	
21.4 m 31.0 m	Upper Chalk	Pre-1960 water: Cl 10-30 mg/l NO_3-N <2 mg/l SO_4 55-155 mg/l Tritium ~1 TU	Modern water: Cl 200 mg/l NO_3-N 40-50 mg/l SO_4 183 mg/l Tritium ~23 TU

There is an increase in porewater sulphate with depth in the Chalk, which, may result from diffusion exchange between the porewaters and the groundwaters at times of high water table. Sulphate concentrations may increase with depth because the deeper porewaters have had longer contact time with the groundwaters. However, if this were the case, a similar trend in porewater chloride and nitrate concentrations would be expected, as these too are present in groundwater at higher concentration. Porewater chloride and nitrate concentrations do increase with depth, but groundwater concentrations of these solutes are still much higher than the porewater concentrations at an equivalent depth (Figure 6.4). The smaller difference in sulphate concentrations between porewaters and groundwater compared to nitrate and chloride could be because groundwater sulphate concentrations have been elevated relative to the porewater concentrations for a longer time than either NO_3 or Cl, and have, therefore, had greater opportunity to reach equilibrium. However, there is no direct evidence to support this hypothesis.

6.4 WATER CHEMISTRY RESULTS: CW1

The porewater data from the borehole at Cowlinge are more sparse than for CLR1 as the water analyses for the till porewaters have yet to be completed. However, on the available evidence the Chalk porewaters (at Cowlinge) are very different from those at CLR1.

The Chalk porewaters are relatively old (^{3}H ~1 TU), have low nitrate concentrations (<0.2 mg/l) and high sulphate concentrations (350–1200 mg/l). These Chalk porewaters resemble the porewaters in the unoxidised till from borehole CLR1 (Table 6.5, Figure 6.3 and Figure 6.6). The pumped Chalk groundwaters are similar to the Chalk porewaters (Table 6.5 and Figure 6.6) and presumably are in equilibrium. The relatively high ratios of Mg/Ca and Sr/Ca are characteristic of incongruent dissolution, which is indicative of longer residence times. These residence time indicators provide only a qualitative estimate, but residence times are likely to be of the order of 10^2 – 10^3 years. This is consistent with a slow 'piston flow' recharge mechanism through the till.

Table 6.5 Summary of porewater and groundwater chemistry for CW1

Depth	Geology	Porewater chemistry	Groundwater chemistry
0 m	Till upper weathered zone, oxidised till	*Awaiting porewater results*	
34.2 m	Unoxidised till zone with sandy seams at 8 and 28 m	*Awaiting porewater results*	Mixed-age water: Cl 100 mg/l NO_3-N < detection CFC 20-30% modern
35.8 m	Basal gravel	Old water: Cl 50-60 mg/l NO_3-N < detection	Old water: Cl 100 mg/l NO_3-N < detection
To 80.0 m	Upper and Middle Chalk	Old water: Cl 40-70 mg/l NO_3-N < detection Tritium ~1 TU	Old water: Cl 50 mg/l NO_3-N < detection Tritium ~1 TU CFC <20% modern

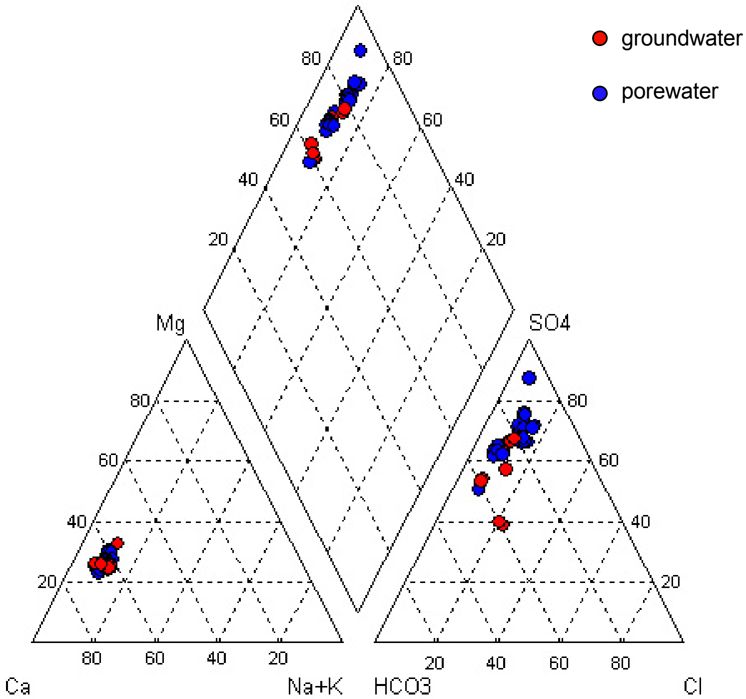


Figure 6.6 Piper diagram, CW1 Chalk porewaters and groundwaters

6.5 REGIONAL WATER CHEMISTRY SURVEY

The results of the regional water chemistry survey are presented in Figure 6.7. The groundwaters show considerable variability both in water type and in apparent residence time. However, a pattern can be discerned (Figure 6.8 and Figure 6.9) which suggests that two groundwaters of different origins are present. The first type includes the Chalk groundwaters from the interfluve at distances greater than 1 km from the edge of the till sheet. These have low nitrate (<0.2 mg/l N) and appear to be relatively old waters (high Sr/Ca ratio, higher Mg/Ca ratio, and proportion of modern water <15% as indicated by CFC measurements). It is not possible to date the old groundwater component accurately, but the high Sr/Ca ratio and relatively high Mg/Ca ratio (>0.25) indicates that the bulk of the water is probably of the order of $10^2 – 10^3$ years in age. The second water type occurs within the main river valleys and beneath the edge of the till sheet. These groundwaters, which have high nitrate concentrations, are of modern origin (proportion of modern water >70% according to CFCs) and are largely derived from rainfall of the last few decades.

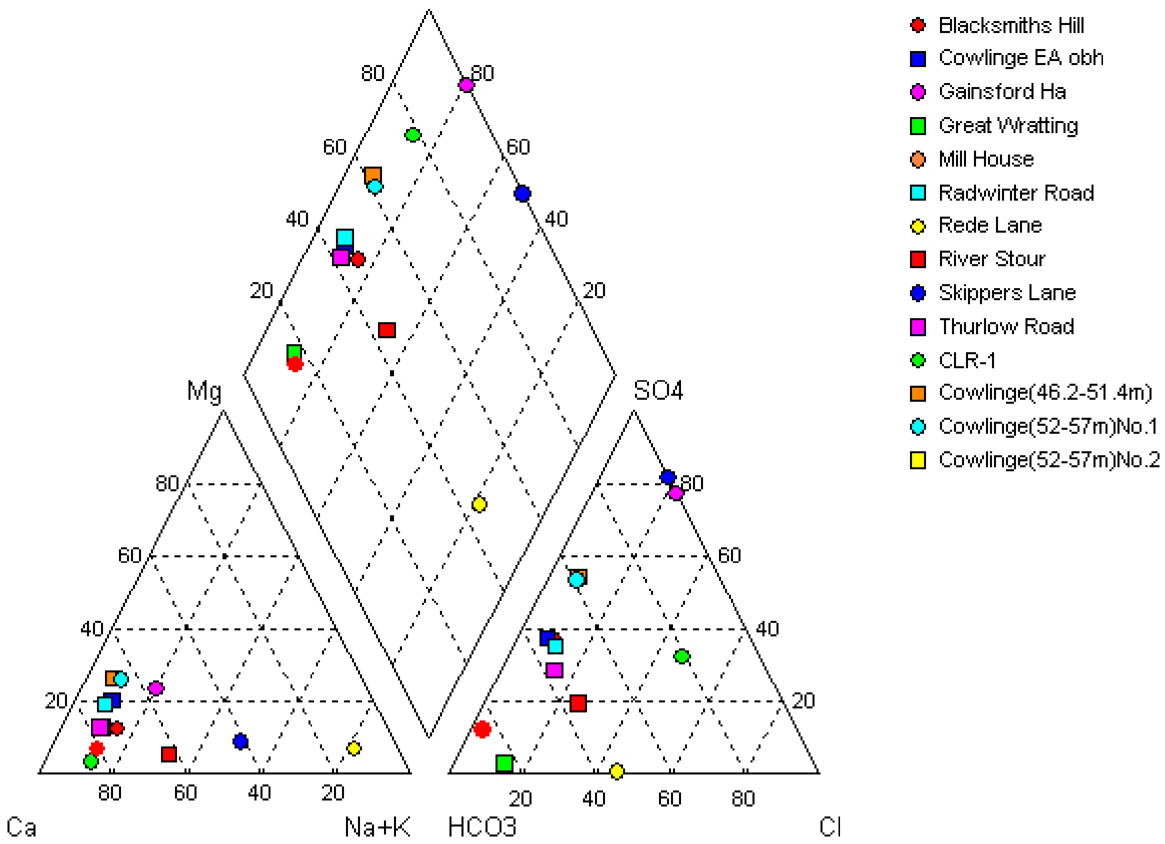


Figure 6.7 Piper diagram, regional water quality survey

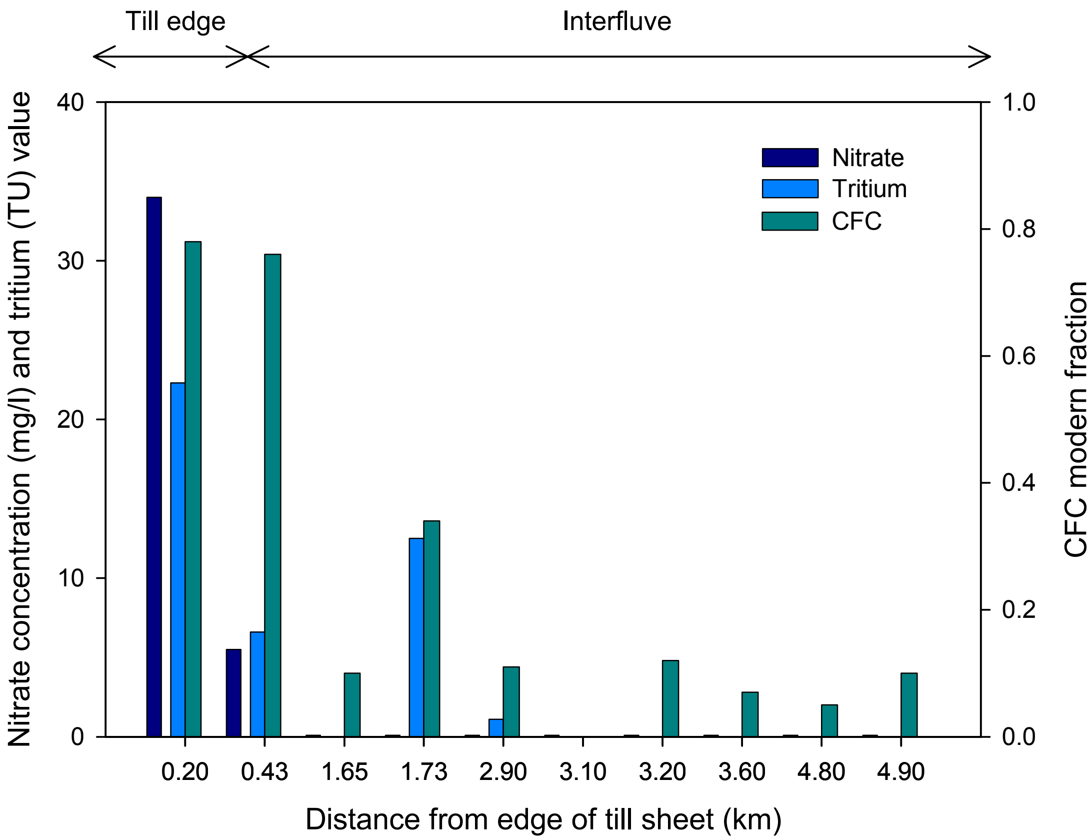


Figure 6.8 Variation in Chalk groundwater NO_3, ^3H and CFC concentrations with distance from edge of till sheet

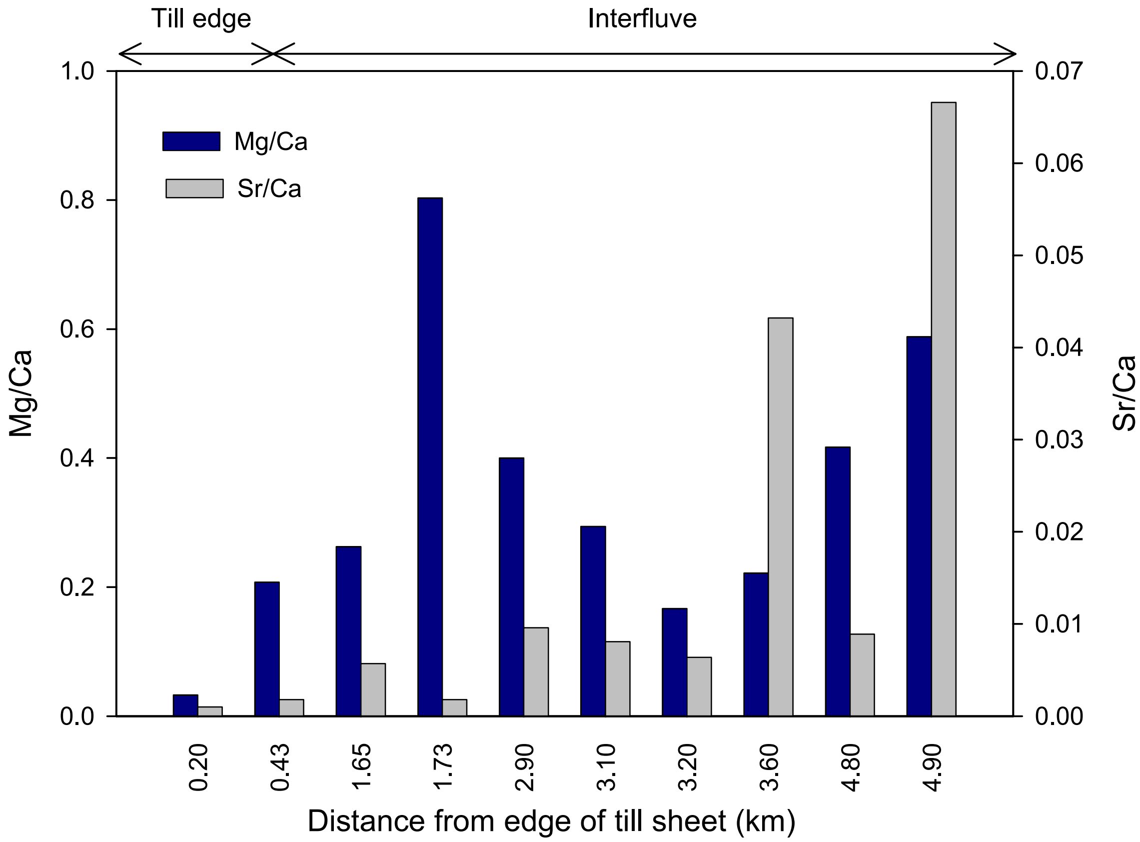


Figure 6.9 Variation in Chalk groundwater Mg/Ca and Sr/Ca ratios with distance from edge of till sheet

6.6 GROUNDWATER LEVEL MONITORING

Groundwater level monitoring at the CLR1 site shows a similar water level response to rainfall for both the Chalk and shallow till piezometers (Figure 6.10 and Figure 6.11). The CLR1 site is in a valley side – till edge setting.

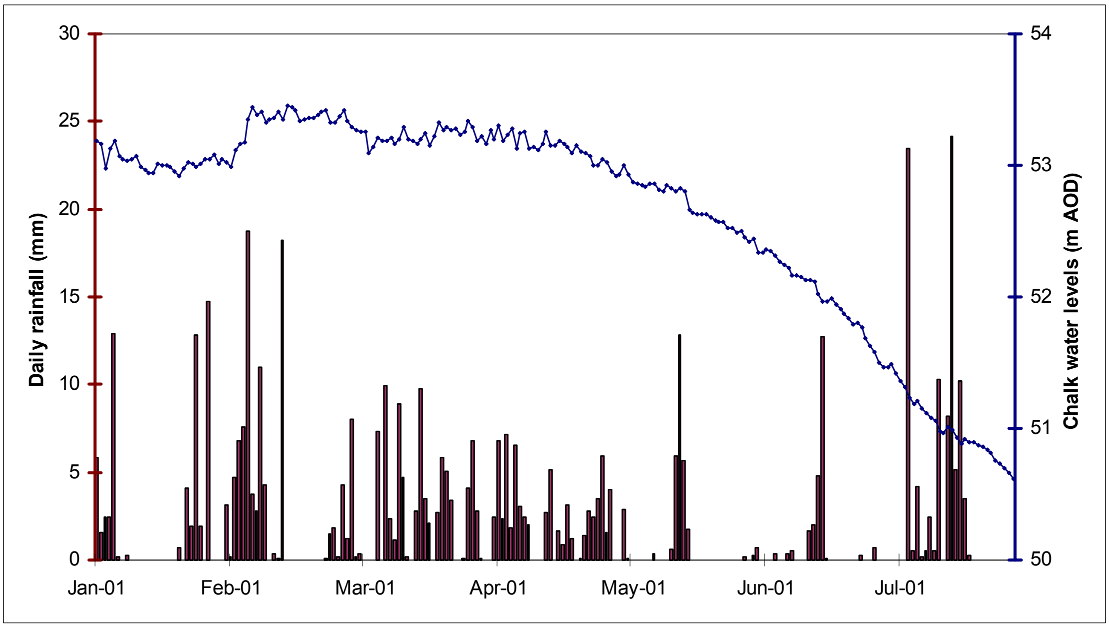


Figure 6.10 Comparison between groundwater levels in Chalk and rainfall (CLR1)

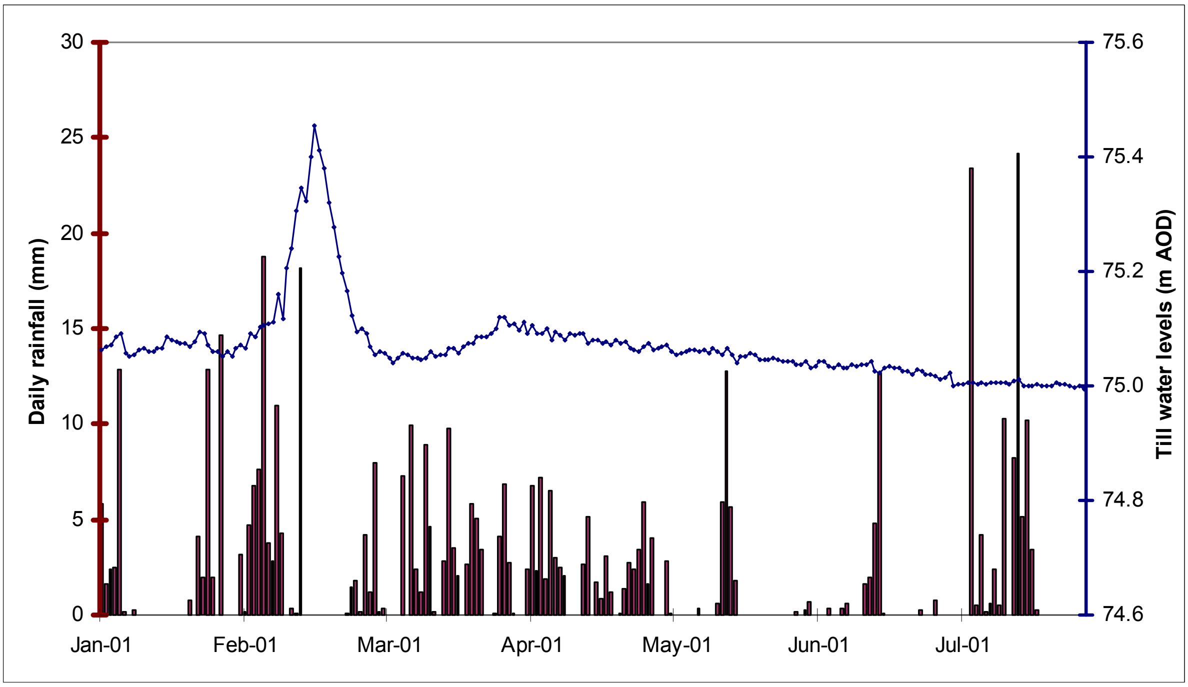


Figure 6.11 Comparison between groundwater levels in till and rainfall (CLR1)

Chalk hydrographs obtained from EA monitoring data show seasonal fluctuations of 2-4 m for boreholes located in valley or valley-side settings, but only about 0.3 m for boreholes located on the interfluves (Figure 3.5).

7 Discussion

The water chemistry data from both the cored boreholes and the regional monitoring survey suggest that there are two principal Chalk groundwater types:

- Type 1 is usually a Ca-HCO_3 water which has high nitrate concentrations and appears to be a relatively 'young', with the proportion of modern water indicated by CFCs exceeding 70%;
- Type 2 waters show considerable variability (from Ca-HCO_3 to Ca-SO_4 type), normally with high sulphate but only low nitrate concentrations (mostly below detection) and only a small proportion of modern water, usually less than 15% as indicated by CFCs.

The Type 1 groundwaters occur both in the river valleys, where the Chalk is either exposed or overlain by permeable sands and gravels, and in the valley sides where the Chalk is frequently overlain by till. The till in the valley sides represents the margins of the clay sheet although it can still be 20 m thick. In the valleys/valley sides the transmissivity of the Chalk is normally in the range 250 – 2000 m^2/d and these areas represent both the major recharge and discharge zones for the aquifer. Where the Chalk is overlain by till, the Type 1 groundwaters are usually unconfined and well hydrographs show a 'normal' unconfined response, with a steep rise in groundwater levels following excess rainfall during late autumn/early winter. Peak groundwater levels occur in early spring and the seasonal fluctuation is typically 2–4 m.

The Type 2 groundwaters occur beneath the interfluves where thick till (typically in excess of 20 m thick) usually confines the Chalk aquifer. Pumping test data is rather sparse in these areas but the limited information available suggests that the Chalk transmissivity is usually less than 50 m^2/d and can be as low as 2 m^2/d. Chalk hydrographs in areas where Type 2 groundwaters are present show a subdued response; annual fluctuations are typically 0.2-0.3 m and there is no obvious response to rainfall events. The Type 2 groundwaters are of similar composition to the porewaters in the unoxidised till (as observed in borehole CLR1) and this suggests that recharge to the Chalk beneath the interfluves is largely derived from infiltration that has migrated though the till and had sufficient time for diffusional exchange with the till porewaters.

It is postulated here that there are also two distinct groundwater flow systems in the Chalk aquifer and at least three recharge mechanisms. One groundwater system is represented by the relatively old Type 2 groundwaters present beneath the interfluves. Here, the aquifer is confined (or semi-confined) and recharge occurs mainly as slow leakage through the till. Discharge from this aquifer system is limited by the low transmissivity of the Chalk and occurs as lateral flow into the more transmissive Chalk of the river valleys.

The other groundwater system is represented by the Type 1 groundwaters, which occur in the valley and valley margins. Here recharge occurs as direct rainfall infiltration on Chalk outcrop with an additional component of runoff/shallow groundwater flow from the adjacent till-covered areas. Groundwater in the Chalk aquifer within the valley discharges as baseflow to streams and as abstraction by boreholes. The Type 1 groundwaters are modern and do not appear to have been modified by mixing with the porewaters in the till, even where thick till directly overlies the Chalk as at CLR1. This suggests that recharge to the Chalk aquifer, where overlain by till, must bypass the clay matrix. Two recharge mechanisms are suggested:

(i) enhanced recharge occurs at the edge of the till sheet (due to runoff from, and shallow groundwater within, the weathered till) and this produces a water table mound allowing groundwater to flow back under the clay cover (Figure 7.1);

(ii) rapid infiltration to the Chalk occurs at the margins of the till sheet because fracturing in the till is better developed (Figure 7.2). Rates of water movement through the till are sufficiently high that there is not enough time for significant diffusional exchange to occur between the infiltration and the till porewaters.

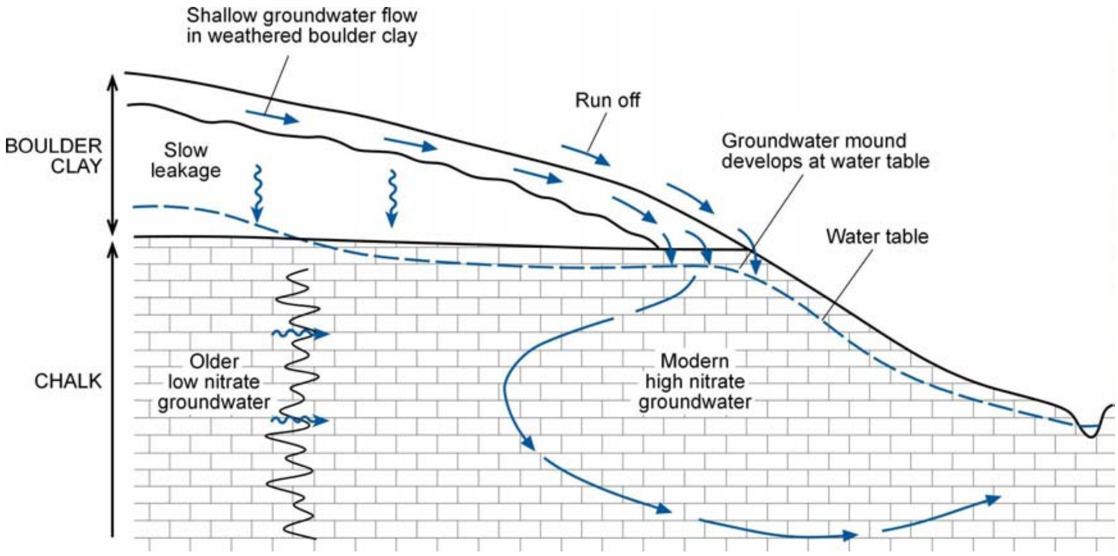


Figure 7.1 Possible recharge scenarios: groundwater mound develops at edge of till sheet

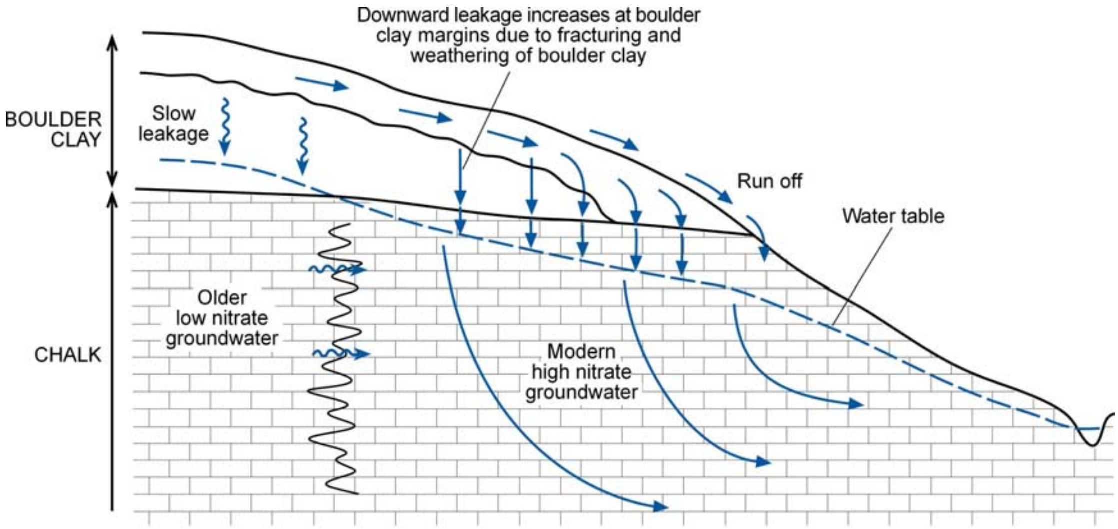


Figure 7.2 Possible recharge scenarios: enhanced recharge to the Chalk occurs where fracturing and weathering develops at the edge of the till sheet

This conceptualisation of the Chalk-till system is broadly similar to that presented earlier (Lloyd et al., 1981, Lloyd and Hiscock 1990). However, for this report it is important to consider what can be inferred about recharge rates from the data collected under this project. For the Type 2 groundwaters, recharge must be slow (because there is time for diffusional exchange between infiltration and the porewaters in the overlying till) and, therefore, it can be assumed to be relatively constant with time. Thus, for the Chalk hydrographs beneath the interfluves to show a temporal fluctuation this must be in response to a charge in the rate of outflow from the confined aquifer rather than a change in recharge rate.

The recharge rate beneath the interfluves cannot be directly measured, however an estimate can be made by considering the depth of penetration of modern water in the porewaters of the till. These data are not available for the Cowlinge site (samples currently with UEA) but are available for the CLR1 site. The porewater profiles obtained from the core at CLR1 are presented in Figure 7.3, which show that tritium has penetrated to 8 m but not yet to 12 m. The other porewater data (chloride, nitrate) suggest that modern (post 1950/60s) water has not penetrated beyond 8 m depth. The moisture content of the till was determined as about 0.2 which suggests that rates of infiltration could be as high as 30 mm/a assuming that downward leakage "starts" at about 1 m depth (e.g. there is rapid flow through the soil to 1 m depth). However, this is likely to be an overestimate because:

(i) the upper 3 – 4 m of the profile includes silt, clayey sand and gravel where vertical permeabilities, and thus infiltration rates, can be expected to be higher; and

(ii) the permeability of the oxidised and weathered till is likely to be higher than that of the unoxidised clay (Hendry 1982).

Indeed it may be more realistic to consider that recharge from the ground surface would reach the base of the sandy gravel at 3.5 m rapidly (e.g. within 3 years) and this would suggest that the infiltration rate is, therefore, closer to 20 mm/a. Again this is probably a maximum rate as permeabilities in the deeper unoxidised till are likely to be lower.

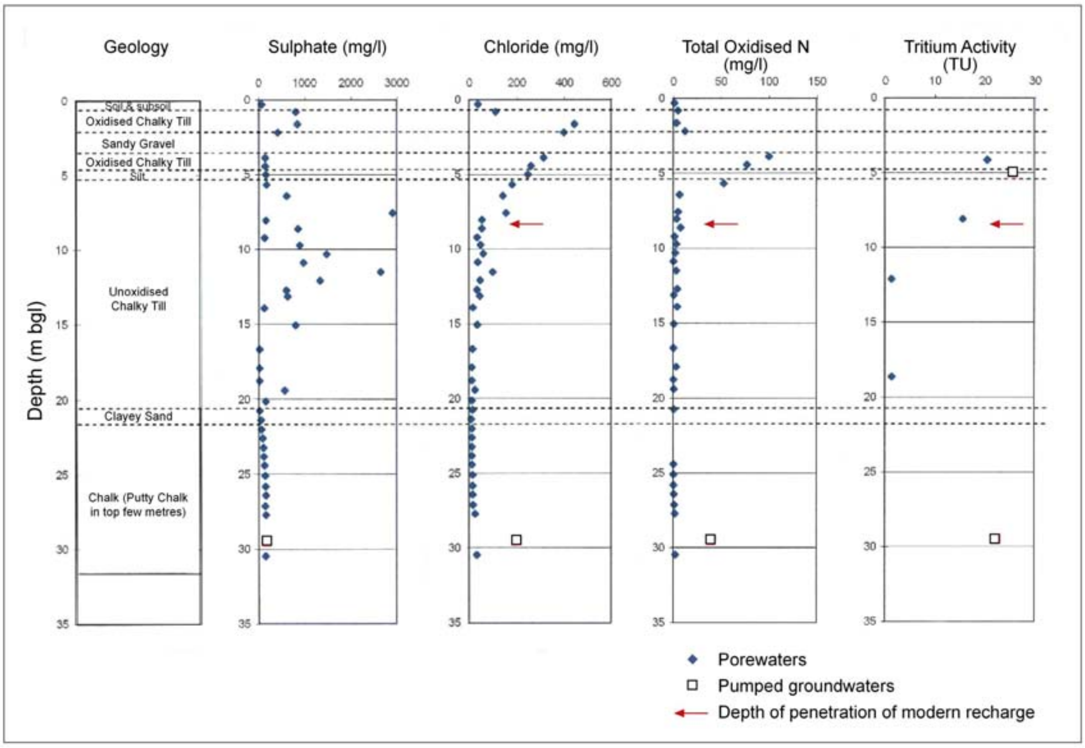


Figure 7.3 Porewater profiles CLR1 H3, C1, NO3, SO4

The permeability of the till matrix was determined in the laboratory using core obtained from borehole CLR1 (Table 6.2). An infiltration rate of ~3 mm/a was estimated assuming a maximum unit vertical hydraulic gradient and an intergranular permeability of 1×10^{-10} m/s. Thus, for the slow component of recharge, the infiltration rate through the till is likely to be in the range 2–20 mm/a. Infiltration rates at the lower end of this range can be accounted for by matrix flow while at rates above 5 mm/a fracture flow would appear to dominate.

To test whether this range (2–20 mm/a) in infiltration rates through till on the interfluve is sensible, a simple spreadsheet model was developed which simulates the shape of the Chalk potentiometric surface along a flowpath from near the groundwater divide to a valley, based on Chalk transmissivities and recharge rates. Details of this simple spreadsheet model and the parameters used are given in Appendix 1. The results are presented in Figure 7.4 and suggest recharge is likely to be in the range 2 – 20 mm/a (and possibly closer to 5 mm/a). Thus, the rates estimated from the porewater chemistry in borehole CLR1 appear realistic.

The hydrologically effective rainfall (rainfall - evapotranspiration) has been estimated at 150 mm/a and, if less than 20 mm/a of this percolates through the till to the Chalk, a very considerable volume of water must flow laterally as (i) runoff, (ii) land-drainage and (iii) shallow groundwater in the upper weathered, and more permeable, zone of the till. The land-drain and ditch infrastructure is likely to account for the majority of this lateral flow.

This lateral flow from the till sheet will recharge the Chalk aquifer either where it discharges directly onto the exposed Chalk (or the overlying sands and gravels at the base of the till) or where the till becomes thinner and more permeable (possibly more fractured). A best fit for the Chalk potentiometric surface along a groundwater flow path from the groundwater divide to the river using the simple spreadsheet model (Appendix 1) was obtained when recharge rates of 5 mm/a beneath the interfluves and 500 mm/a in the valley were applied. The high infiltration rate of 500 mm/a may be consistent with the runoff from the till sheet recharging the exposed chalk in the valleys. As mentioned earlier, enhancement of recharge along the northwest edge of the till sheet (Figure 3.4) is indicated by the observed steepening of the water table contours where the Chalk transmissivity also increases. Some of the streams flowing off the till sheet continue to flow across the exposed Chalk to the River Stour: an important issue that, therefore, needs to be considered is how much of the runoff from the till sheet infiltrates the Chalk and how much flows directly into the river. These recharge waters, as observed in the shallow piezometer at CLR1 and in surface watercourses flowing across the till, are characterised by high concentrations of nitrate and, to a lesser extent, chloride and sulphate.

A conceptual model of the Chalk-till groundwater system is presented in Figure 7.5 and shows two distinct flow systems, one beneath the interfluves characterised by slow water movement, older groundwaters and limited recharge and discharge. The other flow system occurs beneath the valley and valley sides, and is characterised by high transmissivity with rapid flow through fractures of modern, high nitrate groundwater. Recharge to the valley groundwater system is considerable and occurs as both direct rainfall on exposed Chalk outcrop and as lateral flow from adjacent till-covered areas. Thus the conceptual model proposes that higher rates of infiltration occur at the till edge (where high-nitrate runoff flows off the till sheet), and that lower rates occur through the till sheet beneath the interfluves than had previously been assumed. This has implications for water quality in abstraction boreholes. If the model does realistically represent field conditions then it can be anticipated that abstraction boreholes located close to the till edge will pump a greater proportion of recent water than had previously been thought. This in turn is likely to increase the nitrate concentration of the pumped water. However, the model is not sensitive to recharge in the valley but is sensitive to recharge beneath the interfluves.

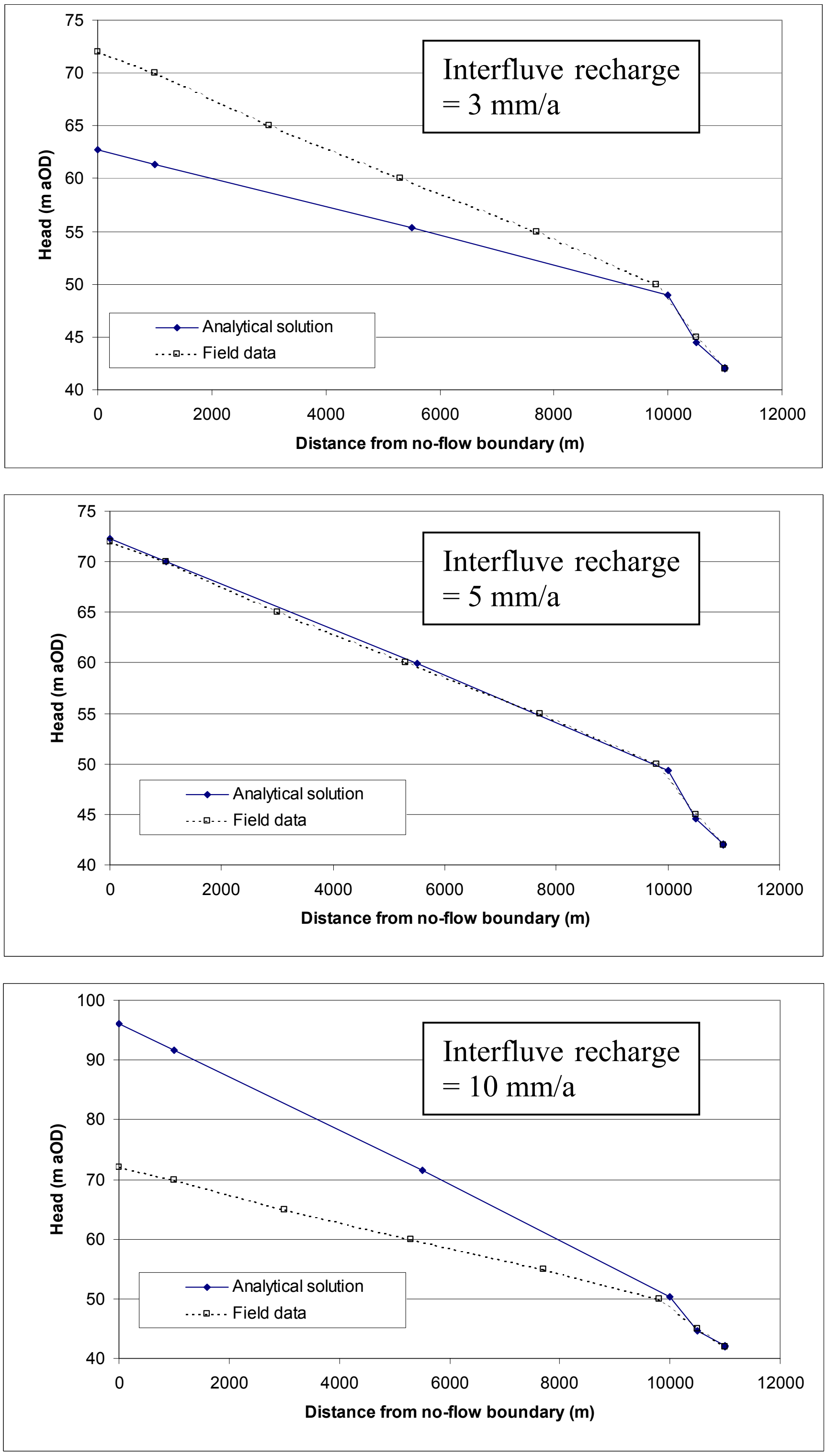


Figure 7.4 Simple spreadsheet model results for various values of interfluve recharge

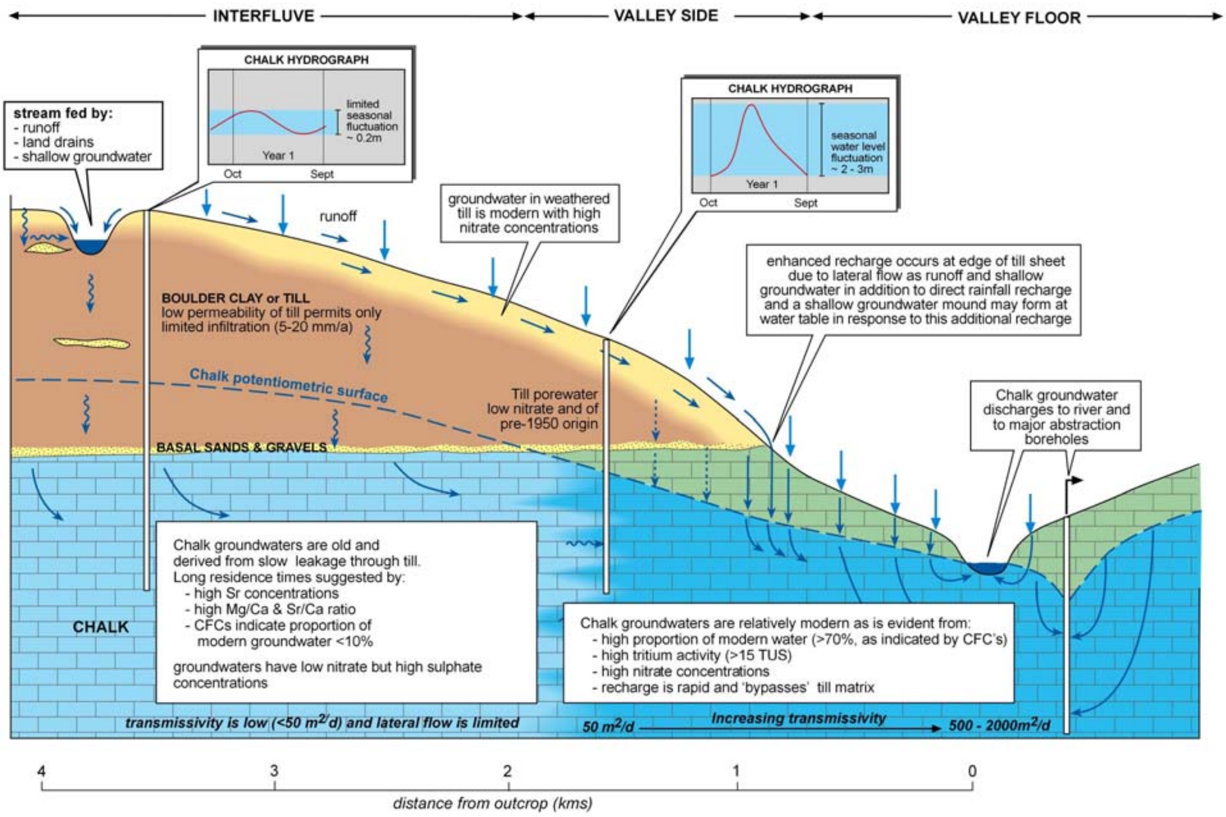


Figure 7.5 Conceptual model

Major outflow from the aquifer occurs as baseflow to rivers and as abstraction by boreholes. Although the conceptual model fits most of the water quality and hydraulic data, the results of groundwater dating using CFCs appear somewhat anomalous. While the CFC data fit well with the conceptual model in as much as a significantly higher proportion of modern water occurs in the valley/valley-sides (proportion of modern water >70%) than beneath the interfluves (proportion of modern water ≤15%), the proportion of modern water in groundwater beneath the interfluves does appear high. No attempt was made to estimate recharge rates using CFC data because this requires a knowledge of how much mixing/diffusion occurs between Chalk porewater and groundwater and the depth interval within the Chalk over which mixing occurs, neither of which are known in this case.

Tritium was also used to date groundwaters and porewaters. This showed a similar pattern to the CFC results with Chalk groundwaters beneath interfluves having older residence times than beneath valley sides. Tritium activity in rainfall of SE England currently averages 7-10 TU. This can be compared with a tritium activity of 1 TU in the groundwater beneath interfluves (Cowlinge site), which gives a proportion of modern water similar to that indicated by CFCs (15%).

However, in borehole CLR1 (close to the edge of the till sheet) tritium activity in both the shallow till groundwaters and in the Chalk groundwaters (Table 6.1) is significantly higher than in the average UK rainfall. One possibility is that tritium activity in modern rainfall in the study area is, or has been in the past decade or so, closer to 25 TU (possibly indicating the influence of nuclear power plant effluent). If so, then the proportion of modern water in the Chalk groundwaters beneath the interfluve would be lower than 15% and closer to 4%. This would 'fit' better with the conceptual model which suggests that most of the recharge to the Chalk beneath the interfluves occurs as slow 'piston flow'. The apparent tritium anomaly in modern rainfall in the study area is being investigated further.

8 Summary

1. It is clear from the chemistry of the groundwater and porewaters in the Chalk-till aquifer system that the till has a major influence on recharge rates to the Chalk aquifer.

   Over large areas of the till sheet the Chalk groundwaters are relatively old (proportion of modern water <15%), have low or undetectable nitrate concentrations and have clearly undergone mixing with the till waters. The implication is that recharge through the till is low; the simple spreadsheet model which attempts to simulate the shape of the Chalk water level beneath the till cover suggests a recharge rate less than 20 mm/a and possibly as low as 5 mm/a. This zone of limited recharge (to the Chalk) appears to coincide with the greater part of the till sheet away from the valley sides. The main component of the underlying Chalk groundwaters appears to have been derived from recharge perhaps hundreds, possibly thousands, of years previously. Nitrate is absent from the groundwaters.

   Chalk groundwaters beneath the edge of the till sheet appear to be very different. Here the Chalk is unconfined, recharge is higher (CFCs suggests >70% modern groundwater) and Chalk groundwaters are of the Ca-HCO_3 type with high nitrate concentrations. The till edge is characterised by steeper slopes, the till reducing in thickness (usually < 20 m) and where the transmissivity of the underlying Chalk aquifer probably exceeds 50 m^2/d.

2. One consequence of the limited recharge (to the Chalk aquifer) through the till sheet is that a considerable quantity of rainfall that reaches the land surface must be transferred laterally (as runoff via land drainage or as shallow groundwater flow in the upper weathered till). The implication of this is that enhanced recharge is likely to occur at or close to the edge of the till sheet. Chalk groundwaters beneath the edge of the till are dominated by modern water and have high nitrate concentrations, which suggest that recharge is considerable and rapid. Two recharge mechanisms are possible:

   (i) Infiltration occurs through fractures in the till, which bypass the clay matrix.

   (ii) Runoff from the till sheet infiltrates from the subsurface where it encounters more permeable strata (basal sands of the till, and the Chalk), and produces a shallow water table mound which permits groundwater to flow back under the till sheet.

   To the northwest of the till sheet some streams flowing off the till cover 'disappear' soon after flowing onto exposed Chalk, while others continue to flow across the Chalk surface and these may act as linear zones of recharge. Along the Stour Valley, streams flowing off the till sheet can flow directly into the river, and an important issue is how much of the runoff infiltrates the Chalk and how much flows directly into the river.

3. The conceptual model developed here broadly agrees with earlier conceptualisations (Lloyd et al. 1981, Jackson and Rushton 1987, Lloyd and Hiscock 1990). However, simple 1-D modelling suggests that recharge estimates through the thick till beneath the interfluves could be as little as 5 mm/a which is significantly lower than has been estimated earlier (Soley and Heathcote 1998, Klinck et al. 1996). Conversely recharge at the edge of the till sheet could be considerable. The 1-D model suggests that recharge of about 500 mm/a in the Stour and tributary valleys would be possible and is compatible with realistic aquifer transmissivities. Such recharge rates, although large are consistent with likely runoff quantities from the till sheet based on HER estimates.

However, the model is not particularly sensitive to recharge in the valley and therefore this recharge estimate should be treated with caution.

4. The conceptual model has implications for delineating borehole catchment areas as follows:

   (i) the boundary of catchment areas should be the boundary between the old and modern Chalk groundwaters (rather than at the groundwater divide) as the contribution from the Chalk groundwater beneath the interfluve is very limited;

   (ii) the shape of the borehole catchment may need to be modified to take into account the anticipated higher recharge rates at the edge of the till sheet;

   (iii) the reduced contribution of groundwater from the Chalk beneath the interfluves to the abstraction boreholes will mean that modelled flow paths to the borehole will be shorter and as a consequence, nitrate concentrations are likely to be higher.

9 Conclusions

1. A conceptual model of the Chalk-till system is presented which indicates that the till has a major impact on recharge. The till restricts recharge to the Chalk aquifer beneath the interfluves (probably reducing this to <20 mm/a and possibly as low as 5 mm/a) but increasing recharge at the edge of the till sheet as a result of runoff from the clay cover. There is a need to improve the understanding of the recharge mechanism at the edge of the till sheet and in particular to quantify the runoff component of recharge to the Chalk aquifer.
2. The Chalk groundwaters beneath the interfluve have a large component of older water (probably 10^2-10^3 years old) and are of low nitrate concentration. The bulk of recharge beneath the interfluves occurs as slow 'piston flow', allowing time for diffusional exchange to occur between infiltration and till porewaters. The Chalk groundwaters beneath the valley and till edge are very different; they have a large component of modern water and generally high nitrate concentrations.
3. The groundwaters beneath the interfluve do have a small modern component; CFC concentrations in the these groundwaters suggest that this could be as much as 15%, which appears to be rather high in terms of the simple spreadsheet model results. Further sampling of such waters to ascertain residence times using both CFCs and tritium (perhaps in conjunction with helium-3) would be useful.
4. The Chalk-till groundwater system and the distribution of recharge to the Chalk aquifer have implications for delineating the catchment areas of abstraction boreholes. This in turn will control the proportion of modern water pumped and its nitrate concentrations. One consequence, if the conceptual model is correct, is that an abstraction borehole close to the till edge would pump a greater proportion of modern recharge than previously believed, probably with higher nitrate concentrations.

Appendix 1

This model utilizes the potentiometric surface of the Chalk based on EA data for March 1999. A flowpath section from the groundwater divide to the River Stour has been chosen in the vicinity of our study site. The hydraulic gradient along this section is a function of both the transmissivity of the Chalk and the recharge. Using Chalk average transmissivity values from Allen et al. (1997) enables estimates of the recharge to be made. A number of transmissivities have been used with high values for outcrop Chalk adjacent to the river and low values beneath the interfluve. This spreadsheet model allows the recharge and transmissivity to be varied to simulate the section hydraulic gradient. The table of the model and the resulting graph is attached.

SPREADSHEET MODEL

Valley transmisivity in order
45
160
200
250
290
300
350
366
380
403
420
440
450
593
750
860
880
950
1116
1253
1333
1624
1785
1800
2273
3000
3150

Length m	Location	Recharge mm/a	Transmissivity m2/d	Fixed Head m aOD
0	Interfluve	5	3	
1000	Interfluve	5	3	
4500	Interfluve	5	20	
4500	Interfluve	5	45	
500	Valley side in till	1000	85	
490	Unconfined chalk	1500	500	
10	River	1500	500	42

x co-ord at LH bnd 0

Flow at LH Bnd 0

Start m	End m	Length m	Flow m3/d	Cum. Flow m3/d	Coefficients A	Coefficients B
0	0	0	0	0	0	-72.2857
0	1000	1000	0.013699	0.013699	0.004566	-72.2857
1000	5500	4500	0.061644	0.075342	0.003767	-70.0026
5500	10000	4500	0.061644	0.136986	0.003044	-59.9855
10000	10500	500	1.369863	1.506849	0.017728	-49.3691
10500	10990	490	2.013699	3.520548	0.007041	-44.5342
10990	11000	10	0.041096	3.561644	0.007123	-42.0708
		11000	3.561644			

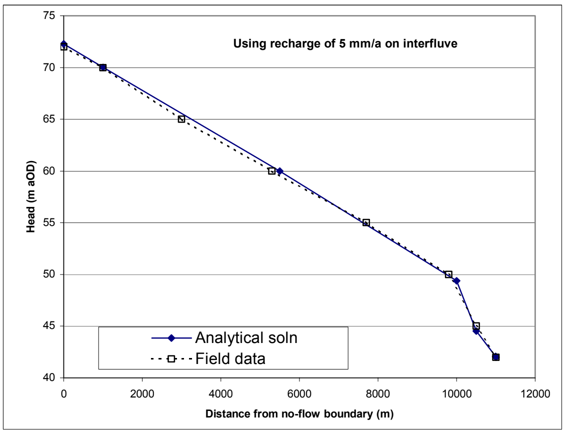
Groundwater head (m aOD) for each element of aquifer

x/l

0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
72.29	72.29	72.29	72.29	72.29	72.29	72.29	72.29	72.29
72.29	71.81	71.28	70.71	70.09	69.43	68.72	67.97	67.17
70.00	68.24	66.33	64.29	62.11	59.79	57.33	54.74	52.00
59.99	58.58	57.12	55.60	54.01	52.37	50.66	48.89	47.05
49.37	48.44	47.44	46.35	45.18	43.93	42.60	41.19	39.70
44.53	44.18	43.80	43.41	43.00	42.56	42.11	41.64	41.14
42.07	42.06	42.06	42.05	42.04	42.04	42.03	42.02	42.01

Field data from contour plot of EA data March 1999

Distance (kr	Head (m aOD)
0	72
1000	70
3000	65
5300	60
7700	55
9800	50
10500	45
11000	42



Appendix 2

Notes:

Less than (<) signs indicate concentration below analytical detection limit.

mbgl = metres below ground level

OxBC = oxidised boulder clay

SaGvl = sand and gravel

UoxBC = unoxidised boulder clay

ClSa = clayey sand

Ck = chalk

CLR1 Porewaters

Sample no	Sample top (mbgl)	Sample bottom (mbgl)	Sample description	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NH_4-N	NO_2-N	TON
					mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
1	0.24	0.35	Soil/OxBC	8.04	270	12.7	103.0	191.0	798	35.5	67.3	0.730	0.020	0.900
2	0.72	0.90	OxBC	8.21	334	10.6	217.0	4.1	338	111.0	808.0	4.160	0.783	4.700
3	1.55	1.70	OxBC	8.22	551	11.3	151.0	2.5	274	443.0	847.0	1.430	0.150	3.100
4	2.16	2.21	OxBC/SaGvl	8.14	387	3.8	70.0	3.3	265	399.0	422.0	0.380	0.853	12.300
5	No sample		SaGvl											
6	No sample		SaGvl											
7i	3.81	3.94	OxBC	8.20	386	5.0	42.0	6.2	272	315.0	150.0	1.500	0.028	100.000
7ii	3.81	3.94	OxBC	8.04	348	5.6	47.4	4.8	119	325.0	151.0	0.070	0.068	90.400
7iii	3.81	3.94	OxBC	8.29	375	5.4	33.5	3.5	313	303.0	142.0	0.090	0.457	88.000
8	4.35	4.50	OxBC	7.73	428	6.6	37.6	5.7	292	261.0	147.0	0.050	0.029	77.000
9a	4.75	5.27	WetSilt	7.66	284	6.9	36.4	13.7	78	247.0	166.0	2.080	0.074	61.200
10	5.60	5.75	UoxBC	8.24	306	10.2	29.2	12.6	309	181.0	179.0	1.100	0.826	53.000
11	6.35	6.50	UoxBC	8.28	292	22.6	19.2	34.2	244	142.0	615.0	2.450	0.180	6.400
12	7.50	7.65	UoxBC	7.84	896	76.2	25.2	120.0	276	156.0	2910.0	2.740	0.303	5.100
13			UoxBC	8.35	140	10.3	9.7	60.3	255	53.5	166.0	1.250	0.210	3.700
14	8.55	8.70	UoxBC	8.21	304	23.6	19.2	105.0	328	53.1	861.0	3.310	0.255	7.600
15	9.15	9.30	UoxBC	8.20	115	8.2	9.7	67.4	323	33.4	136.0	0.740	0.059	1.300
16	9.65	9.80	UoxBC	8.30	321	17.5	14.2	131.0	371	48.0	894.0	1.690	0.079	3.100
17	10.25	10.40	UoxBC	8.06	489	20.7	24.2	142.0	256	58.9	1480.0	2.620	0.451	2.100
18	10.81	10.96	UoxBC	7.46	408	19.5	17.3	119.0	334	36.6	976.0	0.403	0.044	0.500
19	11.45	11.60	UoxBC	8.08	854	40.4	34.5	162.0	312	98.6	2650.0	2.050	0.212	3.300
20i	12.00	12.15	UoxBC	8.08	511	26.9	21.2	78.9	364	59.7	1390.0	2.950	0.039	0.500
20ii	12.00	12.15	UoxBC	8.15	507	25.8	17.5	69.3	326	38.6	1290.0	0.395	< 0.003	< 0.2
20iii	12.00	12.15	UoxBC		507	26.7	16.1	46.2		40.4	1340.0	0.124	< 0.01	< 0.2

Sample no	Sample top (mbgl)	Sample bottom (mbgl)	Sample description	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NH_4-N	NO_2-N	TON
					mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
21	12.65	12.80	UoxBC	8.13	270	12.4	13.6	40.2	325	32.4	610.0	1.910	0.125	4.200
22i	13.10	13.20	UoxBC	8.09	251	13.3	14.5	22.6	307	27.3	485.0	0.400	0.284	0.600
22ii	13.20	13.30	UoxBC	8.12	209	11.4	18.6	23.8	240	27.3	422.0	0.540	0.236	1.100
22ii	13.20	13.30	UoxBC	7.91	233	12.3	12.9	18.9	193	21.1	454.0	0.150	0.008	< 0.2
22iii	13.30	13.40	UoxBC	8.00	407	19.6	17.1	25.5	236	100.0	1180.0	0.630	0.018	0.500
23	13.85	14.00	UoxBC	7.93	143	15.1	11.7	9.4	394	16.1	127.0	2.460	0.052	4.200
24	No sample		UoxBC											
25	15.00	15.15	UoxBC	7.94	337	25.0	19.1	5.1	348	34.5	808.0	0.330	0.085	0.700
26	No sample		UoxBC											
27	16.61	16.76	UoxBC	8.21	115	9.6	15.2	3.3	412	14.4	24.1	0.516	0.021	0.500
28	17.85	18.00	UoxBC	8.02	114	10.1	14.6	3.6	253	11.7	24.8	3.600	0.433	3.200
29	18.72	18.87	UoxBC	7.80	104	9.5	18.5	3.1	387	11.0	22.9	0.689	0.067	0.500
30	19.31	19.46	UoxBC	7.83	264	18.4	27.5	5.8	272	24.7	568.0	3.220	0.054	0.800
31	20.03	20.18	UoxBC	7.84	167	14.0	22.3	3.3	364	11.2	155.0	0.079	0.010	< 0.2
32	20.66	20.81	ClSa	7.79	110	11.2	24.6	4.5	346	13.7	25.0	0.180	0.079	0.700
33	21.28	21.43	ClSa/Ck	7.99	114	13.3	20.3	2.7	398	8.5	54.8	0.078	< 0.003	< 0.2
34	21.70	22.30	Ck	8.50	97	12.4	23.0	3.5	312	11.6	62.8	0.096	0.011	< 0.2
35	22.30	22.90	Ck	8.44	123	15.1	28.4	4.1	335	11.8	86.3	0.058	0.008	< 0.2
36	22.90	23.50	Ck	8.42	101	13.0	26.7	3.2	248	11.8	104.0	0.022	0.005	< 0.2
37	23.50	24.10	Ck	8.57	123	14.9	27.5	3.2	315	12.1	113.0	0.022	0.004	< 0.2
38	24.10	24.70	Ck	8.44	110	14.0	26.5	3.2	269	12.0	126.0	0.018	0.005	0.300
39	24.80	25.40	Ck	8.54	111	14.5	26.9	3.5	247	13.8	139.0	0.027	0.005	0.400
40	25.50	26.10	Ck	8.51	138	17.2	28.9	3.5	316	14.5	147.0	0.027	0.004	0.400
41	26.10	26.70	Ck	8.47	117	15.4	26.8	3.0	272	14.7	153.0	0.018	0.004	0.700

Sample no	Sample top (mbgl)	Sample bottom (mbgl)	Sample description	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NH_4-N	NO_2-N	TON
					mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
42	26.80	27.40	Ck	8.55	130	15.9	25.3	2.9	302	16.4	143.0	0.018	0.005	0.900
43	27.40	28.00	Ck	8.47	126	14.8	25.5	3.1	244	24.5	152.0	0.036	0.005	1.800
44	30.30	30.60	Ck	7.85	151	14.8	25.6	2.9	114	31.3	149.0	< 0.009	0.019	2.200

Results of monitoring from CLR1 and other locations in the region

	Date	pH	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	Cl mg/l	SO_4 mg/l	NO_2-N mg/l	TON mg/l
CLR1 shallow(till) piezometer	07-Feb-01	8.02	397	10.1	168	10.3	398	299	390	0.954	56.9
CLR1 shallow(till) piezometer	03-Jul-01	7.65	373	13.4	361	10.5	429	275	806	2.26	54.1
CLR1 shallow(till) piezometer	11-Sep-01	7.32	331	8.97	191	10.4	408	221	383	0.039	55
CLR1 shallow(till) piezometer	19-Oct-01	7.09	349	7.14	81.4	7.9	405	195	223	0.016	53.8
CLR1 shallow(till) piezometer	06-Nov-01	7.8	350	6.66	87.6	7.5	405	205	229	0.038	55.3
CLR1 shallow(till) piezometer	04-Dec-01	7.13	350	7.29	90.1	8.6	398	205	234	0.045	52
CLR1 shallow(till) piezometer	08-Jan-02	7.5	322	8.18	159	10.2	415	218	346	0.13	50.5
CLR1 shallow(till) piezometer	06-Feb-02	7.66	343	7.1	80.2	7.8	439	210	226	< 0.02	52.3
CLR1 shallow(till) piezometer	04-Mar-02	7.58	331	6.58	65.4	7.7	285	196	204	0.335	49.3
CLR1 shallow(till) piezometer	09-Apr-02	7.23	340	6.99	60.8	8	406	210	209	0.22	48.7
CLR1 shallow(till) piezometer	14-Nov-02	7.4	332	6.25	76.9	7.5	411	208	200	< 0.003	42.9
CLR1 shallow(till) piezometer	16-Dec-02	7.43	338	6.41	59.2	8.31	401	200	203	< 0.003	40.4
CLR1 shallow(till) piezometer	20-Jan-03	7.73	359	5.33	53	5.83	366	224	247	< 0.003	31.6
CLR1 shallow(till) piezometer	20-Feb-03	7.27	357	4.93	68	5.26	347	229	313	0.009	30
CLR1 deep (chalk) piezometer	07-Feb-01	8.16	380	6.98	51.9	11	382	230	198	0.032	52.7
CLR1 deep (chalk) piezometer	03-Jul-01	7.845	309	6.49	41.4	6.6	290	193	180	0.007	42
CLR1 deep (chalk) piezometer	11-Sep-01	7.5	285	6.88	41.2	6.3	248	198	174	0.012	42.8
CLR1 deep (chalk) piezometer	07-Feb-01	7.61	266	5.49	50.7	6.6	205	195	181	0.025	42
CLR1 deep (chalk) piezometer	06-Nov-01	7.87	309	5.06	41.5	5.8	303	243	175	0.011	45.1
CLR1 deep (chalk) piezometer	04-Dec-01	7.51	283	5.37	43.1	6.6	213	205	179	0.022	43.5
CLR1 deep (chalk) piezometer	08-Jan-02	7.73	262	5.48	45.6	7.5	174	198	175	< 0.005	42.2
CLR1 deep (chalk) piezometer	06-Feb-02	7.55	282	5.56	39.3	8.4	245	198	177	< 0.02	41.7
CLR1 deep (chalk) piezometer	04-Mar-02	7.86	249	6.13	38.8	6.6	152	196	183	0.03	40.8
CLR1 deep (chalk) piezometer	09-Apr-02	7.39	248	5.6	44.1	6.3	111	192	190	0.015	41.4
CLR1 deep (chalk) piezometer	14-Nov-02	7.67	270	5.38	34.1	29.5	350	160	141	< 0.003	28.3
CLR1 deep (chalk) piezometer	16-Dec-02	7.78	272	5.96	38.1	7.24	244	190	177	< 0.003	34.3
CLR1 deep (chalk) piezometer	20-Jan-03	7.56	329	5.88	41	5.78	352	197	218	< 0.003	28.9
CLR1 deep (chalk) piezometer	20-Feb-03	7.52	309	6.67	36	6.31	365	192	197	0.005	32

	Date	pH	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	Cl mg/l	SO_4 mg/l	NO_2-N mg/l	TON mg/l
CLR1 White Gas Piezometer	03-Jul-01	7.88	203	17.8	237	66	402	113	644	0.027	0.7
CLR1 White Gas Piezometer	04-Mar-02	8.31	209	17.6	154	72.2	389	91.6	602	< 0.003	0.7
CLR1 Blue Gas Piezometer	06-Feb-02	7.88	135	7.29	38.1	81.7	444	30.2	235	< 0.02	< 1
Boulder Clay Ditch	19-Oct-01	8.15	125	3.89	12.1	3.6	311	14.5	31.9	0.054	11.5
Boulder Clay Ditch	06-Nov-01	8.07	149	4.78	18.9	3.4	349	26	58.5	0.075	4.3
Boulder Clay Ditch	04-Dec-01	8.15	142	3.91	12.2	1.9	332	20.9	38.9	0.05	11.7
Boulder Clay Ditch	08-Jan-02	8.27	137	4.38	12.4	2.2	338	23.5	46.1	0.031	9.4
Boulder Clay Ditch	06-Feb-02	7.83	145	3.77	11.6	1.4	345	17.9	33.8	< 0.02	6
Boulder Clay Ditch	06-Feb-02	7.83	145	3.77	11.6	1.4	345	17.9	33.8	< 0.02	6
Boulder Clay Ditch	04-Mar-02	8.03	140	4.72	15.9	1.8	323	25.9	57.1	< 0.003	6
Spring	07-Feb-01	8.29	181	3.14	13.2	1.3	346	46.3	56.6	0.003	18.1
Spring	03-Jul-01	7.86	261	3.64	27.1	3.2	412	92.3	136	0.004	21.5
Spring	11-Sep-01	7.55	259	4.42	26.2	6.3	386	80.4	174	0.006	19.2
Spring	04-Dec-01	7.56	217	3.69	24.2	5.9	363	69.8	134	< 0.005	18.8
Spring	08-Jan-02	7.62	204	3.29	24.6	5.9	360	61.4	115	< 0.005	17.4
Spring	06-Feb-02	7.65	197	3.31	21.8	3.6	366	51.5	104	< 0.02	13
Spring	09-Apr-02	7.46	188	2.8	23.6	5.1	349	52.5	87	< 0.003	14.1
R. Stour (bridge nr Waterhall Fm)	19-Oct-01	8.01	138	4.09	22	3.9	312	31.7	48.8	0.068	9.5
R. Stour (bridge nr Waterhall Fm)	06-Nov-01	8.11	163	10.4	154	11.5	419	154	132	0.097	10.4
R. Stour (bridge nr Waterhall Fm)	04-Dec-01	7.91	149	6.11	60.5	6.3	369	66	77.7	0.049	8.6
R. Stour (bridge nr Waterhall Fm)	08-Jan-02	7.98	161	9.05	110	9.3	402	137	113	0.082	9.8
R. Stour (bridge nr Waterhall Fm)	06-Feb-02	8.03	150	5.35	46.1	4.3	385	54.3	63.5	< 0.02	5
R. Stour (bridge nr Waterhall Fm)	05-Mar-02	8.16	158	8.29	88.8	9.1	374	100	104	< 0.003	10.3
R. Stour (bridge nr Waterhall Fm)	09-Apr-02	7.72	147	9.8	158	11.3	400	173	122	0.069	10
Great Wratting (Anglian Water bh)	Apr-02	7.5	179	18.2	24.9	6.2	381	36.8	178	< 0.003	4.5
Wixoe No 2 (Anglian Water bh)	Apr-02	7.42	164	23.3	36.9	7.2	374	47.9	202	0.016	1.8

	Date	pH	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	Cl mg/l	SO_4 mg/l	NO_2-N mg/l	TON mg/l
Mill House, Ridgewell (EA obs bh)	09-Apr-02	7.63	102	5.28	9.9	13.6	320	6.9	36.9	< 0.003	1.9
Mill House, Ridgewell (EA obs bh)	14-Nov-02	8.23	94.8	4.68	6.89	11.8	282	6.4	29.9	< 0.003	0.4
Mill House, Ridgewell (EA obs bh)	16-Dec-02	7.85	96.8	4.92	7.67	13.4	292	7	32.1	< 0.003	< 0.3
Mill House, Ridgewell (EA obs bh)	20-Jan-03	7.81	125	6.45	12.2	4.61	360	15	35.8	< 0.003	< 0.2
Mill House, Ridgewell (EA obs bh)	20-Feb-03	7.59	121	6.27	12.4	3.64	349	16	33.4	< 0.003	< 0.8
Blacksmiths Hill (EA obs bh)	09-Apr-02	7.49	110	11.5	23.4	4.4	220	23.5	121	0.004	7.9
Blacksmiths Hill (EA obs bh)	14-Nov-02	7.91	160	9.7	25	5.91	317	25.9	92.9	< 0.003	14.3
Blacksmiths Hill (EA obs bh)	16-Dec-02	7.86	136	11.1	24.5	4.46	294	27	92.4	< 0.003	8.3
Blacksmiths Hill (EA obs bh)	20-Jan-03	7.9	159	19.3	22.2	2.82	328	23	171	< 0.003	5.3
Blacksmiths Hill (EA obs bh)	20-Feb-03	7.54	159	20.4	22.4	2.85	316	23	184	0.004	5.3
Cowlinge TL75/072 (EA obs borehole)	19-Feb-03	7.61	187	32.7	25.3	6.85	424	37	228	< 0.003	< 0.8
Verge, Rede Lane (EA obs borehole)	21-Jan-03	9.81	3.24	1.16	20.4	9.2	43.5	21	0.5	< 0.003	< 0.2
Gainsford Hall, Toppesfield (EA obh)	21-Jan-03	4.64	245	61.2	94	6.91	< 0.5	105	486	< 0.003	< 0.2
Radwinter Road, Ashdon (EA obs bh)	18-Feb-03	7.63	190	30.3	22	4.91	404	50	208	< 0.003	< 0.8
Skippers Lane, Withersfield (EA obh)	19-Feb-03	9.12	67.1	8.97	60	56.9	< 0.5	53	325	< 0.003	< 0.8
Thurlow Road, Carlton Green (EA obh)	19-Feb-03	6.81	165	16.6	21.2	6.13	351	51	137	< 0.003	< 0.8

	Date	CFC-12 pmol/L	CFC-11 pmol/L	N_2/Ar	N_2O µg/l	$\delta^{13}C$ per mil	$\delta^{18}O$ per mil	$\delta^{2}H$ per mil
CLR1 shallow(till) piezometer	07-Feb-01					-17.86	-7.07	-44.59
CLR1 shallow(till) piezometer	03-Jul-01					-17.49	-7.1	-46.2
CLR1 shallow(till) piezometer	11-Sep-01						-7.2	-46.7
CLR1 shallow(till) piezometer	19-Oct-01	0	4.21					
CLR1 shallow(till) piezometer	06-Nov-01					-17.05	-6.58	-47.3
CLR1 shallow(till) piezometer	04-Dec-01					-17.53	-7.14	-48
CLR1 shallow(till) piezometer	08-Jan-02					-17.39	-6.27	-42.9
CLR1 shallow(till) piezometer	06-Feb-02					-18.35	-6.93	-46.2
CLR1 shallow(till) piezometer	04-Mar-02					-18.06	-7	-46.8
CLR1 shallow(till) piezometer	09-Apr-02					-17.2	-6.9	-43.5
CLR1 shallow(till) piezometer	Jun-02					-18.03	-7.83	-44.7
CLR1 shallow(till) piezometer	Oct-02					-14.41	-7.06	-46
CLR1 shallow(till) piezometer	14-Nov-02					-17.83	-7.14	-44.1
CLR1 shallow(till) piezometer	16-Dec-02					-17.55	-7.12	-44.2
CLR1 deep (chalk) piezometer	07-Feb-01					-16.38	-7.17	-43.96
CLR1 deep (chalk) piezometer	03-Jul-01					-13.01	-7.15	-44.4
CLR1 deep (chalk) piezometer	11-Sep-01						-6.99	-47.9
CLR1 deep (chalk) piezometer	06-Nov-01					-12.42	-6.58	-45.6
CLR1 deep (chalk) piezometer	04-Dec-01					-10.81	-7.08	-47.1
CLR1 deep (chalk) piezometer	08-Jan-02					-9.44	-6.67	-44
CLR1 deep (chalk) piezometer	06-Feb-02					-12.07	-7.02	-47.8
CLR1 deep (chalk) piezometer	04-Mar-02					-8.64	-7.18	-48
CLR1 deep (chalk) piezometer	09-Apr-02					-2.75	-6.97	-43.8
CLR1 deep (chalk) piezometer	14-Nov-02					-12.93	-6.830	-46.4
CLR1 deep (chalk) piezometer	16-Dec-02	3.43	4.65	47.5		-13.92	-7.37	-44.7
CLR1 deep (chalk) piezometer	20-Jan-03	2.68	3.91	42.2				
CLR1 deep (chalk) piezometer	20-Feb-03	2.59	4.4	48.9				

	Date	CFC-12 pmol/L	CFC-11 pmol/L	N_2/Ar	N_2O µg/l	$\delta^{13}C$ per mil	$\delta^{18}O$ per mil	$\delta^{2}H$ per mil
CLR1 White Gas Piezometer	03-Jul-01					-7.05	-42.7	-13.57
CLR1 White Gas Piezometer	04-Mar-02					-15.04	-7.16	-45.26
CLR1 Blue Gas Piezometer	06-Feb-02					-19.6	-7.17	-49.7
Boulder Clay Ditch	19-Oct-01							
Boulder Clay Ditch	06-Nov-01					-15.63	-7.01	-42.9
Boulder Clay Ditch	04-Dec-01					-16.48	-6.59	-45.3
Boulder Clay Ditch	08-Jan-02					-14.81	-6.68	-44.2
Boulder Clay Ditch	06-Feb-02					-16.92	-6.37	-40.7
Boulder Clay Ditch	06-Feb-02					-16.92	-6.37	-40.7
Boulder Clay Ditch	04-Mar-02					-15.11	-6.94	-40.8
Boulder Clay Ditch	Apr-02					-15.29	-6.47	42.3
Boulder Clay Ditch	Oct-02					-13.06	-6.11	42.7
Spring	07-Feb-01					-17.67	-7.08	-45.33
Spring	03-Jul-01					-16.85	-7.18	-47.1
Spring	11-Sep-01						-7.08	-48.8
Spring	04-Dec-01					-17.42	-6.97	-44.8
Spring	08-Jan-02					-16.77	-6.97	-45.5
Spring	06-Feb-02					-17.98	-7.09	-46.6
Spring	09-Apr-02					-16.71	-7	-47.6
Spring	Jun-02					-14.71	-7.14	-46.7
Spring	Oct-02					-13.74	-7.15	-46.9

Results of monitoring from Cowlinge research borehole (porewater and pump test samples)

Sample type	Date	Top	Bottom	SEC lab	pH lab	Ca	Mg	Na	K	HCO_3 lab	Cl	SO_4	NH_4	NO_2
		mbgl	mbgl	uS/cm		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Porewater	19-Mar-03	34.0	34.5	2060	7.91	409	92.7	47.0	11.0	105	59	1140	0.38	0.012
Porewater	19-Mar-03	35.5	36.0	1092	8.16	188	48.0	35.6	8.0	118	51	525	0.45	0.046
Porewater	19-Mar-03	36.0	36.5	1112	8.15	192	51.7	36.5	9.0	121	54	533	0.60	0.046
Porewater	19-Mar-03	36.5	37.0	1200	7.85	213	63.0	36.0	8.0	283	51	504	0.71	0.003
Porewater	19-Mar-03	37.0	37.5	1221	7.88	232	66.6	37.2	8.0	278	54	528	0.73	0.003
Porewater	19-Mar-03	38.0	38.5	1255	8.21	199	70.6	40.4	9.0	133	63	591	0.55	0.017
Porewater	19-Mar-03	38.5	39.0	1360	8.12	252	76.0	40.8	8.0	282	65	598	0.74	0.014
Porewater	19-Mar-03	39.0	39.5	1270	8.13	236	72.1	41.5	9.0	198	65	607	0.73	0.004
Porewater	19-Mar-03	40.0	40.5	1165	8.15	194	54.0	37.6	9.0	140	60	523	0.53	0.026
Porewater	19-Mar-03	40.5	41.0	1224	8.13	237	64.1	36.9	8.0	273	60	513	0.63	0.006
Porewater	19-Mar-03	41.0	41.5	1216	8.07	229	59.7	36.1	8.0	282	59	498	0.63	0.004
Porewater	19-Mar-03	43.0	43.5	1209	8.06	243	58.9	35.6	7.0	285	56	494	0.62	0.014
Porewater	19-Mar-03	44.5	45.0	1217	8.01	250	59.2	36.7	7.0	286	48	521	0.57	0.003
Porewater	19-Mar-03	45.0	45.5	1219	7.97	235	53.8	34.5	6.0	276	47	495	0.56	0.003
Porewater	19-Mar-03	46.5	47.0	1179	7.97	198	52.7	33.3	7.0	267	40	492	0.53	0.002
Porewater	19-Mar-03	47.0	47.5	1210	7.92	246	53.5	34.3	7.0	290	41	492	0.53	0.003
Porewater	19-Mar-03	49.5	50.0	1102	8.33	216	45.6	34.2	6.0	277	40	440	0.44	0.004
Porewater	19-Mar-03	50.0	50.5	1069	8.01	219	45.4	33.6	6.0	249	40	439	0.47	0.005
Porewater	19-Mar-03	52.5	53.0	955	8.03	158	36.5	31.5	6.0	120	43	398	0.42	0.013
Porewater	19-Mar-03	53.5	54.0	927	7.93	152	36.7	31.0	5.0	93	44	408	0.41	0.020
Porewater	19-Mar-03	56.0	56.5	953	7.84	152	36.3	32.1	6.0	82	63	386	0.39	0.010
Porewater	19-Mar-03	62.0	62.5	918	8.05	143	34.0	29.2	5.0	104	47	361	0.59	0.021
Porewater	19-Mar-03	63.0	64.0	1092	8.06	173	44.5	32.3	5.0	136	73	408	0.47	0.005
Porewater	19-Mar-03	66.0	67.0	1018	8.30	165	41.3	31.6	5.0	198	44	358	0.59	0.010
Porewater	19-Mar-03	68.0	69.0	1095	8.19	179	43.4	32.7	6.0	154	67	417	0.62	0.009
Porewater	19-Mar-03	70.0	70.5	1051	8.20	199	44.5	32.1	4.0	350	41	343	0.50	0.005
Porewater	19-Mar-03	71.0	72.0	1122	8.18	177	43.3	34.6	5.0	146	70	421	0.52	0.011
Porewater	19-Mar-03	73.0	73.5	1044	7.95	169	40.0	30.7	5.0	99	67	415	0.46	0.022

Sample type	Date	Top	Bottom	SEC lab	pH lab	Ca	Mg	Na	K	HCO_3 lab	Cl	SO_4	NH_4	NO_2
		mbgl	mbgl	uS/cm		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Porewater	19-Mar-03	75.0	75.5	1058	8.05	161	41.4	34.0	6.0	134	61	395	0.49	0.016
Porewater	19-Mar-03	76.0	77.0	1002	8.10	157	39.1	32.1	6.0	159	45	375	0.42	0.021
Porewater	19-Mar-03	79.0	80.0	985	8.11	153	36.7	31.6	5.0	145	46	367	0.37	0.012

Sample type	Date	Top	Bottom	SEC field	pH field	Ca	Mg	Na	K	HCO_3 lab	Cl	SO_4	NH_4	NO_2
		mbgl	mbgl	uS/cm		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Pump test	26-Feb-03	46.2	51.4	1472		240	57.2	25.0	8.1	408	50	464	0.55	<0.003
Pump test	27-Feb-03	52.0	57.0	1624	6.74	246	59.7	35.5	8.3	427	50	466	0.57	<0.003
Pump test	27-Feb-03	52.0	57.0		6.51	250	61.0	27.0	8.5	413	50	483	0.60	<0.003

References

ALLEN, D.J., BREWERTON, L.J., COLEBY, L.M., GIBBS, B.R., LEWIS, M.A., MACDONALD, A.M., WAGSTAFF, S.J. AND WILLIAMS, A.T. 1997, The physical properties of major aquifers in England and Wales, British Geological Survey Technical Report WD/97/34, 312pp.

GERBER, R.E., BOYCE, J.I. AND HOWARD, K.W.F. 2001. Evaluation of heterogeneity and field-scale groundwater flow regime in a leaky till aquitard Hydrogeol J 9, 60–78.

GRISAK, G.E. AND CHERRY, J.A. 1975. Hydrologic characteristics and response of fractured till and clay confining a shallow aquifer. Can. Geotech J 12, 23–43.

GRISAK, G.E., CHERRY, J.A., VONHOF, J.A. AND BLUMELE, J.P. 1976. Hydrogeologic and hydrochemical properties of fractured tills in the interior plains region. In: Glacial Till (ed R F Legget), Roy Soc Can Spec Publ 12, 304–335.

HENDRY, M.J. 1982. Hydraulic conductivity of a glacial till in Alberta. Ground Water 20, 162–169.

HORBERG, L. 1952. Pleistocene drift sheets in the Lethbridge region, Alberta, Canada. J Geol 60, 303–329.

HOSSAIN, D. 1992. Prediction of permeability of fractured tills. Q J Eng Geol 25, 331–342.

INESON, J. 1962. A hydrogeological study of the permeability of the Chalk. J Inst Wat Eng Sci 16, 449–463.

JACKSON, D. AND RUSHTON, K. R. 1987. Assessment of recharge compenents for a Chalk aquifer unit. Journal of Hydrology, 92, 1-15.

KLINCK, B.A., BARKER, J.A., NOY, D.J. AND WEALTHALL, G.P. 1996. Mechanisms and rates of recharge through glacial till: Experimental and modelling studies from a Norfolk site. British Geological Survey Technical Report, WE/96/1

LEWIS, M.A., JONES, H.K., MACDONALD, D.M.J., PRICE, M., BARKER, J.A., SHEARER, T.R., WESSELINK, A.J. AND EVANS, D.J. (1993). Groundwater storage in British aquifers: Chalk. R&D Note 169, National Rivers Authority, Bristol.

LLOYD, J.W., HARKER, D. AND BAXENDALE, R.A. 1981. Recharge mechanisms and groundwater-flow in the Chalk and drift deposits of southern East Anglia. Q J Eng Geol 14, 87–96.

LLOYD, J.W. AND HISCOCK, K.M. 1990. Importance of drift deposits in influencing Chalk hydrogeology. In: Chalk, Thomas Telford, London.

PRICE, M., LOW, R.G. AND MCCANN, C. 2000. Mechanisms of water storage and flow in the unsaturated zone of the Chalk aquifer. Journal of Hydrology, 233, (1–4): 54–71.

PARKER, J.M. AND JAMES, R. 1985. Autochthonous bacteria in the chalk and their influence on groundwater quality in East Anglia. Journal of Applied Bacteriology Symposium Supplement 15S–25S.

PRICE, M., DOWNING, R.A. AND EDMUNDS, W.M. 1993. The Chalk as an aquifer. In: The Hydrogeology of the Chalk of North-west Europe. (eds. Downing R A, Price M and Jones G P.) Clarendon Press, 35–62.

PLUMMER, L. N. AND BUSENBERG, E. (1999) Chlorofluorocarbons. In Environmental Tracers in Subsurface Hydrology (Eds. P Cook and A L Herczeg), Kluwer Academic Publishers, Dordrecht, 441-478.

ROWE, P.W. 1972. The relevance of soil fabric to site investigation practice. Geotechnique 22, 195–200.

SOLEY, R.W.N. AND HEATHCOTE, J.A. 1998. Recharge through the drift: a study of contrasting Chalk catchments near Redgrave Fen, UK. In: Groundwater Pollution, Aquifer Recharge and Vulnerability (ed. N S Robins), Geol Soc Lond Spec Publ 130, 129–141.

VAN DER KAMP, G. 2001. Methods for determining the in situ hydraulic conductivity of shallow aquitards – an overview. Hydrogeol J 9, 5–16.

WILLIAMS, R.E. AND FARVOLDEN, R.N. 1969. The influence of joints on the movement of groundwater through glacial till. J Hydrol 5, 163–170.

WOODLAND, A.W. 1946. Water supply from underground sources of Cambridge–Ipswich District – General discussion. Geol Surv GB Wartime Pamphlet No 20, Part X, 89pp.