British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Chalk Recharge Beneath Thick Till Deposits in East Anglia

Groundwater Systems & Water Quality Programme
Internal Report IR/04/179

BRITISH GEOLOGICAL SURVEY

GROUNDWATER SYSTEMS & WATER QUALITY PROGRAMME

INTERNAL REPORT IR/04/179

Chalk Recharge Beneath Thick Till Deposits in East Anglia

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

Contributor

D C Entwisle

Keywords

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

Front cover

Sampling borehole.

Bibliographical reference

R J MARKS: A R LAWRENCE; E J WHITEHEAD: J E COBBING: M M MANSOUR; W G DARLING AND A G HUGHES. 2004. Chalk Recharge Beneath Thick Till Deposits in East Anglia. *British Geological Survey Internal Report*, IR/04/179. 73pp.

Keyworth, Nottingham British Geological Survey 2004

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham, Edinburgh and London; see contact details below or shop online at www.geologyshop.com

The London Information Office also 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.

British Geological Survey offices

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.geologyshop.com

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, Colby House, Stranmillis Court, Belfast BT9 5BF
☎ 028-9038 8462 Fax 028-9066 2835
e-mail: gsni@detini.gov.uk

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491-838800 Fax 01491-692345
e-mail: hydro@bgs.ac.uk

Sophia House, 28 Cathedral Road, Cardiff, CF11 9LJ
☎ 029–2066 0147 Fax 029–2066 0159

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

Mr S Eyre and Mr M Cook of AWS

Dr K M Hiscock and Mr Mohammad Tabatabai Najafi 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 and Dr C Jackson.

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 to the Chalk aquifer through thick Lowestoft Till (chalky boulder clay). The project has involved drilling two cored boreholes, monitoring groundwater levels, sampling Chalk and till fracture waters[1] and porewaters, numerical modelling of groundwater levels and the development of a conceptual model of the Chalk-till groundwater system.

The main findings of the report are that:

- the till has a significant impact on recharge quantity and distribution to the underlying Chalk aquifer. Beneath the interfluves recharge appears to be lower than previous estimates of 20 – 40 mm/a (Klink et al., 1996; Soley and Heathcote, 1998), maybe as low as 5 mm/a;
- 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;
- recharge rates to the Chalk aquifer at the edge of the till are greater than the effective rainfall (rainfall minus actual evapotranspiration) because of the contribution of large volumes of runoff from the till sheet. This water characterises the modern (post-1960s), high-nitrate, groundwaters of the main Chalk valleys with potentially short travel times from recharge to discharge. The arable land on the till sheet has had field drains installed and these contribute to the bulk of the runoff; as a consequence nitrate concentrations in the runoff are high;
- 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 of the redistribution of recharge by the till is that boreholes close to the edge of the till sheet are likely to pump a greater proportion of modern recharge than previously believed and these are likely to produce water with higher nitrate concentrations;
- the Chalk groundwaters at the edge of the till sheet are vulnerable to pollution because of the potentially high recharge rates (due to runoff recharge) and the relatively shallow depth to the water table. As a consequence, travel times through the unsaturated zone may be short.

---

[1] in this report the term ‘fracture water’ refers to the more mobile groundwater flowing through fractures in the saturated zone, which is sampled by pumping.

1 Introduction

In April 2000, the British Geological Survey (BGS) funded, as part of its core science programme, a 4 year research project to investigate and quantify recharge to the Chalk aquifer beneath thick till (chalky boulder clay) deposits in East Anglia. This project was understood to be of national/strategic value given (a) the importance of the Chalk aquifer to the UK water industry and other users, (b) the sizeable area of Chalk 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, understanding the recharge mechanisms.

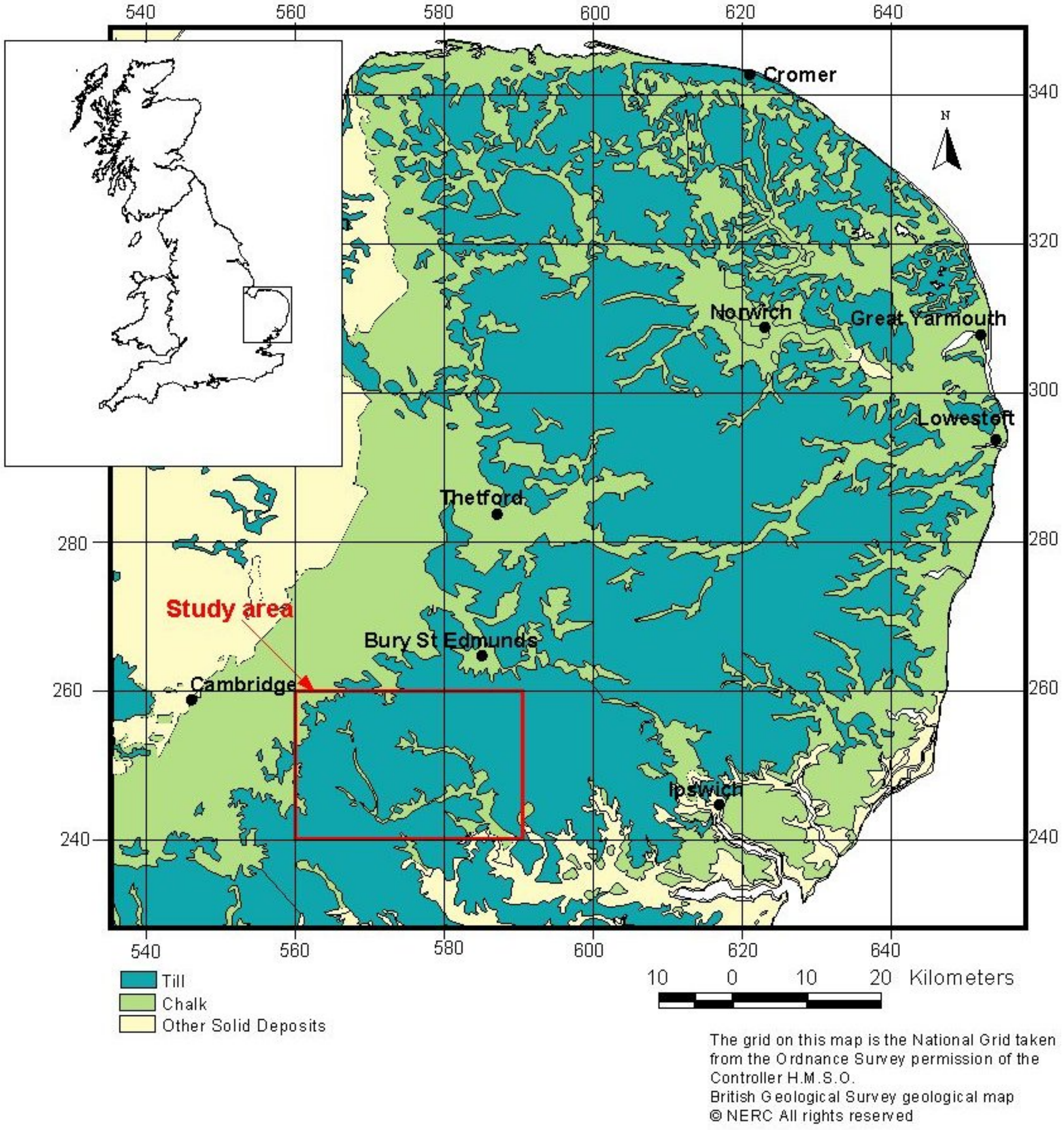
In addition to the funding under the BGS core programme, Anglian Water Services (AWS) and the Environment Agency (EA) contributed financially to the project. AWS and the EA were interested in this research for three principal reasons:

- an understanding of recharge to the Chalk, through till deposits, should allow a better delineation of the catchment areas for abstraction boreholes where till cover is present. 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 or other uses);
- the vulnerability (to pollution) of the Chalk aquifer reflects the spatial distribution and rate of recharge through the till.

2 Background

2.1 CHALK AQUIFER

The Chalk, which is a major aquifer of the UK providing a significant proportion of the public water supply, subcrops beneath Lowestoft Till (chalky boulder clay) over large areas of East Anglia (Figure 2.1). Where the Chalk is exposed at the surface it is usually very permeable permitting infiltration at a high rate. However, in East Anglia most of the Chalk is overlain by glacial deposits, some of low permeability (glacial till) which severely restricts Chalk recharge. 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.



The grid on this map is the National Grid taken from the Ordnance Survey permission of the Controller H.M.S.O.
British Geological Survey geological map
© NERC All rights reserved

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. Intensive cereal cropping, supported by high applications of nitrogen fertilisers, has been widely practised on the Chalk in East Anglia since the 1960s. One consequence is that groundwater nitrate concentrations in areas of exposed Chalk have increased and concentrations in excess of 20 mg N/l 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 till 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 a major aquifer because it is fractured and jointed. The spacing, and more importantly the aperture, of the fractures and joints 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) were the first to observe that, in areas of exposed 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 fractures and joints by carbonate dissolution is considered to be responsible for these high values. Beneath the till covered interfluves, the confined Chalk transmissivity is nearly always <50 m^2/d and is typically about 10 m^2/d. The latter figure is believed to represent the permeability of the primary fractures (Lloyd et al., 1981) with only limited solution enlargement.

In areas of exposed Chalk, groundwater abstraction is largely concentrated in the valleys where aquifer transmissivity and, therefore, borehole yields are higher. Perennial streams are generally restricted to the middle and lower reaches of the valley floor 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. Nevertheless some Chalk 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;

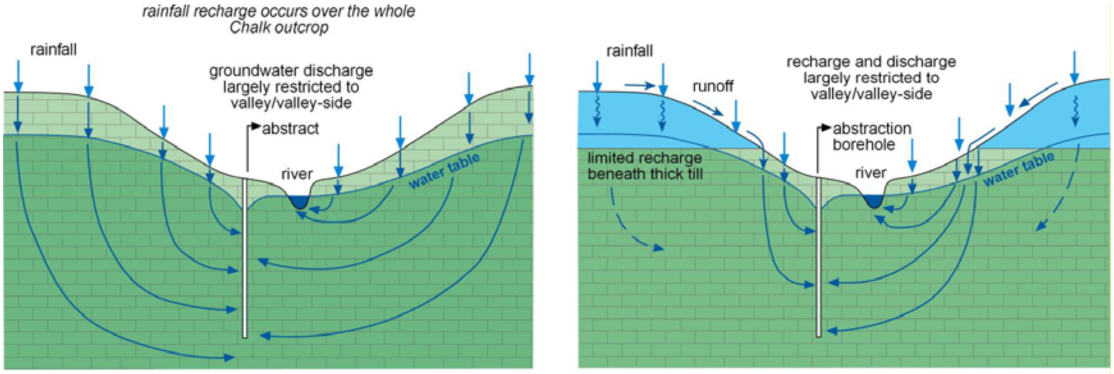
(ii) the till matrix is not completely impermeable and so some downward infiltration to the Chalk will occur. Furthermore, fractures in glacial tills have been widely reported (Horberg, 1952; Williams and Farvolden, 1969; Grisak and Cherry, 1975; Grisak et al., 1976; Hendry, 1982) and these could increase 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 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 20%.

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).



(a) Unconfined Chalk groundwater flow system **(b) Confined Chalk groundwater flow system**

Figure 2.2 Unconfined Chalk groundwater flow system

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 Lowestoft Till (chalky boulder clay) of East Anglia, which is a lodgement till deposited during the Anglian glaciation, is of relatively uniform lithology and consists predominantly of clay with subordinate lenses of sand and gravel, and contains pebbles of chalk and flint. It can be divided into a thin upper weathered (oxidised) zone (generally more permeable) and a lower, thick, unweathered (unoxidised) layer.

3 Description of Case Study Area

3.1 LOCATION

The area selected for detailed research lies between the River Stour, which drain 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 3.1). The land is characterised by gentle slopes and differences in elevation between interfluves and valley floors are typically 50 to 70 m.

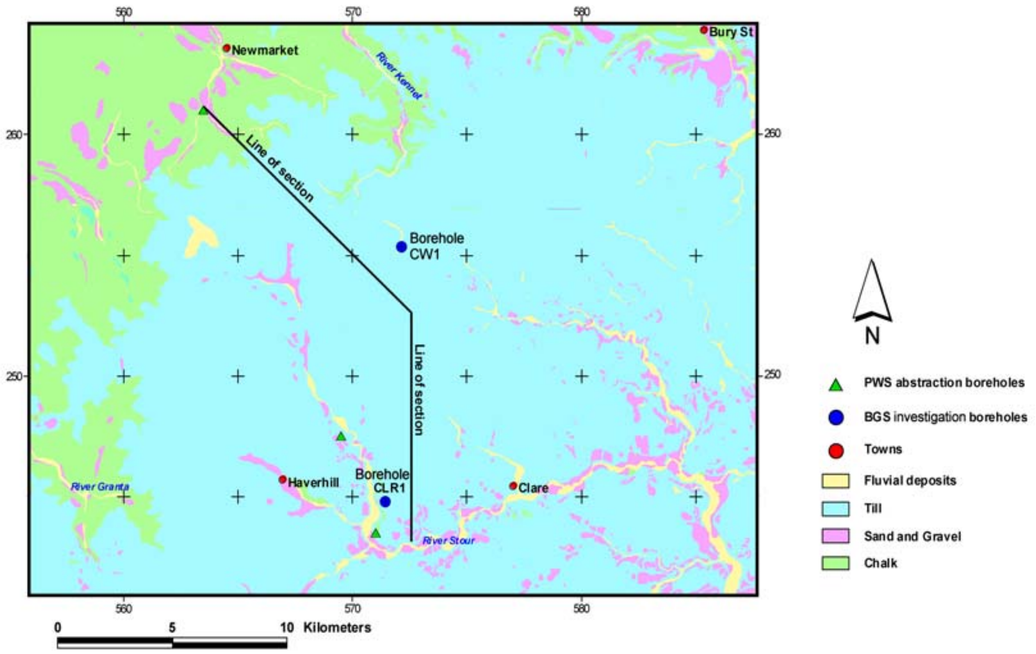


Figure 3.1 Geology of study area, showing main towns and rivers

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 superficial sand and gravel deposits 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, personal communication). On this basis excess rainfall is about 155 mm/a, making it one of the drier areas of the UK. This excess rainfall is also known as effective rainfall (ER).

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 augment 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 Upper Chalk formations dip gently to the southeast and over most of the area subcrop beneath the Lowestoft Till, which can exceed 30 m in thickness (Figure 3.2). However, the till is absent from the main river valleys and here the Chalk is either exposed or covered by permeable superficial deposits. The till sheet is absent in the northwest of the area where the

Chalk is exposed. Occasional sand and gravel lenses occur within the till, but these are not generally extensive (Cox, 2002). A sand and gravel layer is widely developed beneath the till, but in the study area this is typically only 1 – 2 metres thick.

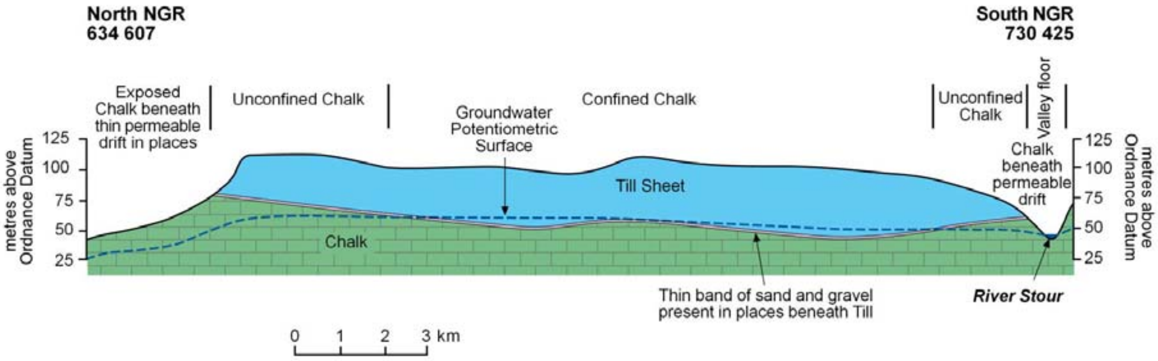


Figure 3.2 Geological cross-section (line of section shown on Figure 3.1)

The Chalk is the major aquifer in East Anglia and, in the main river valleys, 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 about 10 m^2/d (Figure 3.3). The higher transmissivity Chalk occupies a relatively narrow zone within the valley of the Stour 1 – 2 km in width. The transition to the lower transmissivity Chalk beneath the interfluve appears to be sharp, although pumping test data from beneath the interfluves are sparse. Intermediate Chalk transmissivities of 50 – 120 m^2/d are occasionally observed in the Chalk aquifer beneath the interfluves and are usually associated with minor streams flowing over the till sheet (e.g. Hundon, NGR TL 733 486).

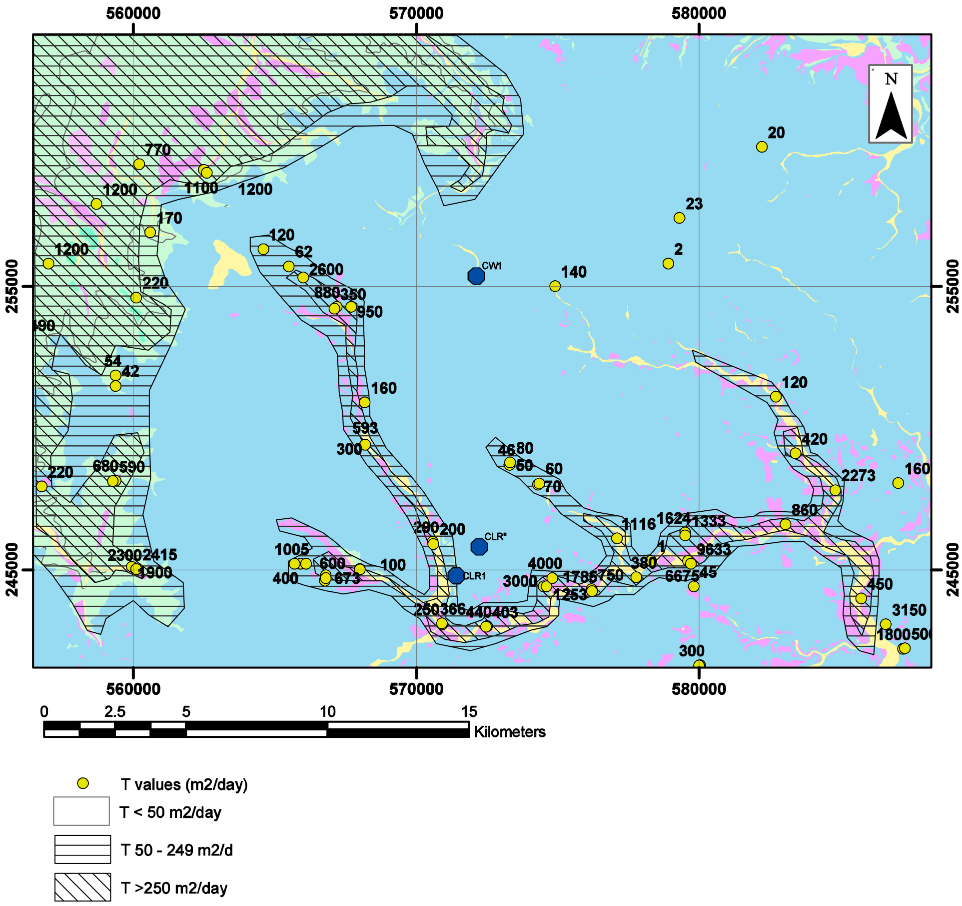


Figure 3.3 Plot of transmissivity distribution across study area

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 $7 \times 10^{-2} - 10^{-3}$ (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 sand and gravel 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). Lewis et al. (1993) estimated 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. They 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 valleys (Figure 3.4), 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 coincides with increasing chalk transmissivity. This presumably reflects greater lateral flow within the aquifer and suggests that recharge is enhanced along the edge of the till sheet.

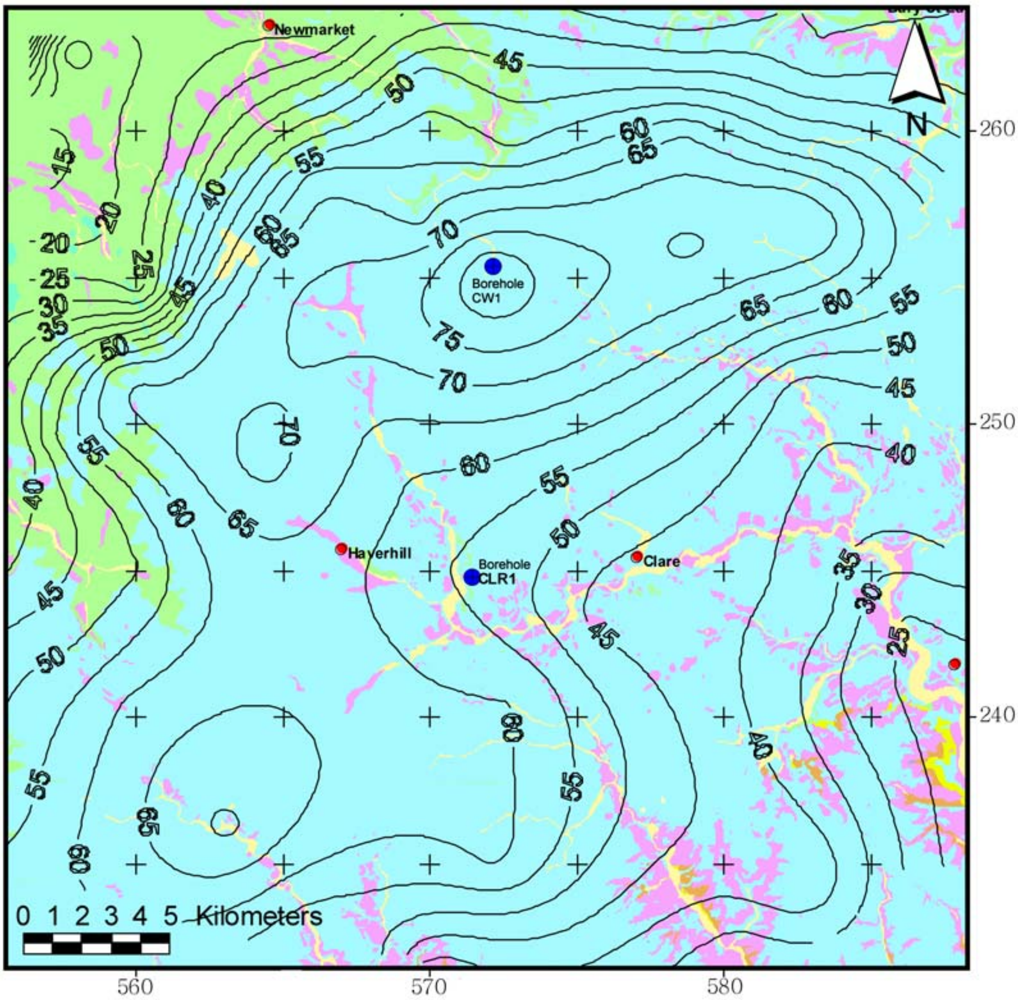
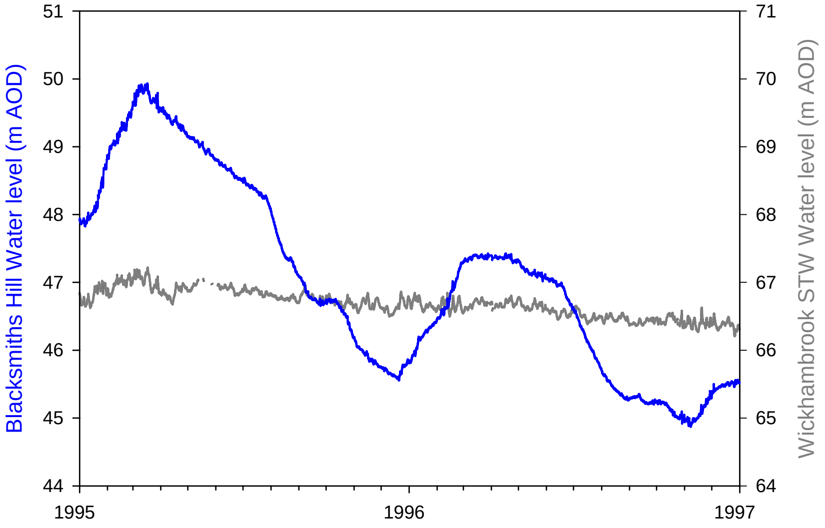


Figure 3.4 Contours of Chalk rest water level, March 1999 (mAOD) (key as Figure 3.1)

Chalk groundwater level fluctuations beneath the interfluve are low and where the till confines the Chalk a seasonal fluctuation of about 0.2 – 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).



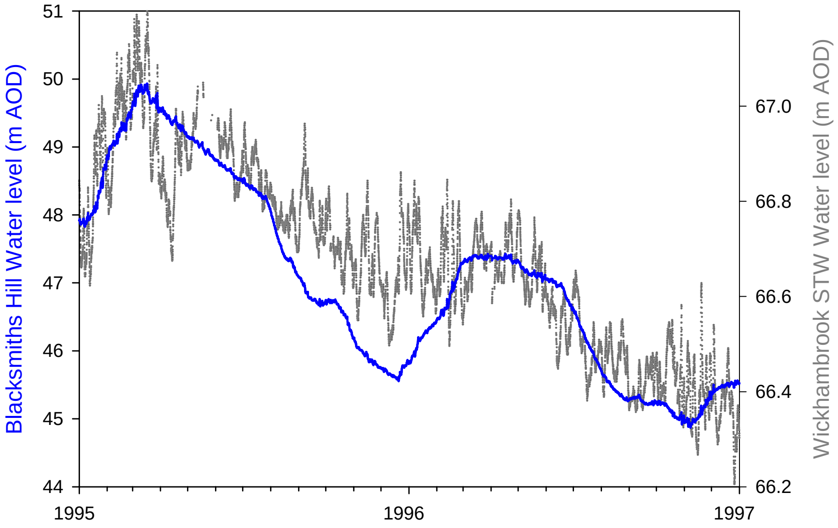


Figure 3.5 Groundwater hydrographs for Blacksmith's Hill borehole (located in a valley side setting) and Wickhambrook STW borehole (located in an interfluve setting)(note different scales)

4 Work Programme

4.1 WORK PROGRAMME OUTLINE

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

1. drill two 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 the Chalk (i.e. is there evidence for modern recharge moving through the till to the Chalk?);
2. determine regional water quality variations by sampling boreholes (EA monitoring boreholes, AWS abstraction boreholes) and to set the data obtained from the research boreholes into a regional context;
3. compare Chalk groundwater hydrographs in the confined and unconfined hydrogeological settings. Monitor groundwater level response within the Chalk and till groundwaters to rainfall events;
4. develop groundwater level models to assess likely recharge characteristics and rates,
5. attempt to quantify recharge rates to the Chalk aquifer through till;
6. develop a conceptual model of the Chalk-till groundwater system, which identifies the recharge components of the groundwater system and the flow pathways.

4.2 CLR1 CORED BOREHOLE AND INSTALLATION

Investigation borehole CLR1 (Figure 4.1) was drilled northwest of Boyton End on an agricultural track between arable fields in November 2000. The borehole is sited in a till edge (valley side) setting and was drilled by the percussion method. The borehole was fully cored by driving U100 tubes to a total depth of 31 m (Figure 4.1), through 21.4 m of superficial deposits and into the unsaturated and upper part of the saturated Chalk. Most of the superficial deposit thickness was unweathered till, but it also included a sequence of sandy gravel and saturated silt between 2.1 and 5.3 mbgl. There was a clayey sand layer beneath the till between 20.5 and 21.4 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 ions, 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 fracture water[1] 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

---

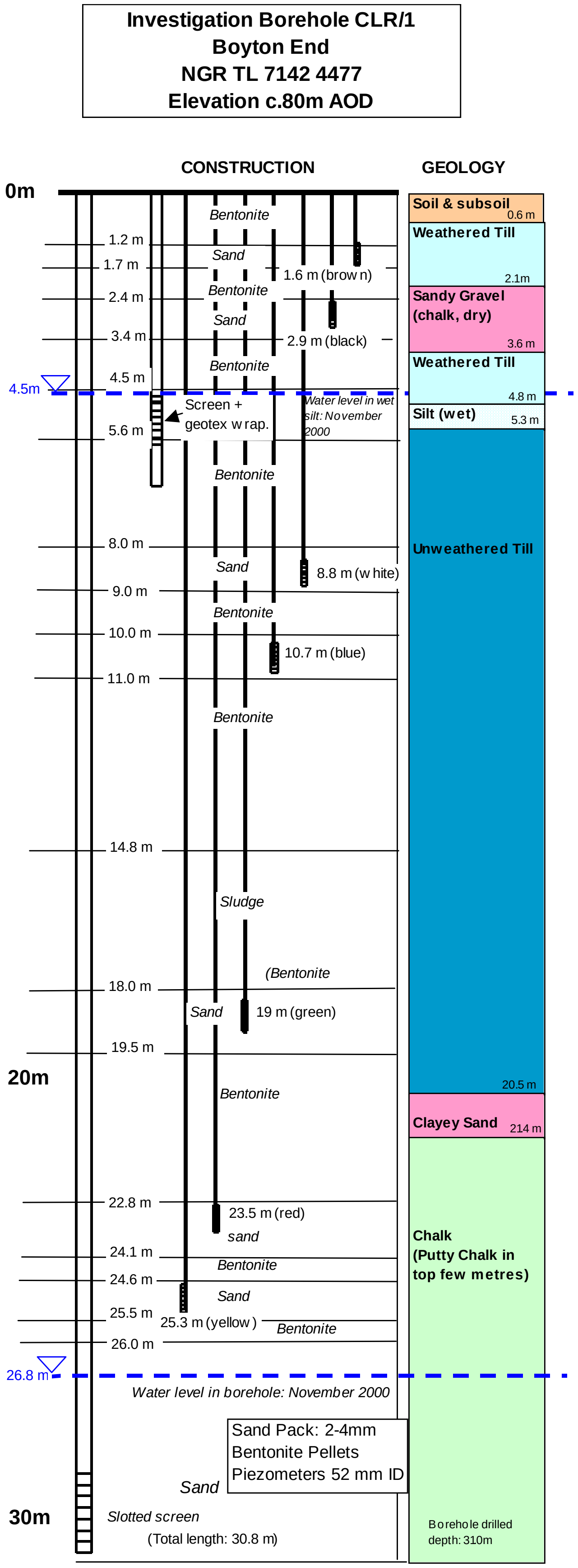
[1] in this report the term ‘fracture water’ refers to the more mobile groundwater flowing through fractures in the saturated zone, which is sampled by pumping.

with a slotted geotextile wrap screen was installed against the wet silt band for the collection of fracture water samples and monitoring of perched water levels in the superficial deposits. The water level in the shallow piezometer was 4.5 mbgl in November 2000, showing the silt seam to be confined. Test bailing showed that the piezometer could be pumped dry after drawing 11 litres and it took 24 hours 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 6 mm 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 4.1) and a further three piezometers are installed within the unweathered till beneath the silt seam. A sixth gas piezometer has been placed within the sandy gravel seam and a seventh positioned within the weathered 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.

A spring occurs down gradient of the borehole and probably forms the outfall of a perched water table within the till. The clayey sand sequence between the base of the till and the Chalk is exposed in a ditch lower down the valley side and gives an approximate elevation of the top of the Chalk of 63 mAOD, which agrees with the geological map (Berridge et a., 1991). This compares with an elevation of 59 mAOD, for the top of the Chalk, in the borehole. The ditch was flowing in November 2000 and water continued to flow across the Chalk outcrop down to the alluvium of the flood plain.



Investigation Borehole CLR/1
Boyton End
NGR TL 7142 4477
Elevation c.80m AOD

Figure 4.1 Geology and construction logs for borehole CLRl

4.3 CW1 PART-CORED BOREHOLE AND INSTALLATION

Investigation borehole CW1 (Figure 4.2) was drilled by the percussion method to a total depth of 80 m, near Cowlinge in February 2003. Representative core samples from both the till and Chalk formations were obtained by driving U100 tubes, though only about a quarter of the total drilled depth was cored.

The core was logged on site and samples of the till (in U100 tubes) were sent to the University of East Anglia (UEA) to support a research project. The till was squeezed at the UEA and the porewater chemistry analysis of major ions was made available to BGS. The Chalk porewaters were extracted by centrifugation and were analysed for major ions, stable isotopes and tritium.

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

(i) permeability 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 testing equipment failed and it was only possible to carry out a short pumping test with a depth interval from 40 to 80 m in the Chalk. The borehole was completed with three monitoring piezometers, one in the till at 6.3 to 10.3 mbgl, and two in the Chalk (46.1 to 50.0 and 70.0 to 74.0 mbgl).

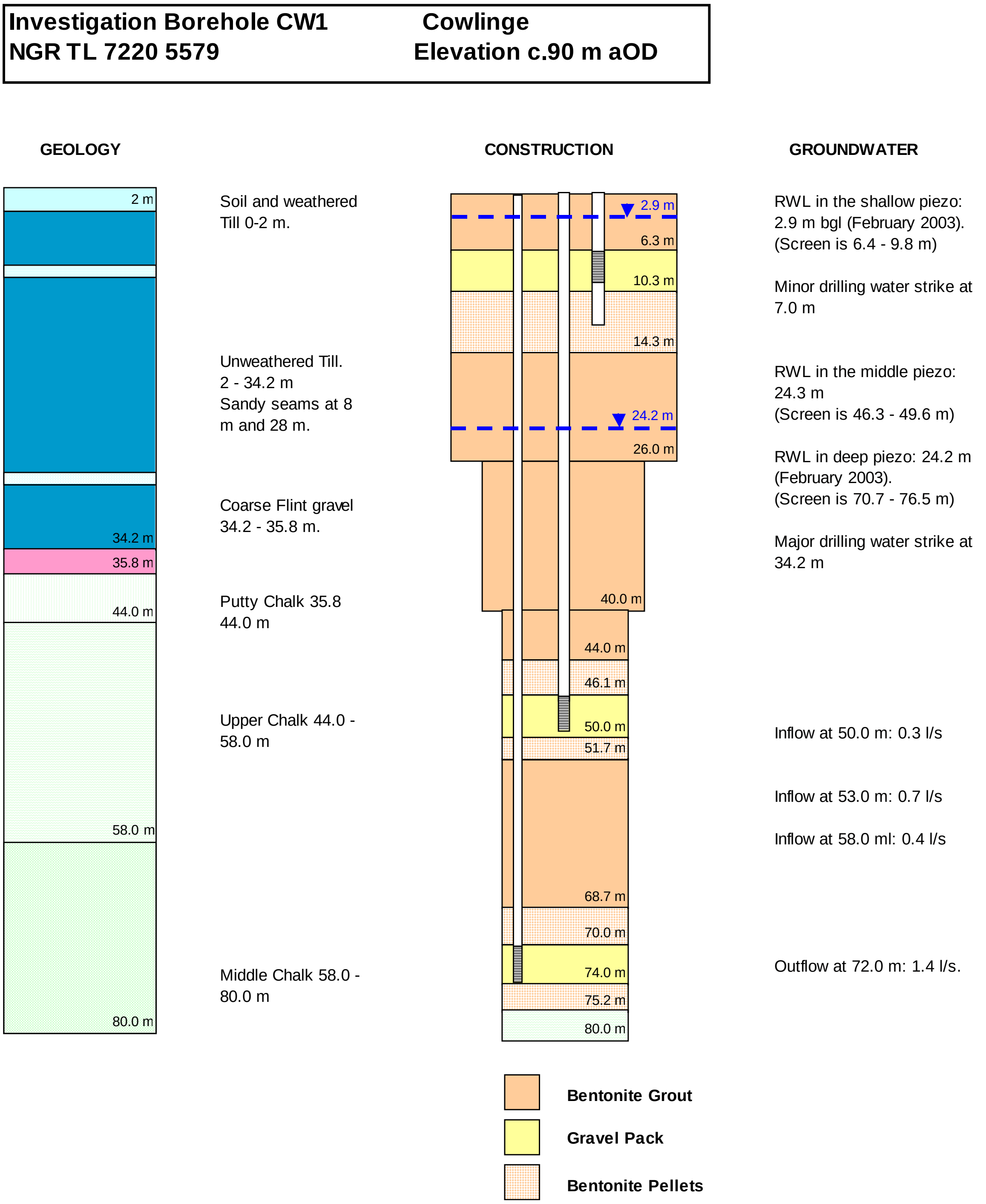


Figure 4.2 Geology and construction logs for borehole CW1

4.4 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, fracture water samples were collected by pump and bailer from the two piezometers over a period of a year. These were analysed for major ions, O and H stable isotopes, δ^{13}C, tritium and CFCs (for dating the water) to characterise the aquifers and to monitor for seasonal variations in water chemistry that might be attributed to recharge. There are seven colour-coded piezometers in the till and Chalk unsaturated zone intended for gas sampling (results of which are not discussed further in this report), two of which (white at 8.8 m, blue at 10.7 m) were subject to flooding and were occasionally sampled for water chemistry.

4.5 REGIONAL WATER CHEMISTRY MONITORING

To set the data collected from the two investigation boreholes in a broader context, fracture water samples were collected from EA monitoring boreholes and from AWS abstraction boreholes. The boreholes sampled are located in a variety of settings including interfluves, valley side and valley floor (Figure 4.3). In addition some surface water samples were also collected.

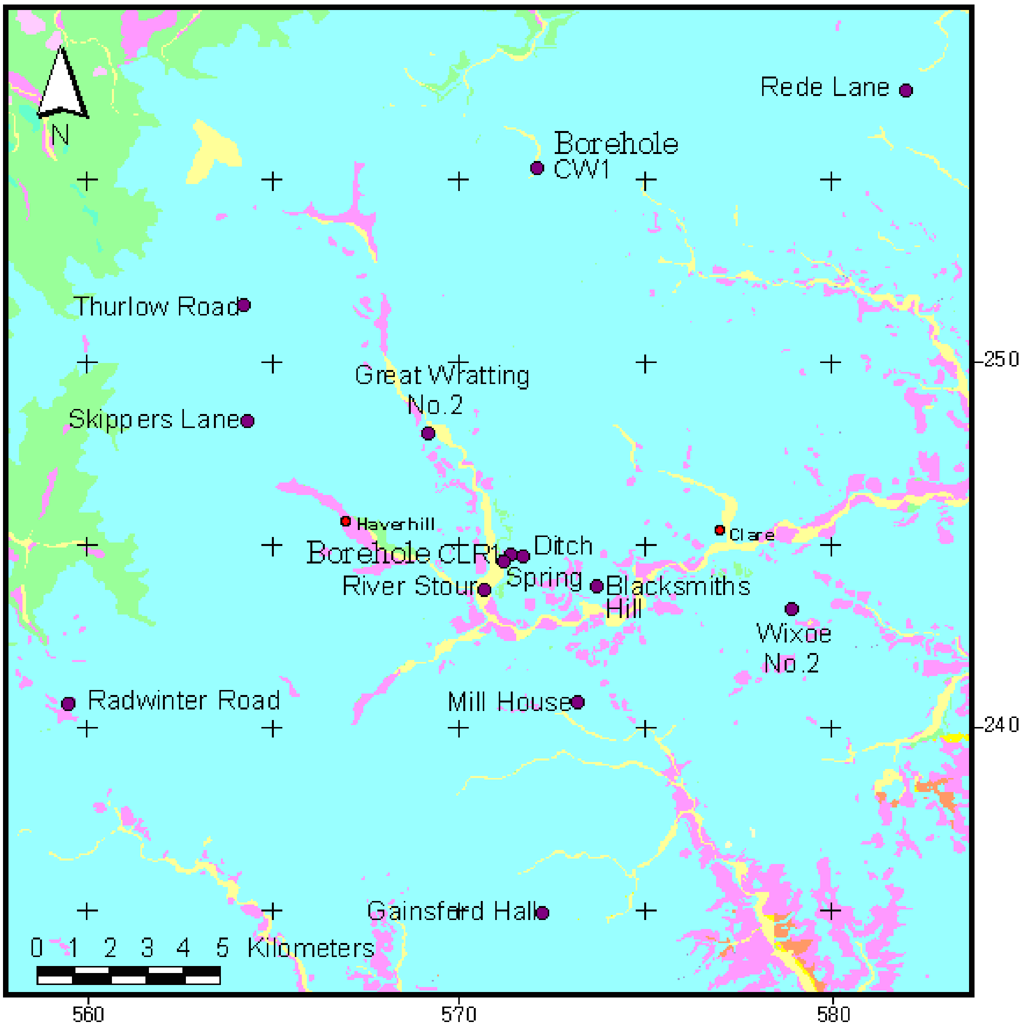


Figure 4.3 Locations of sampling points (key as Figure 3.1)

5 Results

5.1 DRILLING RESULTS: BOREHOLE CLR1

The till in borehole CLR1 can be subdivided into 3 layers (Table 5.1):

- an upper weathered zone that extends to a depth of 5.3 m and includes clay, sandy gravel and silt;
- an unweathered grey clay which extends from 5.3 to 20.5 m depth; and
- a 0.9 m thick basal clayey sand seam.

Table 5.1 Sub-division of till and Chalk at borehole 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 and a value of 1.8×10^{-10} m/s obtained. The bulk 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 and spring. Land drainage will route some infiltration to surface watercourses.
5.3 to 20.5 m	Unweathered (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/s was determined using a triaxial cell. Recharge rates through the matrix are likely to be <1 mm/a. However, if fractures are present the bulk permeability could be significantly higher. No sand lenses were observed in this sequence although such lenses are known to occur within the till elsewhere in this area.
20.5 to 21.4 m	Basal clayey sand	This thin sequence is likely to have a low to moderate permeability that is higher than the overlying till.
21.4 to 31.0 m	Upper Chalk	The Chalk is unconfined and consists of putty chalk in the upper part, which may limit downward water movement to the underlying more permeable zones in the Chalk.

The upper weathered zone at this site is probably of higher permeability than the underlying unweathered till because, (a) the weathered zone includes silt, sand and gravel which can be assumed to be more permeable than clay and (b) it is not uncommon for weathered tills to be fractured (Hendry, 1982). Two consequences of the higher permeability of this layer are, (a) that higher infiltration rates are possible than for the bulk of the till layer, and (b) that some lateral flow within the weathered zone can be anticipated.

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

The permeability of the till matrix is low (Table 5.2). Therefore, for significant quantities of water to be transferred from the near surface to the Chalk aquifer would require fractures to provide a by-pass pathway. The basal clayey sand layer is probably of higher permeability than the overlying clay-rich deposits but is unlikely to transmit much water at this site.

Table 5.2 Triaxial constant flow permeability results of glacial till samples from borehole CLR1

Geological description of till	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	Permeability m/s
Weathered	17.3	2.189	1.866	20	60	8.2	1.8×10^{-10}
Unweathered	14.8	2.174	1.893	74	30	9.9	1.2×10^{-10}
Unweathered	18.3	2.18	1.843	186	20	7.1	1.1×10^{-10}

The till appears to be locally saturated in places with small quantities of water entering the borehole at certain depths during drilling. However, since completion of the borehole most of the gas sampling cells have remained dry.

5.2 DRILLING RESULTS: BOREHOLE CW1

In borehole CW1, at Cowlinge (near the centre of the interfluve), the weathered zone is much thinner (only 2 m thick) and no sand or silt is present (Figure 4.2). The underlying unweathered till (again defined by the colour change from brown to grey) extends from 2 to 34.2 m depth (Table 5.3) and contains two thin sandy seams at 8 and 28 mbgl (Figure 4.2). The till is saturated, with some water entering the borehole overnight during drilling.

Table 5.3 Subdivision of till (and Chalk) for borehole CW1

Depth (mbgl)	Geology	Hydrogeological significance
0 to 2 m	Upper weathered (oxidised) till zone	The intergranular permeability of the weathered till is probably similar to that measured in borehole CLR1 (1.8×10^{-10} m/s). This near-surface zone will 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 to 34.2 m	Unweathered (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 will be low, similar to that measured in CLR1 (1.1 to 1.2×10^{-10} m/s). The bulk permeability of this layer could be higher if fractures are present. The sandy bands at 8 m and 28 m appeared saturated during drilling and limited lateral groundwater flow within these bands is possible.
34.2 to 35.8 m	Basal gravel	This thin sequence was saturated during drilling with a piezometric surface at about 24.2 mbgl. It will 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 about 24.2 mbgl. The putty Chalk in the upper part can act to limit groundwater movement, although the main Chalk aquifer below appears to be in hydraulic continuity with the gravel above.

The basal gravels were saturated and relatively “clean” (containing a low proportion of fine-grained material) and, therefore, will have a 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 (Appendix 1).

5.3 WATER CHEMISTRY: BACKGROUND

5.3.1 Sampling

Porewater samples were collected by squeezing (till) or centrifugation (Chalk). Neither of these techniques is considered to cause significant fractionation in chemical or isotopic terms.

Fracture waters were sampled by bailing or pumping. Samples for chemical analysis were passed through a 0.45 µm filter before being divided into acidified and unacidified aliquots and stored in Nalgene bottles. Samples for isotopic analysis were collected unacidified and stored in airtight glass bottles. Chlorofluorocarbon (CFC) samples were collected into glass bottles without atmospheric contact.

5.3.2 Analysis

Cations and SO_4 were determined on acidified sample aliquots by inductively-coupled plasma optical emission spectroscopy. Anions were measured by automated colorimetry or titrimetry, on the unacidified aliquots. Stable isotopes were analysed by mass spectrometry following standard preparation methods (CO_2 equilibration for $\delta^{18}O$, zinc reduction for δ^2H, and acidification with phosphoric acid for $\delta^{13}C$-DIC). CFCs and SF_6 were analysed by gas chromatography after pre-concentration by cryogenic methods.

5.3.3 Interpretation

The chemistry of Chalk and other groundwaters is well characterised and reasonably well understood in terms of the distribution of major elements, stable isotopes and tritium. The CFC groundwater dating technique, on the other hand, is less familiar. Concentrations of 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 years old) and ‘modern’ recharge (within the past few years) is often assumed for simplicity. This latter interpretation is usually preferred for fractured aquifers as they are considered more likely to promote mixing than in a aquifer where simple intergranular flow occurs.

5.4 WATER CHEMISTRY RESULTS: BOREHOLE CLR1

The water chemistry data (major ion, stable isotope and CFC) for borehole CLR1 and other sampling locations are presented in Appendix 2.

5.4.1 Till waters

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) (Table 5.4), have high nitrate concentrations (12 to 100 mg N/l), and bicarbonate usually accounts for less than half of the total anions (Figure 5.1). Chloride concentrations are high (110 to 400 mg/l) as are the sulphate concentrations (150 – 800 mg/l). Fracture water sampled from the shallow piezometer, which is screened against the silt and the weathered till layer, is of similar chemistry to the weathered till porewaters. The nitrate and chloride (and possibly some of the sulphate) in the weathered till is likely to be of anthropogenic origin;

(ii) the porewaters in the unweathered till below 8 m are relatively old (^{3}H ~1 TU) (Table 5.4) suggesting pre-1960 water, and nitrate concentrations are mostly below 1 mg N/l. Chloride concentrations are mostly below 50 mg/l and the sulphate concentrations have generally increased and become more variable than in the overlying weathered zone (25 to 1500 mg/l). Calcium accounts for between 70 and 90% of the total cations. These porewaters trend along a line from bicarbonate- to sulphate-dominated, with chloride accounting for <10% of the total anions (Figure 5.2). 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 unweathered 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.

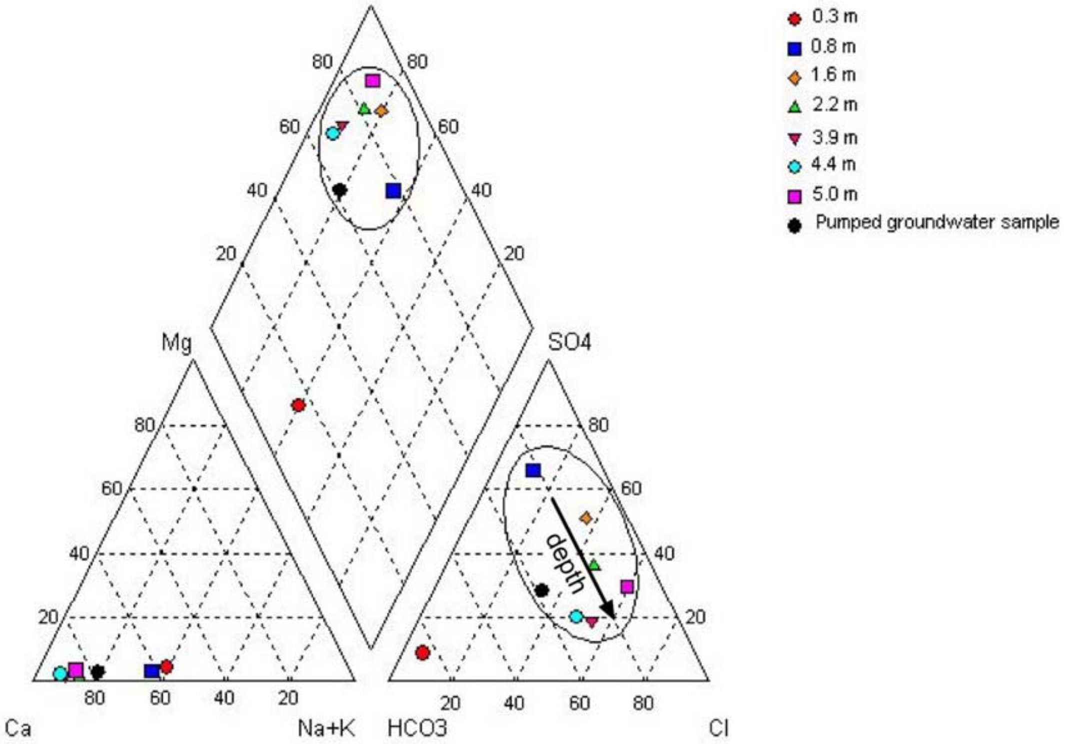


Figure 5.1 Piper diagram, borehole CLR1 weathered till porewaters

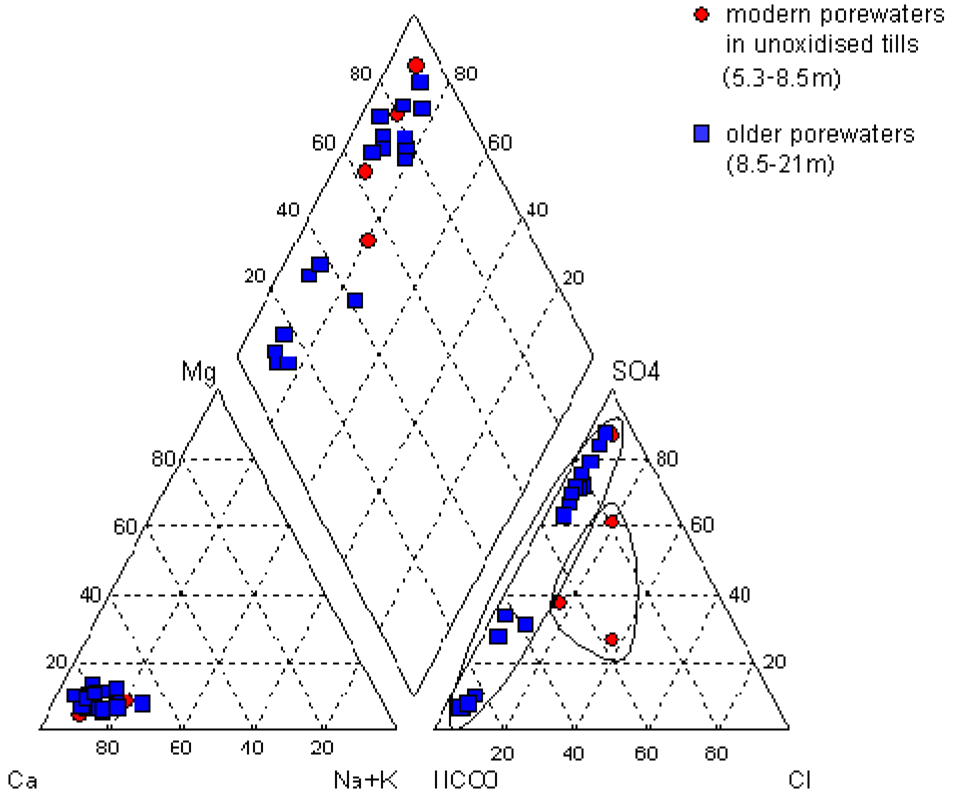


Figure 5.2 Piper diagram, borehole CLR1 unweathered till porewaters

5.4.2 Chalk waters

The underlying Chalk porewaters are mostly of the Ca-HCO_3 type but show a trend of increasing sulphate concentrations with depth (Figure 5.3 and 5.4). These porewaters are relatively old, pre-1960 (<1 TU) and have low nitrate concentration (<2 mg N/l).

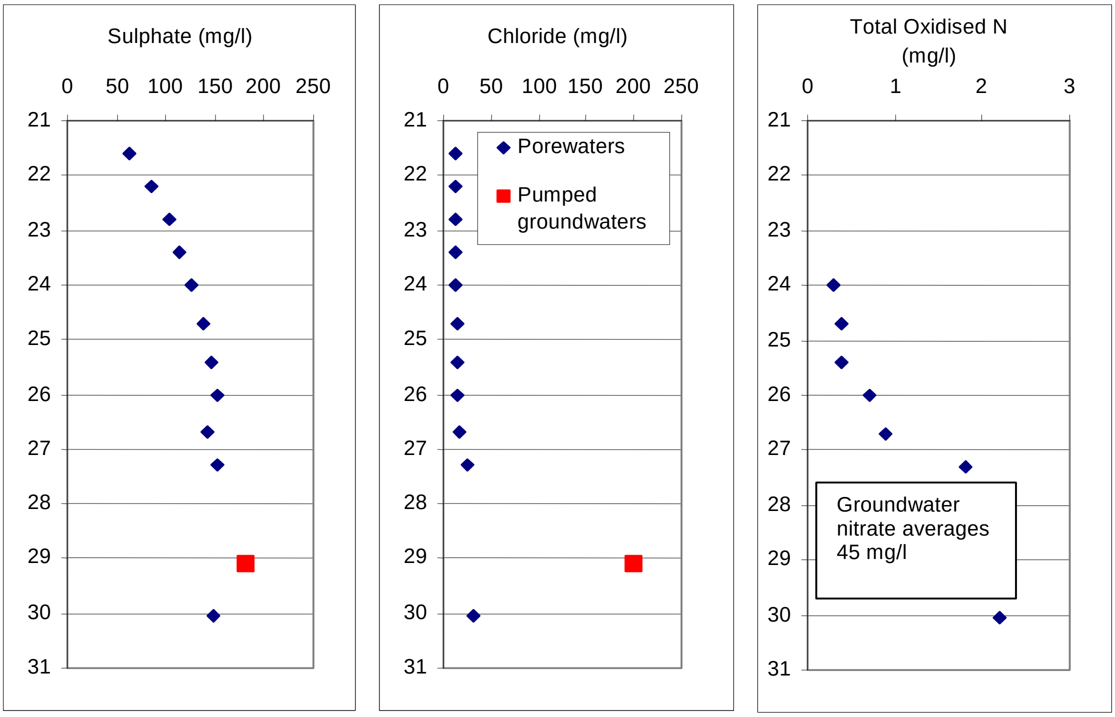


Figure 5.3 Borehole CLR1 Chalk porewater profiles and fracture water concentrations SO_4, NO_3, Cl

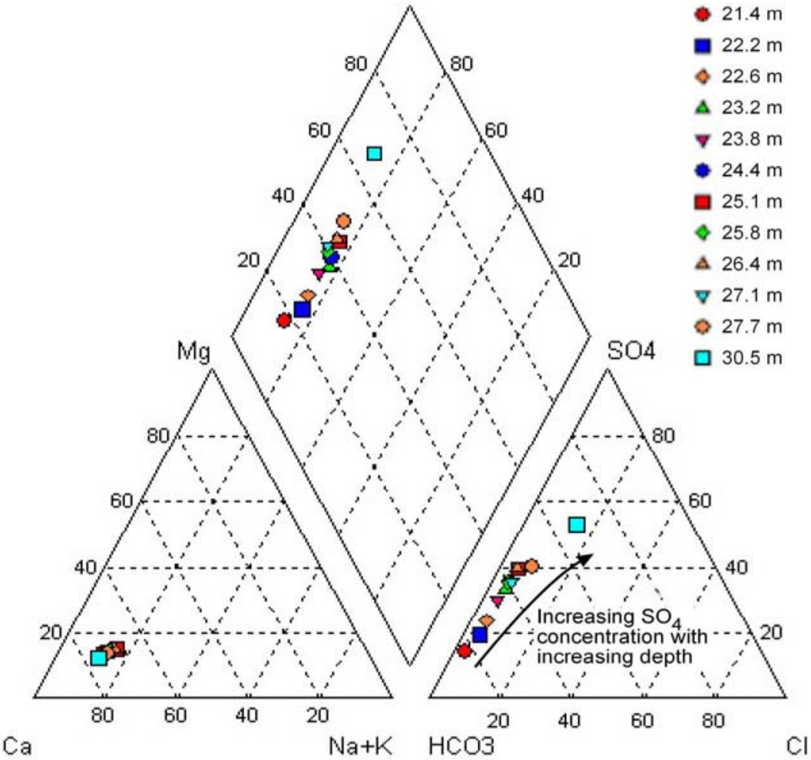


Figure 5.4 Piper diagram, borehole CLR1 Chalk porewaters

Borehole CLR1 penetrated the unsaturated zone and the upper part of the zone of water table fluctuation. As a consequence only the lower part of the sequence penetrated by CLR1 comes into contact with mobile fracture water and then only on a seasonal basis during periods of high groundwater levels. The mobile Chalk fracture waters are different to the porewaters; they are modern (Table 5.4), have high nitrate concentrations (average 45 mg N/l), and chloride and sulphate concentrations are also relatively high (Table 5.5). 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 and the Chalk matrix in the unsaturated zone.

Table 5.4 CFC data from Borehole CLR1 (see Appendix 2) interpreted in terms of recharge year (piston flow) or modern fraction (mixing).

Site	**Date**	**CFC-12**	**CFC-11**	**CFC-12**	**CFC-11**
		year of recharge (piston)		**modern fraction (mixing)**	
CLR1 Chalk	Dec-02	>modern	1986	1.14	0.84
CLR1 Chalk	Jan-03	1990	1981	0.89	0.70
CLR1 Chalk	Feb-03	1988	1984	0.86	0.79

Table 5.5 Summary of porewater and fracture water chemistry for borehole CLR1

Depth	**Geology**	**Porewater chemistry**	**Fracture water chemistry**
0 m	Weathered (oxidised) till	Modern water: Ca 340-380 mg/l Cl 110-400 mg/l SO_4 150-800 mg/l NO_3-N 12-100 mg/l Tritium >15 TU	Modern water:: Ca 330-370 mg/l Cl 200-280 mg/l SO_4 200-400 mg/l NO_3-N 30-55 mg/l Tritium ~26 TU
5.3 m	Unweathered (unoxidised) till	Modern water penetrates upper part of unweathered till	
8.0 m		Pre-1960 water: Ca 110-850 mg/l Cl 10-60 mg/l SO_4 25-1500 mg/l NO_3-N <0.2-4.0 mg/l Tritium ~1 TU	Pre-1960 water: Ca 140-210 mg/l Cl 30-90 mg/l SO_4 240-640 mg/l NO_3-N 0.7 mg/l Tritium ~1 TU
21.4 m 31.0 m	Upper Chalk	Pre-1960 water: Ca 100-125 mg/l Cl 12-25 mg/l SO_4 90-150 mg/l NO_3-N <0.2-1.8 mg/l Tritium ~1 TU	Modern water: Ca 250-310 mg/l Cl 190-230 mg/l SO_4 180-200 mg/l NO_3-N 30-50 mg/l Tritium ~23 TU

There is an increase in porewater sulphate with depth in the Chalk (Figure 5.4), which may result from diffusion exchange between porewater and fracture water at times of high water table. Sulphate concentrations may increase with depth because the deeper porewaters have had longer contact time with the fracture waters. However, if this were the case, a similar trend in porewater chloride and nitrate concentrations would be expected, as these too are higher in the fracture water. Porewater chloride and nitrate concentrations do increase with depth, but fracture water concentrations of these solutes are still much higher than the porewater concentrations at an equivalent depth (Figure 5.3). The smaller difference in sulphate concentrations between porewaters and fracture water compared to nitrate and chloride could be because fracture water 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.

5.5 WATER CHEMISTRY RESULTS: BOREHOLE CW1

Fewer porewater samples were obtained from borehole CW1 than borehole CLR1.

5.5.1 Till waters

The few analyses of the weathered till porewater suggest that concentrations of calcium are the range 140 to 180 mg/l and sulphate in the range 300 to 550 mg/l. In the underlying unweathered till porewaters, both ions have increased in concentration markedly. This suggests that sulphate dissolution is a major control on the water chemistry. High sulphate concentrations in till porewaters are not unexpected: the clay often contains disseminated pyrite, the oxidation of which releases sulphate ions. This was also seen in borehole CLR1. Samples of fracture water from the unweathered till were obtained from the shallow (6.3 to 10.3 m) piezometer. They show old water with low nitrate concentrations (Table 5.5) and a relatively small fraction of modern water (20 to 30% modern as determined by CFC analysis). The chloride concentration is relatively high and the sulphate is relatively low compared to the porewater.

5.5.2 Gravel waters

The gravel layer between the till and the Chalk was coarse-grained. Porewaters were drained from the gravel samples and the fracture water was sampled during drilling. The fracture water samples were of similar chemistry to the Chalk porewater and fracture water and unlike the till porewater with low nitrate (<0.2 mg N/l). The chloride and bicarbonate concentration are relatively high up to 105 mg/l and 355 mg/l respectively, but the sulphate is relatively low at 280 to 350 mg/l.

5.5.3 Chalk waters

The Chalk porewaters in borehole CW1 are very different from those in borehole CLR1. They are relatively old (~1 TU), have low nitrate concentrations (<0.2 mg N/l) and high sulphate concentrations (350 – 510 mg/l). These Chalk porewaters resemble the porewaters in the unweathered till from borehole CLR1 (Table 5.6, Figure 5.2 and 5.5). The pumped Chalk fracture waters are chemically similar to the Chalk porewaters (Table 5.5 and Figure 5.5) and are presumably in equilibrium. Interpretation of CFC data indicates the presence of <20% modern water (Table 5.7). The relatively high ratios of Mg/Ca and Sr/Ca are characteristic of incongruent dissolution, suggesting a residence time of the order of 10^2 to 10^3 years for the major part of the water. This is consistent with a slow ‘piston flow’ recharge mechanism through the till.

Table 5.6 Summary of porewater and fracture water chemistry for borehole CW1

Depth	Geology	Porewater chemistry	Fracture water chemistry
0 m	Till upper weathered (oxidised) zone	Modern water: Ca 140-180 mg/l SO_4 300-550 mg/l	
2.0 m	Unweathered (unoxidised) till zone with sandy seams at 8 and 28 m	Pre-1960 water: Ca 600-900 mg/l SO_4 2800-4900 mg/l	Pre-1960 water: Ca 185 mg/l Cl 100 mg/l SO_4 245-270 mg/l NO_3-N <detection CFCs 20-30% modern
34.2 m	Basal gravel	Pre-1960 water: Ca 190-400 mg/l Cl 50-60 mg/l SO_4 500-1100 mg/l NO_3-N <detection	Pre-1960 water: Ca 200 mg/l Cl 105 mg/l SO_4 280-350 mg/l NO_3-N <detection
35.8 m To 80.0 m	Upper and Middle Chalk	Pre-1960 water: Ca 170-230 mg/l Cl 40-60 mg/l SO_4 380-510 mg/l NO_3-N <detection Tritium ~1 TU	Pre-1960 water: Ca 240-250 mg/l Cl 50 mg/l SO_4 460-480 mg/l NO_3-N <detection Tritium ~1 TU CFCs <20% modern

Table 5.7 CFC data from Borehole CW1 (see Appendix 2) interpreted in terms of recharge year (piston flow) or modern fraction (mixing).

Site	CFC-12	CFC-11	CFC-12	CFC-11
	year of recharge (piston)		modern fraction (mixing)	
Cowlinge Pump Test 1a Sample 1	1967	1968	0.17	0.18
Cowlinge Pump Test 1b sample 1	1969	1967	0.21	0.14
Cowlinge Pump Test 1a Sample 2	1966	1965	0.15	0.1
Cowlinge Pump Test 1b sample 2	1966	1965	0.15	0.11
Cowlinge Pump Test 2a	1967	1965	0.18	0.11
Cowlinge Pump Test 2b	1967	1966	0.16	0.12
Cowlinge pumped piezo sample 1	1972	1970	0.31	0.22
Cowlinge pumped piezo sample 2	1973	1971	0.34	0.25

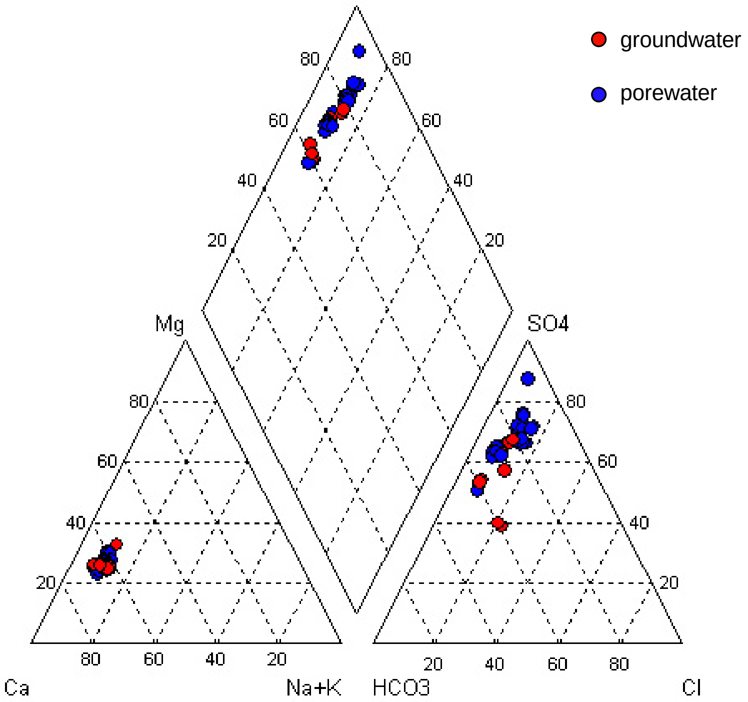


Figure 5.5 Piper diagram, borehole CW1 Chalk porewaters and fracture waters

5.6 REGIONAL WATER CHEMISTRY SURVEY

The results of the regional water chemistry survey are presented in Appendix 2. The fracture waters show considerable variability both in water type (Figure 5.6) and in apparent residence time (Table 5.8). However, a pattern can be discerned (Figure 5.7 and Figure 5.8) 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 N/l) and appear to be relatively old waters (high Sr/Ca ratio, higher Mg/Ca ratio, and proportion of modern water is usually <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 (>0.10) 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% based on CFC measurements) and are largely derived from rainfall of the last few decades.

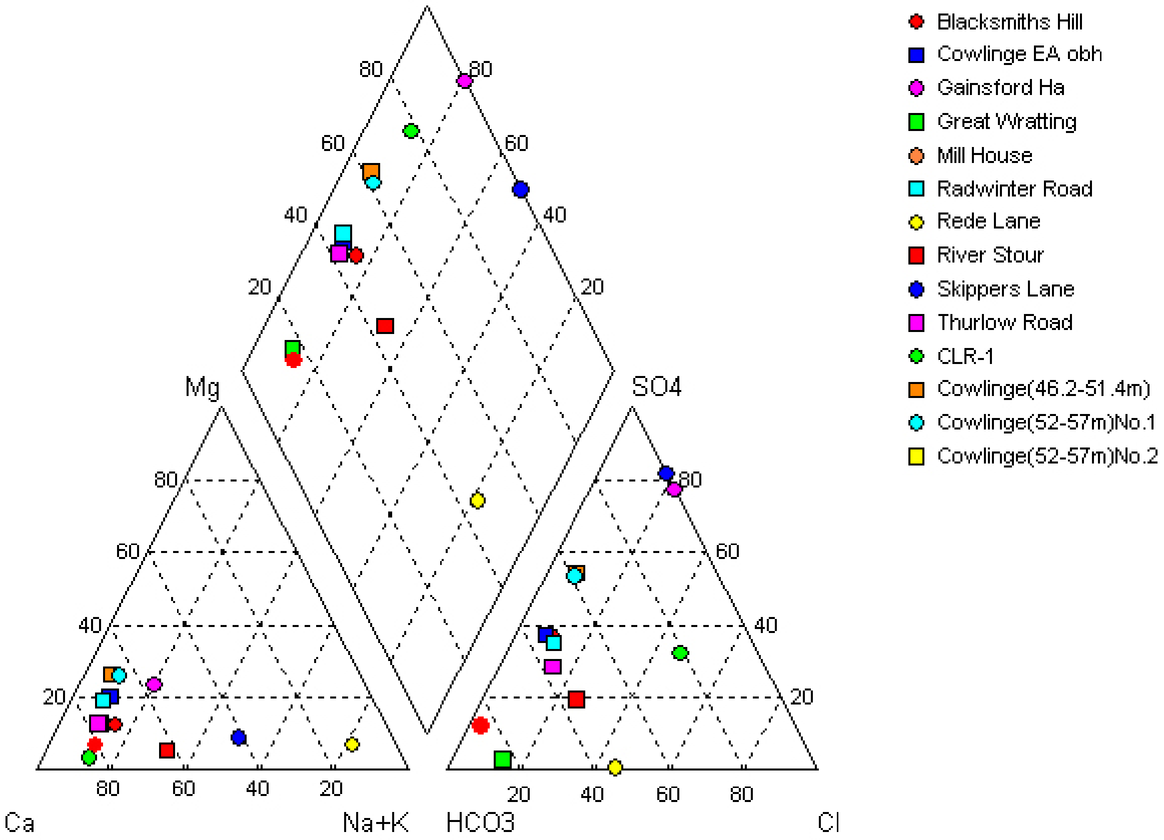


Figure 5.6 Piper diagram, regional water quality survey

Table 5.8 CFC data from regional boreholes (see Appendix 2) interpreted in terms of recharge year (piston flow) or modern fraction (mixing).

Site	**Date**	**CFC-12**	**CFC-11**	**CFC-12**	**CFC-11**
		year of recharge (piston)		**modern recharge (mixing)**	
Blacksmith's Hill	Jun-02	modern	1986	1.02	0.86
Blacksmith's Hill	Aug-02	1989	1983	0.87	0.74
Blacksmith's Hill	Oct-02	1985	1984	0.74	0.77
Blacksmith's Hill	Nov-02	1984	1984	0.71	0.79
Blacksmith's Hill	Dec-02	1985	1979	0.75	0.62
Mill House	Jun-02	>modern	1967	1.17	0.14
Mill House	Aug-02	1957	1968	0.13	0.17
Mill House	Oct-02	1988	1963	0.84	0.07
Mill House	Nov-02	1988	1986	0.85	0.89
Mill House	Dec-02	modern	1969	1.01	0.20
Mill House	Jan-03	1978	1973	0.52	0.37
Mill House	Feb-03	1970	1970	0.26	0.24
Great Wratting No. 1	Oct-02	>>modern	>>modern	10.2	4.3
River Stour	Oct-02	modern	modern	1.00	1.00
Rede Lane	Jan-03	1980	1965	0.58	0.10
Gainsford Hall	Jan-03	1967	1961	0.15	0.05
TL75/072	Feb-03	1960	1965	0.06	0.11
Radwinter Rd	Feb-03	1963	1965	0.09	0.10
Skippers Lane	Feb-03	1982	1963	0.66	0.06
Thurlow Road	Feb-03	1962	1966	0.08	0.11

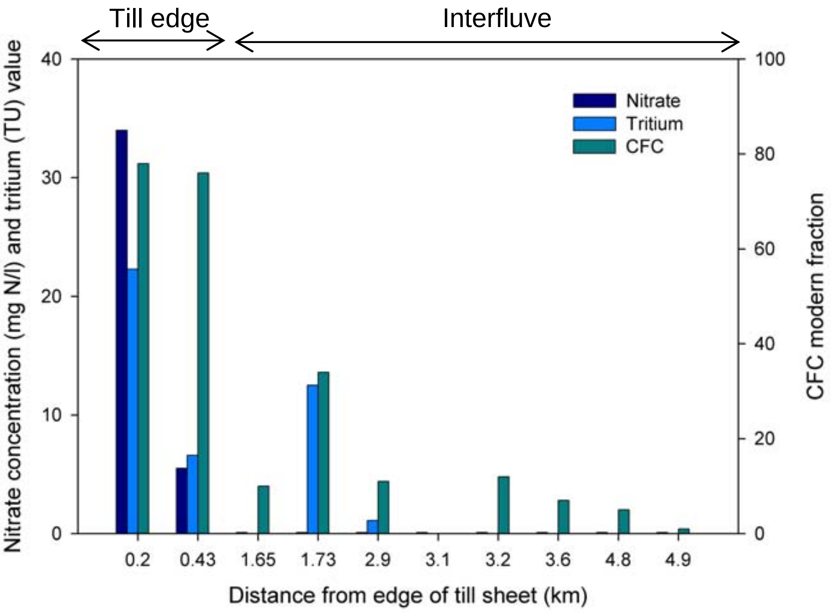


Figure 5.7 Variation in Chalk groundwater NO_3, ^3H and CFC concentrations with distance from edge of till sheet

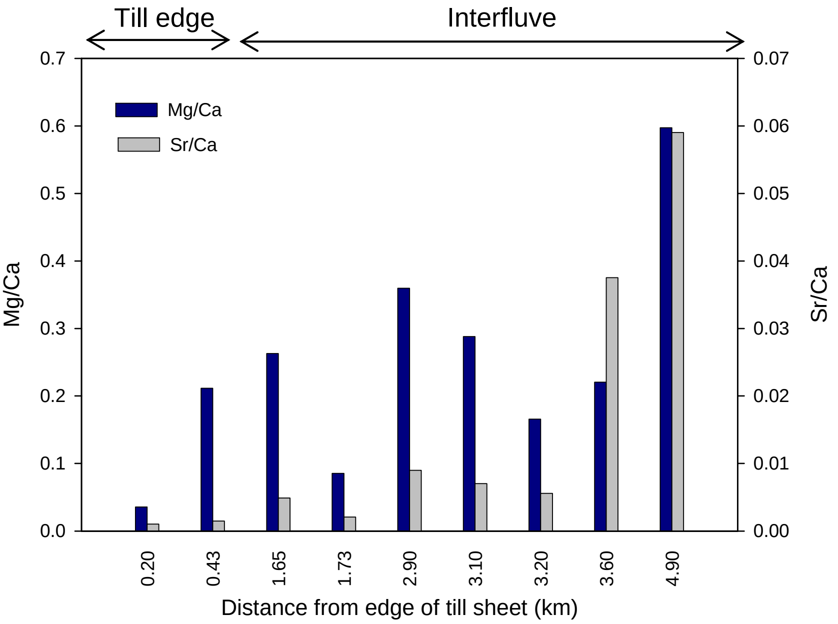


Figure 5.8 Variation in Chalk groundwater Mg/Ca and Sr/Ca ratios with distance from edge of till sheet

5.7 GROUNDWATER LEVEL MONITORING

Groundwater level monitoring at borehole CLR1 shows a similar water level response to rainfall for both the Chalk and shallow till piezometers (Figure 5.9 and 5.10). The borehole CLR1 site is in a valley side – till edge setting.

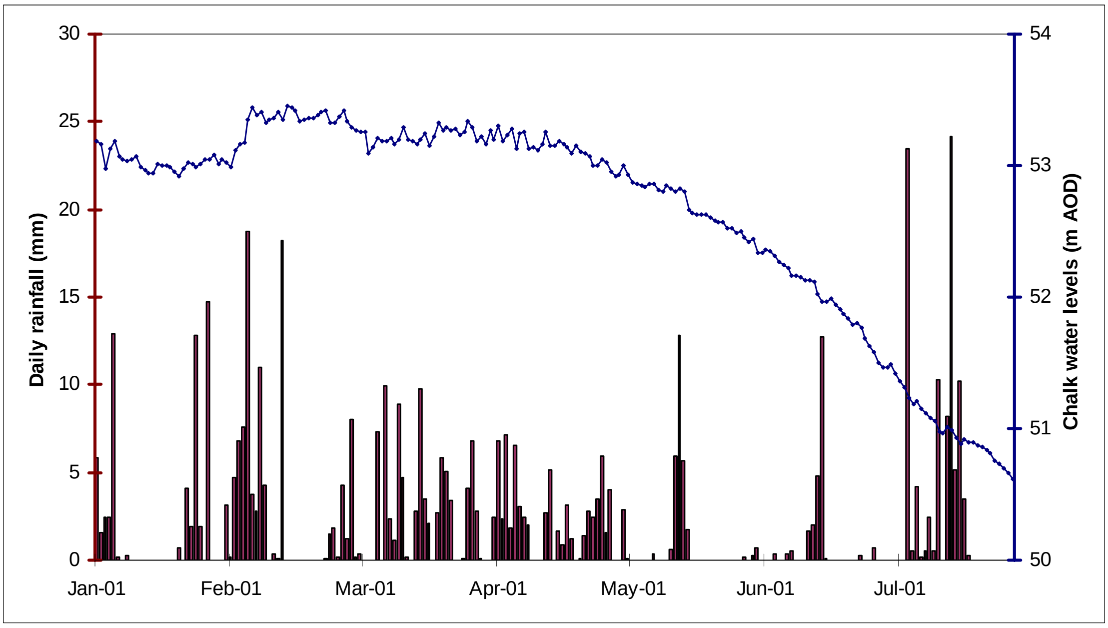


Figure 5.9 Comparison between groundwater levels in Chalk (borehole CLR1) and rainfall

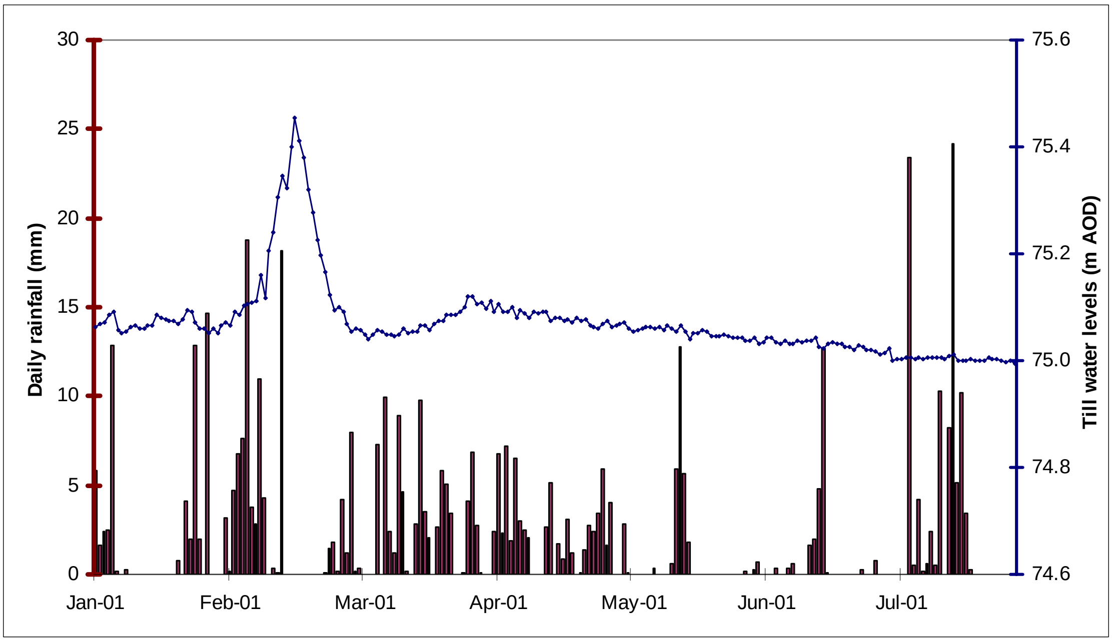


Figure 5.10 Comparison between groundwater levels in till (borehole CLR1) and rainfall

Chalk hydrographs obtained from EA monitoring data show a similar seasonal fluctuations of 2 to 4 m for boreholes located in the valley side settings, but only about 0.2 to 0.3 m for boreholes located on the interfluves and where the aquifer is confined (Figure 3.5).

5.8 GROUNDWATER LEVEL MODELLING

Two types of groundwater model were used on this project:

(i) 1-D spreadsheet model

(ii) Numerical groundwater flow model

The first was a 1-D spreadsheet model which was used to test the sensitivity of Chalk groundwater levels to differences in Chalk transmissivity and recharge along a flow path from the interfluve to the River Stour. The second was a numerical groundwater flow model which was used to investigate spatial and temporal variations in groundwater recharge rates.

5.8.1 SPREADSHEET MODEL

The purpose of this model was to assess what recharge rates are reasonable, for realistic aquifer transmissivity, to test whether low infiltration rates (<10 mm/a) could account for the elevated Chalk groundwater levels observed beneath the interfluves. A vertical slice model was constructed down a flowpath from the groundwater divide to the River Stour using contoured EA groundwater level data for March 1999 (Figure 3.4). This spreadsheet model predicted steady state for a range of realistic Chalk transmissivities and recharge rates along the flow path when compared to the groundwater level data. Details of this 1-D spreadsheet model and the parameters used are given in Appendix 3. The results are presented in Figure 5.11 and these suggest that recharge rates in the range 5 to 10 mm/a could produce elevated Chalk groundwater levels, similar to those observed, beneath the interfluve for realistic Chalk transmissivity values. A recharge rate of 20 mm/a, however, would appear to be too high as this would require Chalk transmissivities beneath the interfluve to exceed 35 m^2/d.

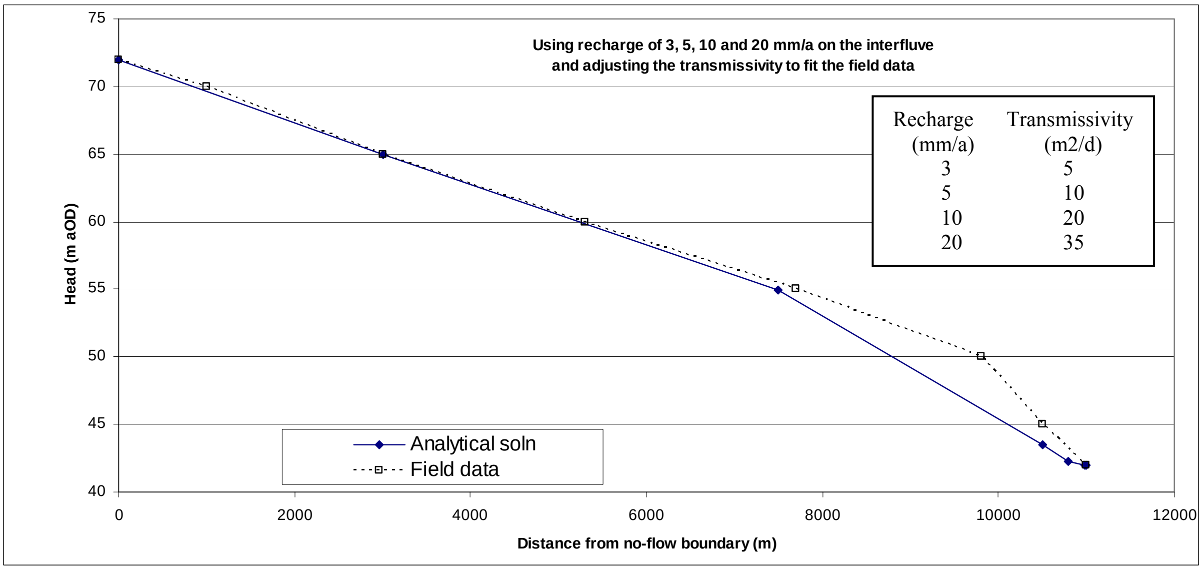


Figure 5.11 1-D spreadsheet model (best fit)

5.8.2 NUMERICAL GROUNDWATER FLOW MODEL

A numerical groundwater flow model, ZOOMQ3D (Jackson, 2001), was used to determine likely recharge rates to the Chalk aquifer both through the till on the interfluves and directly into the Chalk in the valleys (Mansour, 2004). A vertical slice through the Chalk aquifer from the groundwater divide to the river was considered. The model output, hydraulic head, was compared with observed Chalk groundwater level inputs for a range of realistic values for aquifer parameters (permeability and specific storage) and recharge rates. A best fit was obtained when using recharge values of 5 mm/a over the Chalk beneath the interfluves and 300 mm/a in the valley (Figure 5.12). This fit was achieved by using a maximum horizontal permeability in the valleys of 6.0 m/d and a horizontal permeability under the interfluves ranging from 0.05 to 0.8 m/d. Full details have been presented by Mansour (2004).

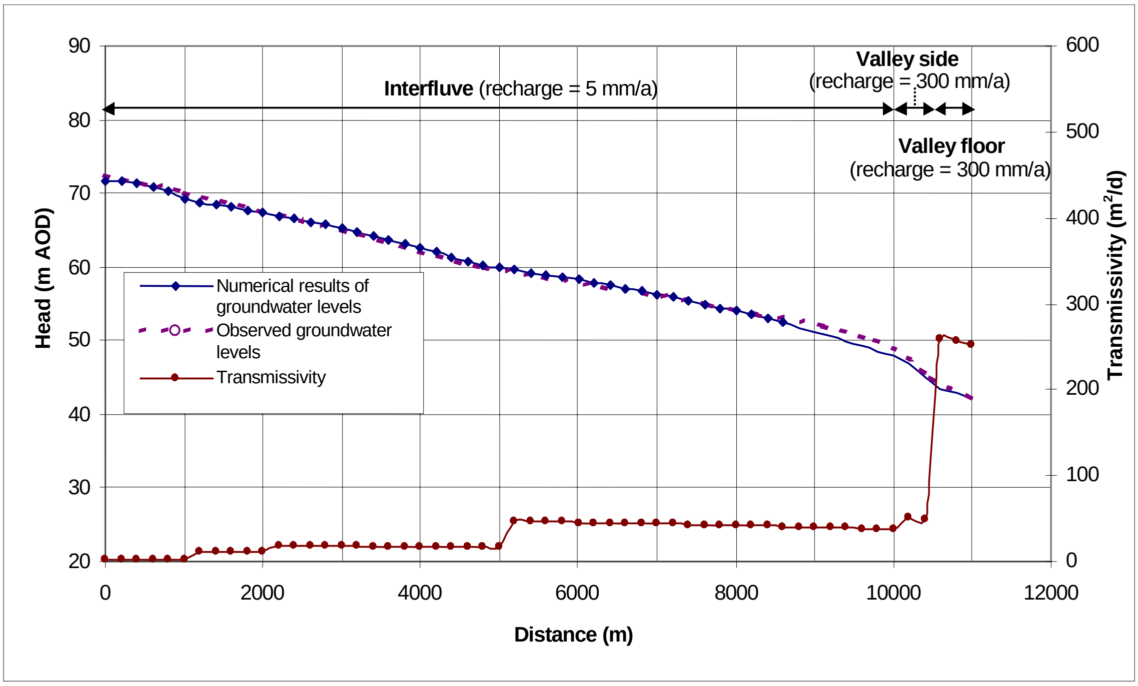


Figure 5.12 ZOOMQ3D model output compared with observed groundwater profiles

The model was also used to investigate the response of groundwater heads to seasonal variation in recharge within the valley. The model initially assumed recharge beneath the interfluves was constant (with time) at 5 mm/a and that recharge in the valley was 300 mm/a and occurred over a 5-month period (November to March). The model produced a reasonable fit for groundwater hydrographs in the valley side but produced a more subdued seasonal fluctuation (millimetres instead of 0.3 m) for the Chalk hydrographs beneath the interfluves. This suggests that our initial conceptual model is wrong. Further, if the Chalk groundwater levels beneath the interfluve respond to head changes in the valley there should be a time lag of 200 days (Mansour, 2004). However, no time lag was observed between the Chalk water level response in the valley and beneath the interfluve.

The possibility of a seasonal fluctuation in recharge beneath the interfluve was also considered; a small seasonal change in recharge rate (c. 1%) beneath the interfluve could produce the observed fluctuations of about 20–30 cm. One possible mechanism which could produce a seasonal variation in recharge is a variation in the till groundwater level (beneath the interfluves) in response to rainfall recharge, which would increase the vertical gradient during periods of excess rainfall.

6 Discussion

6.1 PHYSICAL MODEL

The Chalk-till system can be conveniently subdivided into three physical settings: the valley floor, the valley side and the interfluve (Figure 6.1). The valley floor, which is flat, is typically 200 to 400 m wide (although it can be up to 600 m wide), and is usually underlain by fluvial deposits and Chalk. This setting accounts for about 10 to 20% of the total catchment area.

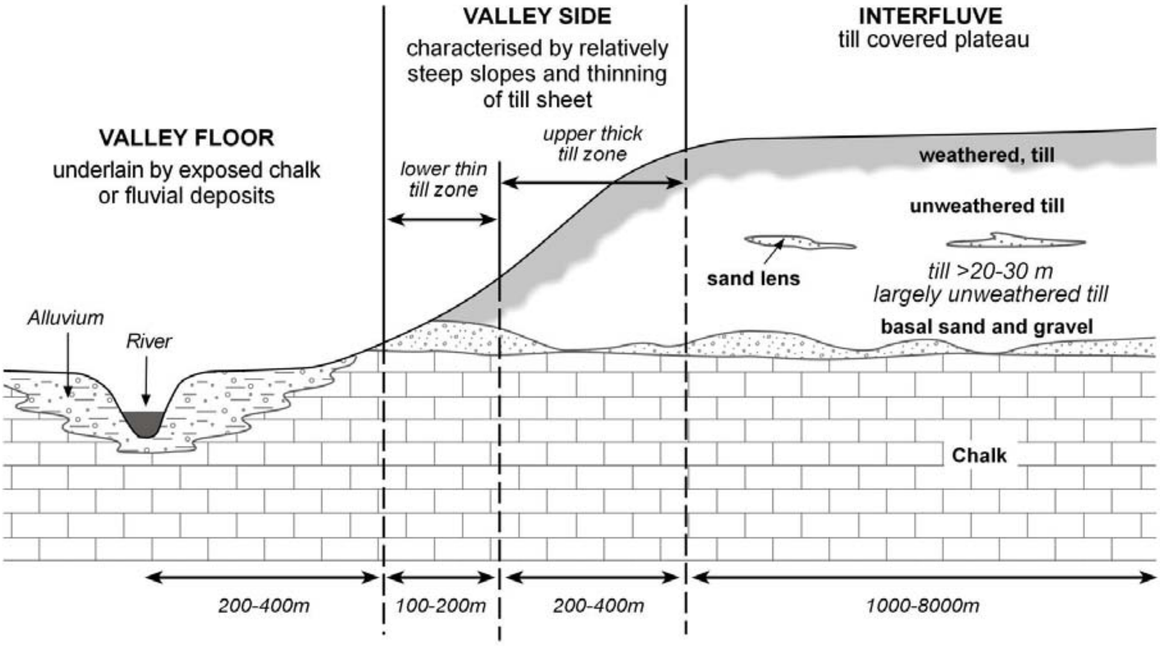


Figure 6.1 Schematic geological section

The valley side is subdivided between the upper and lower valley slopes. On the lower slopes the till is usually less than 10 m thick, of which unweathered till is only a small component. The slopes are usually gentle on this thin till zone which accounts for about 10% of the catchment and is typically between 100 to 200 m wide. On the upper slopes, the till thickens and a significant layer of unweathered till is usually present. This setting is characterised by steeper slopes, commonly has a width of 200 to 400 m and accounts for about 20 to 30% of the catchment.

The interfluve is defined here as the till-covered undulating plateau. The till beneath the interfluve is typically more than 20 m thick and this setting accounts for 50 to 60% of the catchment.

A schematic hydrogeological section is presented which has been superimposed upon the till-Chalk settings described above (Figure 6.2); this shows that beneath the interfluve, the Chalk is of low transmissivity (<50 m^2/d and typically 10 m^2/d) and borehole hydrographs have only a small annual water level fluctuation (0.2 – 0.3 m). The Chalk is confined over must of the interfluve away from the valley sides. Chalk transmissivity is greatest in the valley, where it may exceed 1000 m^2/d, and decreases rapidly away from the valley floor. Pumping test data are rather sparse, especially away from the valley, so that the boundaries between these different transmissivity zones in the Chalk are difficult to delineate accurately and may not necessarily coincide precisely with the Chalk-till settings described above. Nevertheless, the schematic section appears to be a reasonable representation of the groundwater system and broadly agrees with previous conceptual models (Ineson, 1962; Lloyd et al., 1981; Lloyd and Hiscock, 1990).

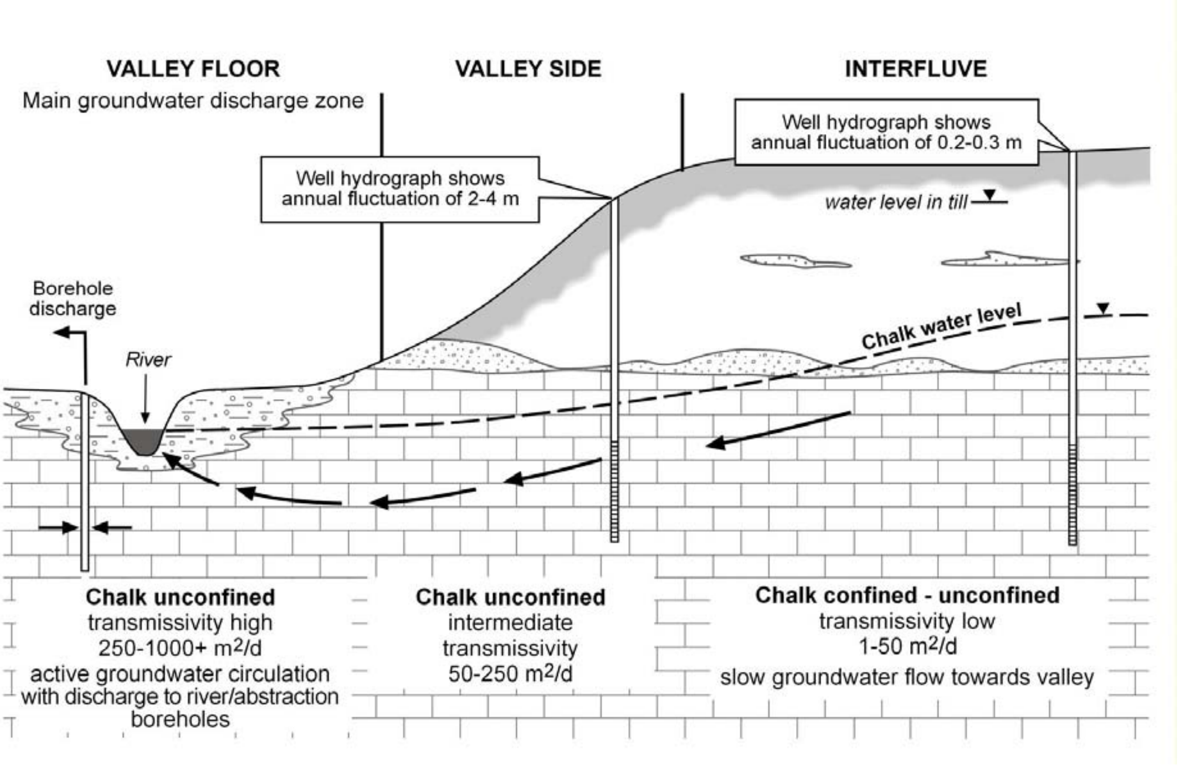


Figure 6.2 Schematic hydrogeological section

6.2 GEOCHEMICAL MODEL

The fracture (pumped) water chemistry data from both the investigation boreholes and the regional monitoring network suggest that there are two principal Chalk fracture water types:

- Type 1 is usually a Ca-HCO_3 water which has high nitrate concentrations and appears to be relatively ‘young’, with the proportion of modern water, as indicated by CFC results, exceeding 70%;
- Type 2 water shows considerable variability (from Ca-HCO_3 to Ca-SO_4 type), and normally has high sulphate but low nitrate concentrations (mostly below detection) and only a small proportion of modern water, usually <15% as indicated by CFC results. The relatively high Sr/Ca and Mg/Ca ratios suggest the water is probably about 10^2 to 10^3 years in age.

The Type 1 Chalk fracture water occurs both in the valley floor and valley side settings, which coincides with the zone of more active groundwater circulation and higher transmissivities. The Type 2 Chalk fracture water occurs beneath the interfluves where Chalk transmissivity is low and flow is limited.

The fracture water chemistry can be compared with porewater chemistry obtained from the two cored boreholes CLR1 and CW1. The cored borehole CLR1 is located close to the boundary between the valley side and interfluve settings while CW1 was drilled near the centre of the interfluve. Borehole CLR1 provides the more comprehensive data set.

The porewaters in the weathered zone of the till are modern (>10 TUs) and of high nitrate concentration (50 to 100 mg N/l). The porewater chemistry of the unweathered till is different (with the exception of the porewater immediately beneath the weathered till zone in CLR1) and is characterised by low nitrate concentrations (<0.5 mg N/l) and low tritium (<1 TU). This suggests that the unweathered till porewaters are derived from infiltration of a pre-1960 origin and that the 'front' of modern recharge has not migrated beyond a few metres into the unweathered till. This is consistent with the Chalk fracture waters beneath the interfluves, away from the edge of the till sheet, being mostly of pre-1960 origin (residence time is probably in the range 10^2 to 10^3 years) and confirms that the thick till layer significantly restricts recharge to the Chalk aquifer. However, CFC analyses suggest that the Chalk fracture waters beneath the interfluves do also have a small fraction of modern groundwater which varies between about 5 to 15%. This modern component must have effectively 'bypassed' the till matrix (so that diffusion exchange with the till porewaters is minimal); the most likely mechanism is that recharge moves rapidly down fractures which extend through the full thickness of the till sheet. A schematic hydrochemical section is presented in Figure 6.3.

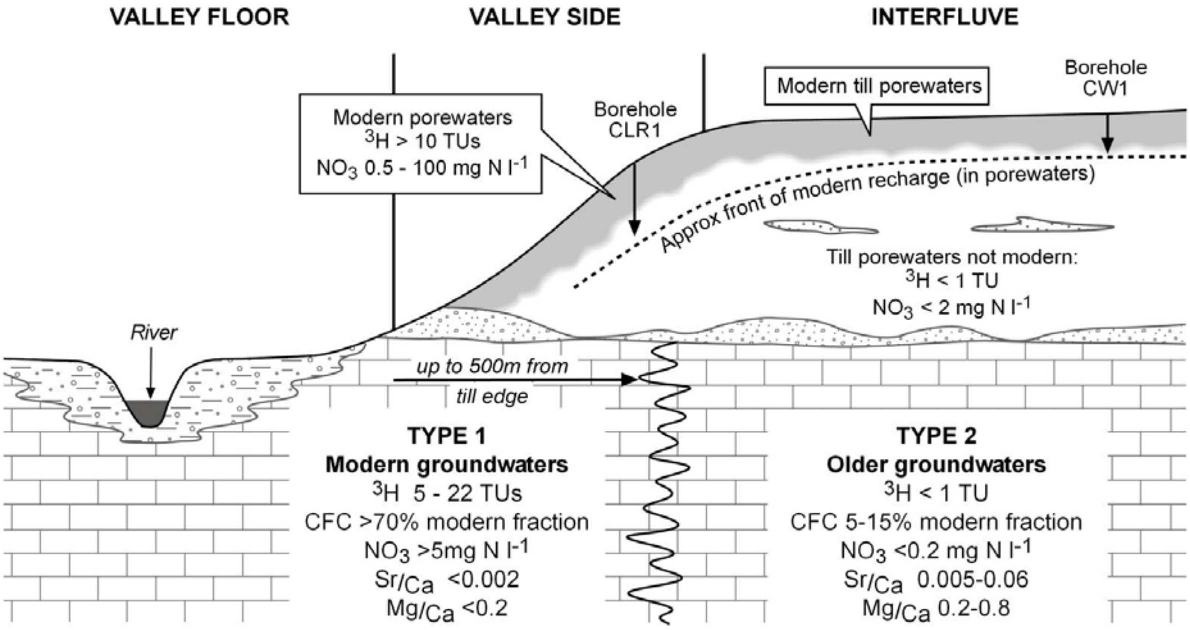


Figure 6.3 Schematic hydrochemical section

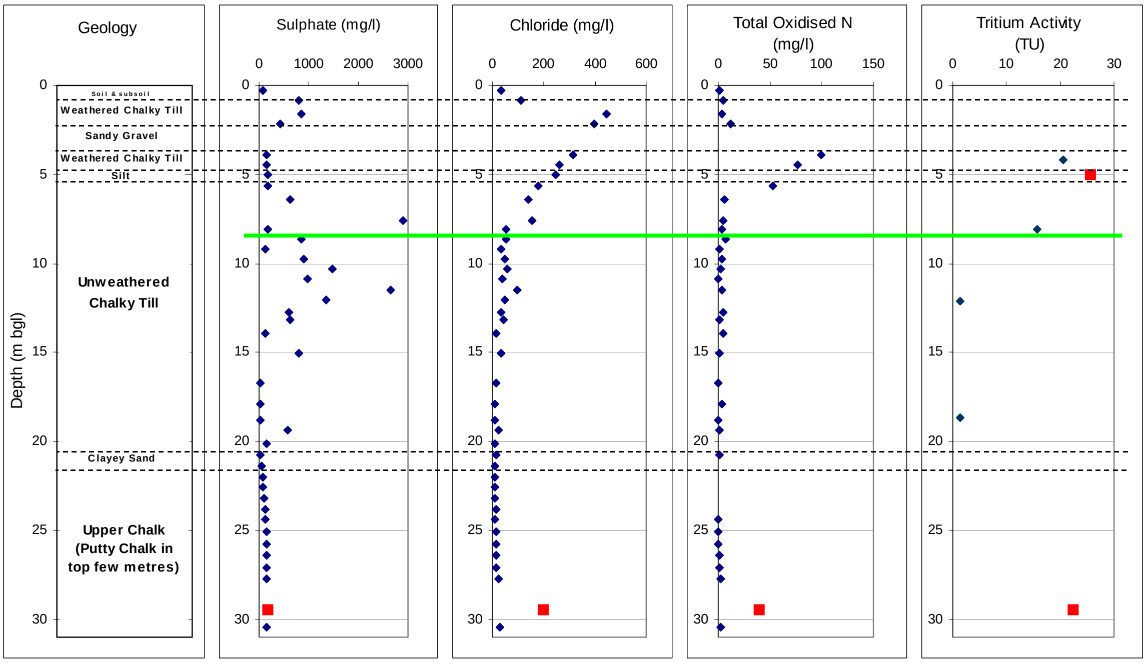
6.3 RECHARGE MODEL

The slow component of recharge beneath the interfluve can be estimated by considering the depth of penetration of modern water in the porewaters of the till. The slow recharge component is defined here as infiltration that undergoes diffusional exchange with porewater in the till. The porewater profiles obtained from core at borehole CLR1 are presented in Figure 6.4, and show that tritium has penetrated to 8 m but not yet to 12 m. The other porewater data (chloride, nitrate) for borehole CLR1 suggest that modern water (post-1960s) 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. However, this is likely to be an overestimate of infiltration rates through thick till because:

(i) the upper 5.3 m of the profile includes silt and sandy and gravel where vertical permeabilities, and thus infiltration rates, can be expected to be higher, and

(ii) the bulk permeability of the weathered till is likely to be higher than that of the unweathered till (Hendry, 1982; Klink et al., 1996) because of more intensive fracturing at shallow depths.

Clare borehole CLR1



Cowlinge borehole CW1

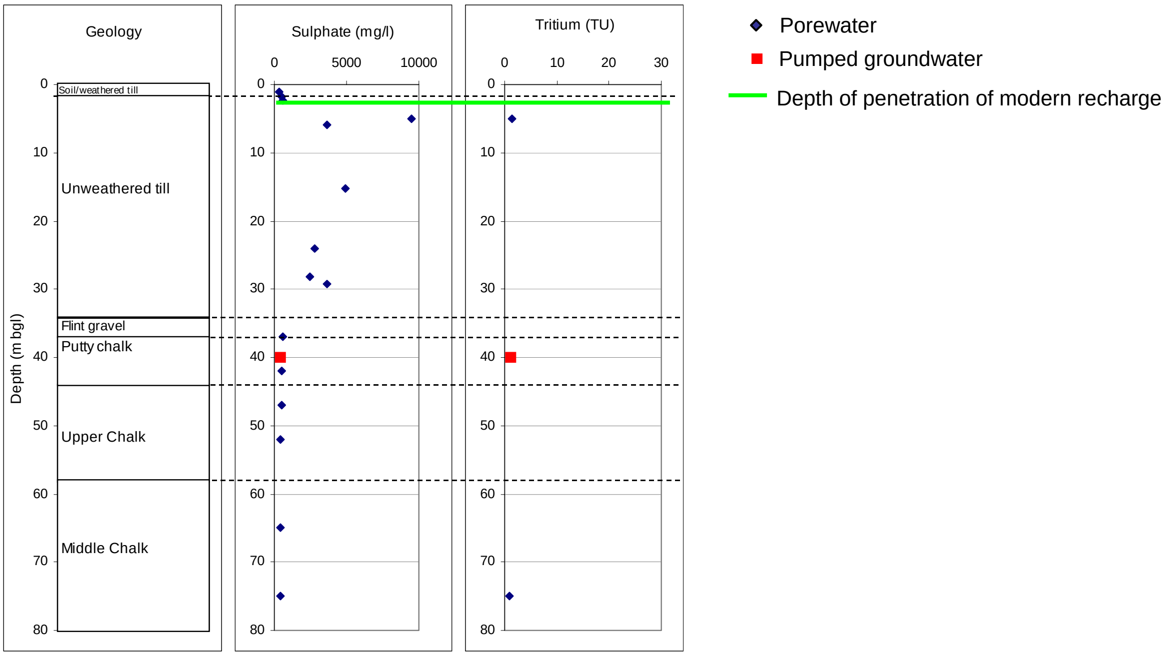


Figure 6.4 Borehole porewater chemistry profiles

Indeed, it may be more realistic to consider that recharge from the ground surface at borehole CLR1 would rapidly reach the base of the sandy gravel at 5.3 m and this would suggest that the infiltration rate in the shallow weathered zone of the till may be closer to 20 mm/a.

The porewater profiles obtained from borehole CW1 are less detailed than those for CLR1as this borehole was not continuously cored. These data show that modern (post-1960) water has not penetrated beyond 5 m depth and probably has not reached 3 m (Figure 6.4, Table 5.5), which suggests an infiltration rate for the slow component of recharge of <25 mm/a, and probably <15 mm/a. This infiltration rate is applicable to the upper weathered zone only and it can be anticipated that this infiltration overestimates recharge rates through the deeper, unweathered till where any fracturing is likely to be less frequent. This is supported by evidence provided by the modelling (Section 5.7.2).

A permeability of 1 x 10^{-10} m/s for the till matrix was determined in the laboratory using core obtained from borehole CLR1 (Table 5.2). Based on this value and assuming a maximum unit vertical hydraulic gradient, an infiltration rate through the matrix, of 3 mm/a at most was estimated. If the slow component of recharge for the upper weathered zone is as much as 15 – 20 mm/a as estimated from the porewater profiles then it suggests that water movement is mostly through fractures. Diffusion between the water in the fractures and the porewater causes the 'front' of modern water to advance more rapidly through the matrix than would occur by advective flow alone. Thus three recharge mechanisms through the till are proposed: (i) matrix flow which probably contributes <3 mm/a and would take more than 1000 years to migrate through a 20 m thick till layer, (ii) flow through fractures with diffusion exchange between porewaters and water in fractures (this recharge mechanism constitutes approximately 15 – 20 mm/a within the upper weathered zone of the till), and (iii) rapid flow through fractures with minimal diffusion exchange with the matrix. The latter recharge mechanism contributes the small component of modern water (as indicated by CFC results) observed in the Chalk aquifer beneath thick till. As discussed earlier (Section 5.7.2) modelling of groundwater levels suggests that recharge to the Chalk aquifer beneath the interfluves is likely to be <20 mm/a and could be as low as 5 mm/a.

The effective rainfall (ER) has been estimated at 155 mm/a (Section 3.1) and, if only 5 mm/a of this percolates through the till (interfluve) to the Chalk, a very considerable volume of water must flow laterally as (i) runoff, (ii) land-drainage and (iii) through flow 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 above and within the till sheet may recharge the Chalk aquifer either where it discharges directly onto the exposed Chalk in the valley floor or where it crosses the lower thin till zone within the valley side (where the till and basal sands are <10 m thick and where unweathered till is either absent or thin).

Given that the interfluves and upper slopes of the valley side comprise about 75% of the catchment area, and that most of the ER will runoff from these areas to the valley and lower slopes of the valley side, then the water available for infiltration may approach 600 mm/a in the latter recharge areas. However, not all of this available water will necessarily recharge the Chalk aquifer and some of this water may flow directly into the River Stour.

Figure 6.3 shows that the boundary between the Type 1 and Type 2 Chalk fracture waters broadly coincides with the valley side/interfluve boundary (e.g. borehole CLR1) rather than with the edge of the till sheet. Where modern Type 1 Chalk fracture waters occur beneath thick till (as at borehole CLR1) and the overlying till porewaters are of pre-1960s origin it suggests that recharge to the Chalk must bypass the till 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 produces a water table mound allowing groundwater to flow back under the till cover (Figure 6.5);

(ii) rapid infiltration to the Chalk occurs at the margins of the till sheet because fracturing in the till is better developed (Figure 6.6). Rates of water movement through the till are sufficiently high that there is insufficient time for significant diffusional exchange to occur between the infiltration in the fractures and the till porewaters.

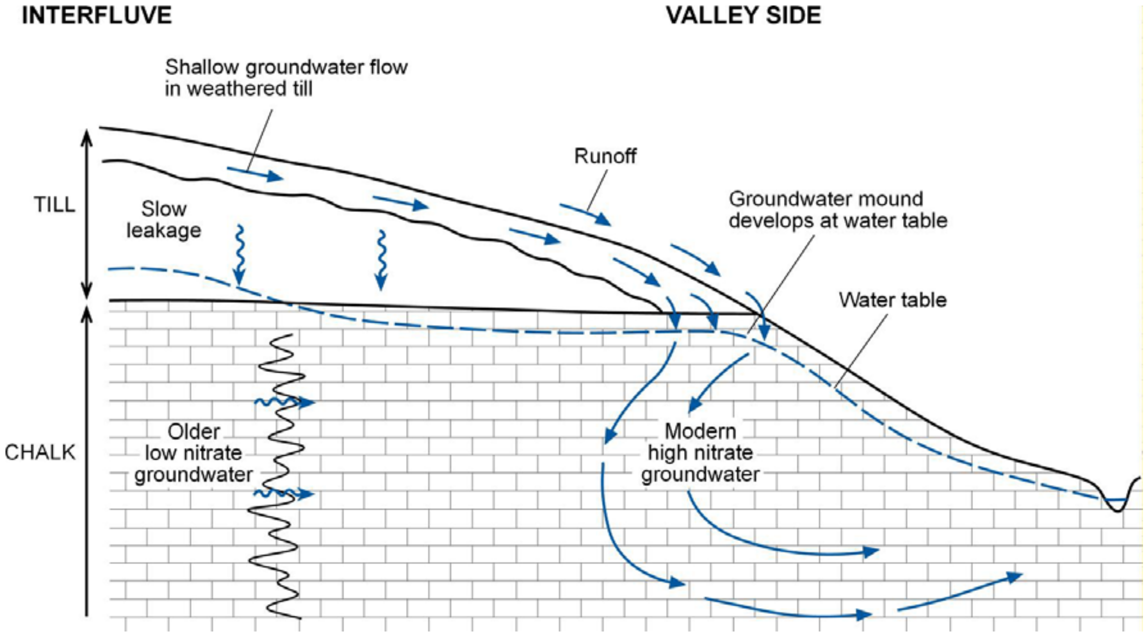


Figure 6.5 Possible recharge scenarios: groundwater mound develops at edge of till sheet

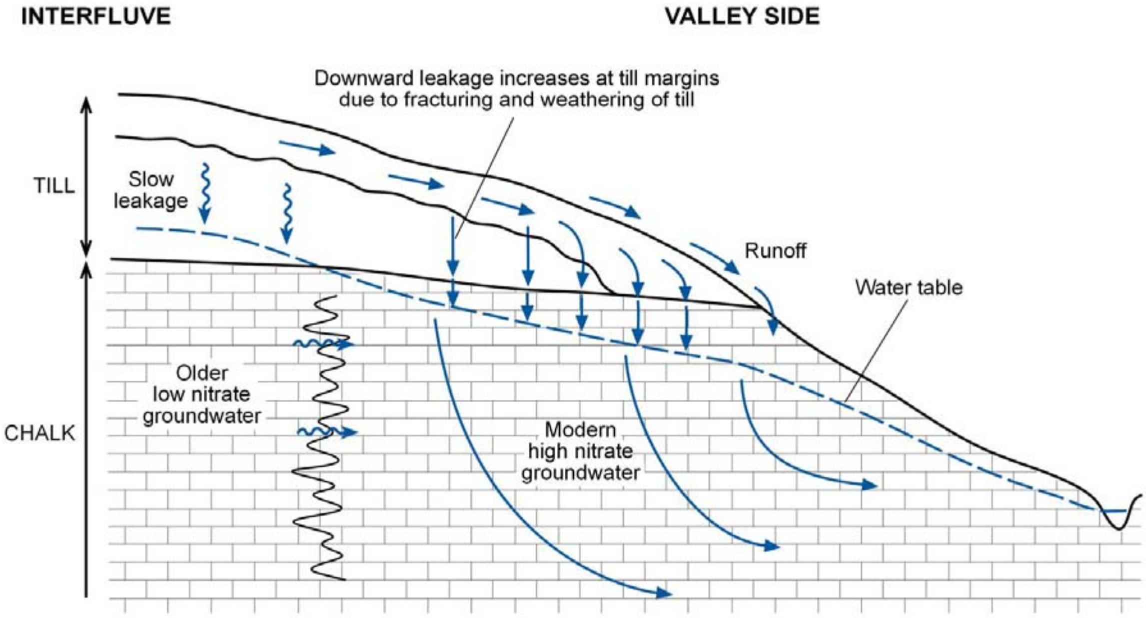


Figure 6.6 Possible recharge scenarios: enhanced recharge to the Chalk occurs where fracturing and weathering develops at the edge of the till sheet

6.4 CONCEPTUAL MODEL

A conceptual model of the Chalk-till groundwater system is presented in Figure 6.7 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 floor and valley sides, and is characterised by high transmissivity with rapid flow through fractures of modern, high nitrate groundwater. The conceptual model proposes that recharge beneath the interfluves is relatively constant with time and that the observed seasonal water level fluctuations of 0.2 to 0.3 m are in response to seasonal changes in vertical hydraulic gradient through the till. Recharge to the valley groundwater system is considerable and occurs both as direct rainfall recharge on exposed Chalk outcrop and via lateral flow from adjacent till-covered areas. Estimated recharge rates of about 5 mm/a for the Chalk aquifer beneath the interfluve are less than had previously been assumed and, if true, have implications for water quality in abstraction boreholes. If the conceptual 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 result in higher nitrate concentration in the pumped water than might have been anticipated.

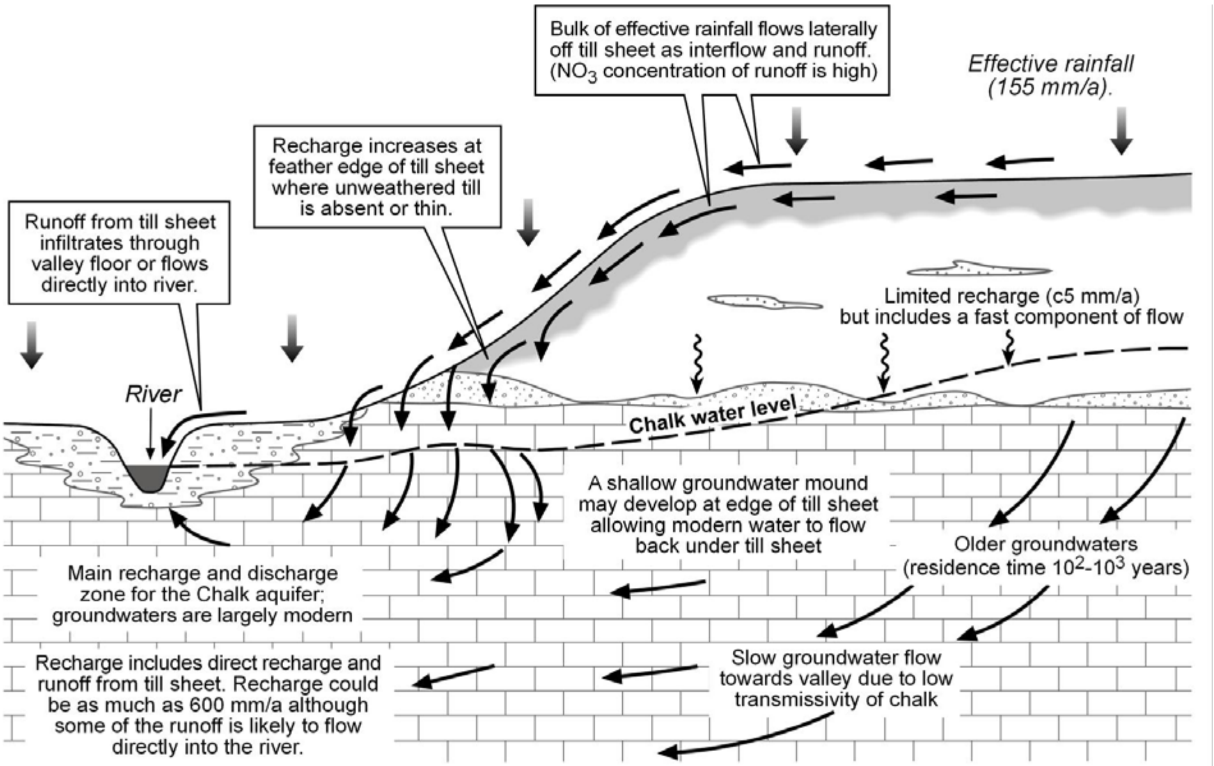


Figure 6.7 Conceptual model

Although the conceptual model fits most of the water quality and hydraulic data, the results of groundwater dating using CFC results appear somewhat anomalous. The CFC data fit well with the conceptual model in as much as a significantly higher proportion of modern water occurs in the valley floor/valley sides (fraction of modern water >70%) than beneath the interfluves (fraction of modern water <15%). Nevertheless, 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 fracture water 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 fracture waters and porewaters. These results 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 south east England currently averages 7 to 10 TU. This can be compared with a tritium activity of 1 TU in the groundwater beneath interfluves (borehole CW1), which gives a proportion of modern water similar to that indicated by CFC results (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 typical values for 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 emissions). 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’. Further work is required to investigate the relative contribution of the slow and rapid components of recharge.

Table 6.1 Comparison of tritium activity in borehole CLR1 and average UK rainfall

Sample	**Date**	**Tritium activity (TU)**
R Stour (likely to equate approximately to rainfall with groundwater mixing)	October 2002	7.6 ±0.5
Rainfall (estimate based on bulked value for the River Darent in Kent)	2002/03	11
Till fracture water CLR1	February 2002	25.6 ±1.2
Chalk fracture water CLR1	February 2002	22.3 ±1.1

7 Summary

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

   Beneath large areas of the till sheet, away from the valley sides Chalk groundwaters appear to have been largely derived from recharge perhaps hundreds, possibly thousands, of years previously. These waters have low nitrate concentrations (<0.2 mg Nl^{-1}) and the proportion of modern (post-1960s) water is relatively small (<15%). These data are consistent with limited recharge to the Chalk aquifer occurring as slow leakage through the till.

   Chalk groundwater beneath the edge of the till sheet and within the valleys appear to be very different. Here, the Chalk is unconfined, recharge is higher (CFC results indicate >70% modern water) and Chalk groundwaters are of the Ca–HCO_3 type with high nitrate concentrations.

2. 1-D modelling together with numerical modelling using the ZOOMQ3D (Jackson, 2001) flow model suggests that recharge estimates through the thick till beneath the interfluves could be as little as 5 mm/a. Recharge rates through the upper, weathered, zone of the till appear to be higher (approximately 15 to 25 mm/a) and these infiltration rates broadly agree with those estimated earlier (Klink et al., 1996; Soley and Heathcote, 1998). This suggests that some of the shallow infiltration may migrate laterally within the weathered zone of the till.

3. One consequence of the low rates of recharge through thick till is that most of the effective rainfall is transferred laterally either via land drains or as shallow groundwater flow within the weathered zone of the till. This water may significantly increase recharge at the edge of the till sheet. Streams flowing over the till sheet and fed by the land drainage network may act as linear recharge zones when they reach the valley sides. An important issue is how much of the runoff infiltrates to the Chalk aquifer and how much flows directly into the Chalk stream within the valley.

4. Infiltration through the thick till sheet on the interfluves comprises two main components:

   (i) a slower component which moves through the till matrix; this component which is estimated at 1 to 3 mm/a will take more than 1000 years to migrate through a 20 m thick till layer;

   (ii) a rapid flow component which migrates through the till via fractures with only limited diffusion exchange with the matrix.

   The presence of up to 15% modern water in the Chalk groundwater beneath the interfluve suggests that this rapid component of recharge may not be insignificant.

5. The Chalk beneath the thick till interfluve is largely confined and only forms a minor aquifer. The major Chalk aquifer is restricted to the main valleys and valley sides for both recharge and discharge.

6. The conceptual model presented in the project has implications for Chalk valley borehole protection zones as follows:

   (i) the contribution to abstraction water from the Chalk aquifer beneath the interfluve is small;

(ii) the shape of the borehole catchment may be modified by the anticipated higher recharge rates at the edge of the till sheet;

(iii) the reduced contribution of groundwater from beneath the interfluve to the abstraction borehole will result in flow paths to the borehole being shorter. A likely consequence is that nitrate concentrations and other pollutants in the pumped water will be higher than previously anticipated.

8 Conclusions

1. A conceptual model of the Chalk-till groundwater 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 <10 mm/a and possibly as low as 5 mm/a) but increases recharge at the edge of the till sheet as a result of runoff from the till 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 appear to be largely of older water (probably $10^2 – 10^3$ years old) and are of low nitrate concentration. 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 results in these groundwaters suggest that this could be as much as 15%, which appears to be rather high (in terms of the 1-D spreadsheet model results and analyses). Further sampling of such waters to ascertain residence times using both CFC results 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 will control the proportion of modern water pumped and its nitrate concentration. 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

Borehole CW1 pumping test data and results

Data summary for pumping test at Cowlinge, 27 February 2003

Initial transducer reading: 7.4919 mA

Initial water level 25.210 mbd (datum = casing top)

Pumping rate changed at 14:30

Time	Flow meter (cc x10)	Q (l/min)	Dip (mbd)	Transducer (mA)	Drawdown (m)	Elapsed time (min)	Time (min)	Drawdown (m)
9:30:00	*Pump started*					0:00:00	0.0	
9:32:00	169240					0:02:00	2.0	
9:33:00	168620	38				0:03:00	3.0	
9:34:00	170005	38.5				0:04:00	4.0	
9:34:30				7.4172	0.4747185	0:04:30	4.5	0.47
9:35:00	170390	38.5				0:05:00	5.0	
9:35:30				7.4124	0.5052225	0:05:30	5.5	0.51
9:36:00	170770	38				0:06:00	6.0	
9:36:30				7.4076	0.5357265	0:06:30	6.5	0.54
9:37:00	171155	38.5				0:07:00	7.0	
9:37:30				7.4049	0.552885	0:07:30	7.5	0.55
9:38:00	171540	38.5				0:08:00	8.0	
9:38:30				7.4022	0.5700435	0:08:30	8.5	0.57
9:39:00	171920	38				0:09:00	9.0	
9:39:30				7.3989	0.591015	0:09:30	9.5	0.59
9:40:00	172310	39				0:10:00	10.0	
9:40:30				7.3965	0.606267	0:10:30	10.5	0.61
9:42:00	173075	38.25				0:12:00	12.0	
9:43:00				7.3907	0.643126	0:13:00	13.0	0.64
9:44:00	173845	38.5				0:14:00	14.0	
9:45:00				7.3866	0.6691815	0:15:00	15.0	0.67

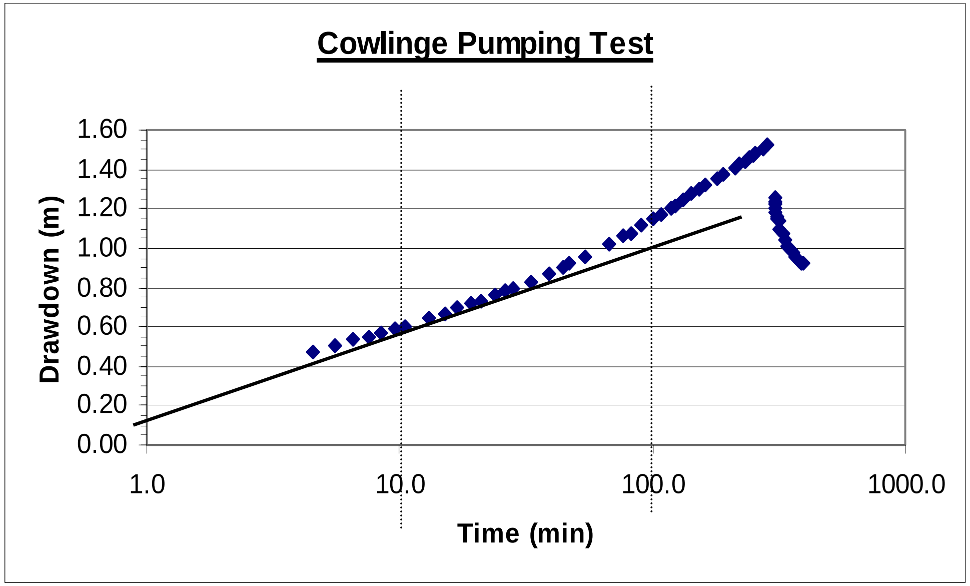
Time	Flow meter (cc x10)	Q (l/min)	Dip (mbd)	Transducer (mA)	Drawdown (m)	Elapsed time (min)	Time (min)	Drawdown (m)
9:46:00	174615	38.5				0:16:00	16.0	
9:47:00				7.3827	0.693966	0:17:00	17.0	0.69
9:48:00	175385	38.5				0:18:00	18.0	
9:49:00				7.3791	0.716844	0:19:00	19.0	0.72
9:50:00	176155	38.5				0:20:00	20.0	
9:51:00				7.3762	0.7352735	0:21:00	21.0	0.74
9:54:00				7.3718	0.7632355	0:24:00	24.0	0.76
9:55:00	178080	38.5				0:25:00	25.0	
9:56:00				7.3692	0.7797585	0:26:00	26.0	0.78
9:58:00				7.3669	0.794375	0:28:00	28.0	0.79
10:00:00	180000	38.4	26.025			0:30:00	30.0	
10:03:00				7.3612	0.8305985	0:33:00	33.0	0.83
10:05:00	181925	38.5				0:35:00	35.0	
10:09:00				7.3549	0.870635	0:39:00	39.0	0.87
10:10:00	183850	38.5				0:40:00	40.0	
10:14:00				7.3503	0.899868	0:44:00	44.0	0.90
10:15:00	185770	38.4	26.125			0:45:00	45.0	
10:17:00				7.347	0.9208395	0:47:00	47.0	0.92
10:24:00				7.341	0.9589695	0:54:00	54.0	0.96
10:25:00	189610	38.4	26.18			0:55:00	55.0	
10:30:00	191520	38.2				1:00:00	60.0	
10:32:00	192295	38.75				1:02:00	62.0	
10:34:00	193060	38.25				1:04:00	64.0	
10:35:00	193450	39				1:05:00	65.0	
10:37:00	194215	38.25		7.3319	1.0168	1:07:00	67.0	1.02
10:38:00	194600	38.5				1:08:00	68.0	
10:40:00	195360	38				1:10:00	70.0	
10:45:00	197290	38.6	26.27			1:15:00	75.0	
10:47:00				7.3253	1.058743	1:17:00	77.0	1.06
10:51:00	199590	38.33	26.285			1:21:00	81.0	
10:52:00				7.3223	1.077808	1:22:00	82.0	1.08

Time	Flow meter (cc x10)	Q (l/min)	Dip (mbd)	Transducer (mA)	Drawdown (m)	Elapsed time (min)	Time (min)	Drawdown (m)
10:55:00	201130	38.5				1:25:00	85.0	
11:00:00	203050	38.4	26.33			1:30:00	90.0	
11:01:00				7.3169	1.112125	1:31:00	91.0	1.11
11:10:00	206890	38.4				1:40:00	100.0	
11:11:00				7.3113	1.147713	1:41:00	101.0	1.15
11:18:00				7.308	1.1686845	1:48:00	108.0	1.17
11:20:00	210720	38.3	26.39			1:50:00	110.0	
11:29:00				7.3026	1.2030015	1:59:00	119.0	1.20
11:30:00	214560	38.4	26.42			2:00:00	120.0	
11:32:00				7.3007	1.215076	2:02:00	122.0	1.22
11:40:00	218400	38.4				2:10:00	130.0	
11:42:00				7.2966	1.2411315	2:12:00	132.0	1.24
11:50:00	222240	38.4				2:20:00	140.0	
11:52:00				7.2915	1.273542	2:22:00	142.0	1.27
12:01:00	226480	38.5	26.5			2:31:00	151.0	
12:03:00				7.2877	1.297691	2:33:00	153.0	1.30
12:10:00	229950	38.5				2:40:00	160.0	
12:13:00				7.2842	1.3199335	2:43:00	163.0	1.32
12:20:00	234800	38.5				2:50:00	170.0	
12:30:00	237660	38.6				3:00:00	180.0	
12:31:00				7.2787	1.354886	3:01:00	181.0	1.35
12:40:00	241480	38.2				3:10:00	190.0	
12:41:00				7.2759	1.37268	3:11:00	191.0	1.37
12:50:00	245310	38.3				3:20:00	200.0	
13:01:00	249515	38.2				3:31:00	211.0	
13:02:00				7.27	1.4101745	3:32:00	212.0	1.41
13:10:00	252955	38.2				3:40:00	220.0	
13:11:00				7.2674	1.4266975	3:41:00	221.0	1.43
13:15:00			26.645			3:45:00	225.0	
13:20:00	256780	38.25				3:50:00	230.0	
13:21:00				7.2647	1.443856	3:51:00	231.0	1.44

Time	Flow meter (cc x10)	Q (l/min)	Dip (mbd)	Transducer (mA)	Drawdown (m)	Elapsed time (min)	Time (min)	Drawdown (m)
13:30:00			26.67			4:00:00	240.0	
13:31:00	260985	38.2				4:01:00	241.0	
13:32:00				7.2624	1.4584725	4:02:00	242.0	1.46
13:40:00	264430	38.2				4:10:00	250.0	
13:41:00				7.2598	1.4749955	4:11:00	251.0	1.47
13:45:00	267540		26.695			4:15:00	255.0	
13:47:00				7.2588	1.4813505	4:17:00	257.0	1.48
13:50:00	268250	38.2				4:20:00	260.0	
14:00:00	272180	38.3	26.72			4:30:00	270.0	
14:02:00				7.2557	1.501051	4:32:00	272.0	1.50
14:11:00	276290					4:41:00	281.0	
14:12:00	276670	38				4:42:00	282.0	
14:15:00	277820	38.3				4:45:00	285.0	
14:16:00				7.2526	1.5207515	4:46:00	286.0	1.52
14:21:00	280115	38.25				4:51:00	291.0	
14:30:00	283555	38				5:00:00	300.0	
14:31:00	283745	14				5:01:00	301.0	
14:32:00	283885	14.5				5:02:00	302.0	
14:33:00	284030	14.5				5:03:00	303.0	
14:33:30				7.2939	1.25829	5:03:30	303.5	1.26
14:34:00	284175	14				5:04:00	304.0	
14:34:30				7.2969	1.239225	5:04:30	304.5	1.24
14:35:00	284315	14.5				5:05:00	305.0	
14:35:30				7.2997	1.221431	5:05:30	305.5	1.22
14:36:00	284460	14				5:06:00	306.0	
14:36:30				7.3021	1.206179	5:06:30	306.5	1.21
14:37:00	284600	14.5				5:07:00	307.0	
14:38:00	284745	14.5				5:08:00	308.0	
14:38:30				7.3053	1.185843	5:08:30	308.5	1.19
14:39:00	284890	14				5:09:00	309.0	
14:40:00	285030	14				5:10:00	310.0	

Time	Flow meter (cc x10)	Q (l/min)	Dip (mbd)	Transducer (mA)	Drawdown (m)	Elapsed time (min)	Time (min)	Drawdown (m)
14:41:00				7.3093	1.160423	5:11:00	311.0	1.16
14:42:00	285317	14.35				5:12:00	312.0	
14:43:00				7.3119	1.1439	5:13:00	313.0	1.14
14:44:00	285605	14.4				5:14:00	314.0	
14:45:00				7.3136	1.1330965	5:15:00	315.0	1.13
14:46:00	285890	14.25				5:16:00	316.0	
14:49:30				7.3183	1.103228	5:19:30	319.5	1.10
14:50:00	286460	14.25				5:20:00	320.0	
14:55:00	287180	14.4				5:25:00	325.0	
14:56:30				7.3234	1.0708175	5:26:30	326.5	1.07
15:00:00	287895	14.3				5:30:00	330.0	
15:02:30				7.3277	1.043491	5:32:30	332.5	1.04
15:08:00	288995	13.75				5:38:00	338.0	
15:09:30				7.3323	1.014258	5:39:30	339.5	1.01
15:10:00			26.23			5:40:00	340.0	
15:11:00	289400	13.5				5:41:00	341.0	
15:13:00				7.3334	1.0072675	5:43:00	343.0	1.01
15:15:00	289947	13.67				5:45:00	345.0	
15:17:00				7.3343	1.001548	5:47:00	347.0	1.00
15:20:00			26.205			5:50:00	350.0	
15:21:00	290780	13.9				5:51:00	351.0	
15:22:00				7.3365	0.987567	5:52:00	352.0	0.99
15:28:00	291745	13.8				5:58:00	358.0	
15:29:00				7.3385	0.974857	5:59:00	359.0	0.97
15:30:00			26.185			6:00:00	360.0	
15:31:00	292165	14				6:01:00	361.0	
15:35:00	292717	13.65				6:05:00	365.0	
15:37:00				7.3414	0.9564275	6:07:00	367.0	0.96
15:40:00			26.17			6:10:00	370.0	
15:41:00	293547	13.83				6:11:00	371.0	
15:42:00				7.3425	0.949437	6:12:00	372.0	0.95

Time	Flow meter (cc x10)	Q (l/min)	Dip (mbd)	Transducer (mA)	Drawdown (m)	Elapsed time (min)	Time (min)	Drawdown (m)
15:49:00	294658	13.89				6:19:00	379.0	
15:50:00			26.155			6:20:00	380.0	
15:51:00				7.3445	0.936727	6:21:00	381.0	0.94
15:55:00	295493	13.92				6:25:00	385.0	
15:59:00	296046	13.82				6:29:00	389.0	
16:00:00			26.145			6:30:00	390.0	
16:01:00				7.3465	0.924017	6:31:00	391.0	0.92
16:05:00	296912	14.43				6:35:00	395.0	
16:06:00			26.14			6:36:00	396.0	
16:07:00				7.347	0.9208395	6:37:00	397.0	0.92
16:08:00	*Pump off*			7.3474	0.9182975	6:38:00	398.0	0.92
16:08:15				7.567	-0.4772605	6:38:15	398.3	-0.48
16:08:30				7.68	-1.1953755	6:38:30	398.5	-1.20
16:08:45				7.759	-1.6974205	6:38:45	398.8	-1.70
16:09:00				7.3812	0.7034985	6:39:00	399.0	0.70
16:09:15				7.3853	0.677443	6:39:15	399.3	0.68
16:09:30				7.3877	0.662191	6:39:30	399.5	0.66
16:09:45				7.3895	0.650752	6:39:45	399.8	0.65
16:10:00				7.3907	0.643126	6:40:00	400.0	0.64
16:10:30				7.3918	0.6361355	6:40:30	400.5	0.64



Jacob: T = 2.3Q/4pi(ho-h)

T = 12.7 m^2/d

q = 38.5 l/min

q = 55.4 m^3/day

(ho-h) = 0.8

Appendix 2

Water chemistry

(a) Chemistry and stable isotope results for porewaters from Borehole CLR1

Sample no	Sample top (mbgl)	Sample bottom (mbgl)	Sample description	pH	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	Cl mg/l	SO_4 mg/l	NH_4-N mg/l	NO_2-N mg/l	TON mg/l	$\delta^{18}O$ ‰	δ^2H ‰
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	0.9	-6.70	-41.8
2	0.72	0.90	OxBC	8.21	334	10.6	217.0	4.1	338	111.0	808.0	4.160	0.783	4.7	-6.78	-44.8
3	1.55	1.70	OxBC	8.22	551	11.3	151.0	2.5	274	443.0	847.0	1.430	0.150	3.1	-7.11	-47.8
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	12.3	-6.65	-41.7
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	-7.02	-44.6
7ii	3.81	3.94	OxBC	8.04	348	5.6	47.4	4.8	119	325.0	151.0	0.070	0.068	90.4	-7.10	-46.9
7iii	3.81	3.94	OxBC	8.29	375	5.4	33.5	3.5	313	303.0	142.0	0.090	0.457	88.0	-7.14	-46.1
8	4.35	4.50	OxBC	7.73	428	6.6	37.6	5.7	292	261.0	147.0	0.050	0.029	77.0	-7.18	-46.3
9a	4.75	5.27	WetSilt	7.66	284	6.9	36.4	13.7	78	247.0	166.0	2.080	0.074	61.2		
10	5.60	5.75	UoxBC	8.24	306	10.2	29.2	12.6	309	181.0	179.0	1.100	0.826	53.0	-7.20	-48.9
11	6.35	6.50	UoxBC	8.28	292	22.6	19.2	34.2	244	142.0	615.0	2.450	0.180	6.4	-7.15	-48.5
12	7.50	7.65	UoxBC	7.84	896	76.2	25.2	120.0	276	156.0	2910.0	2.740	0.303	5.1	-7.42	-51.5
13			UoxBC	8.35	140	10.3	9.7	60.3	255	53.5	166.0	1.250	0.210	3.7	-7.22	-47.1
14	8.55	8.70	UoxBC	8.21	304	23.6	19.2	105.0	328	53.1	861.0	3.310	0.255	7.6	-7.40	-50.6
15	9.15	9.30	UoxBC	8.20	115	8.2	9.7	67.4	323	33.4	136.0	0.740	0.059	1.3	-7.11	-48.9
16	9.65	9.80	UoxBC	8.30	321	17.5	14.2	131.0	371	48.0	894.0	1.690	0.079	3.1	-7.30	-50.0
17	10.25	10.40	UoxBC	8.06	489	20.7	24.2	142.0	256	58.9	1480.0	2.620	0.451	2.1	-7.14	-48.3
18	10.81	10.96	UoxBC	7.46	408	19.5	17.3	119.0	334	36.6	976.0	0.403	0.044	0.5	-7.50	-50.1
19	11.45	11.60	UoxBC	8.08	854	40.4	34.5	162.0	312	98.6	2650.0	2.050	0.212	3.3	-7.12	-46.8
20i	12.00	12.15	UoxBC	8.08	511	26.9	21.2	78.9	364	59.7	1390.0	2.950	0.039	0.5		
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		

Sample no	Sample top (mbgl)	Sample bottom (mbgl)	Sample description	pH	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	HCO_3 mg/l	Cl mg/l	SO_4 mg/l	NH_4-N mg/l	NO_2-N mg/l	TON mg/l	$\delta^{18}O$ ‰	δ^2H ‰
20iii	12.00	12.15	UoxBC		507	26.7	16.1	46.2		40.4	1340.0	0.124	<0.01	<0.2		
21	12.65	12.80	UoxBC	8.13	270	12.4	13.6	40.2	325	32.4	610.0	1.910	0.125	4.2	-7.08	-45.3
22i	13.10	13.20	UoxBC	8.09	251	13.3	14.5	22.6	307	27.3	485.0	0.400	0.284	0.6	-7.47	-51.3
22ii	13.20	13.30	UoxBC	8.12	209	11.4	18.6	23.8	240	27.3	422.0	0.540	0.236	1.1	-7.39	-47.5
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	-7.24	-49.2
22iii	13.30	13.40	UoxBC	8.00	407	19.6	17.1	25.5	236	100.0	1180.0	0.630	0.018	0.5	-7.20	-45.8
23	13.85	14.00	UoxBC	7.93	143	15.1	11.7	9.4	394	16.1	127.0	2.460	0.052	4.2	-7.17	-46.4
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	0.7	-7.14	-46.0
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	0.5	-7.20	-47.5
28	17.85	18.00	UoxBC	8.02	114	10.1	14.6	3.6	253	11.7	24.8	3.600	0.433	3.2	-7.35	-47.9
29	18.72	18.87	UoxBC	7.80	104	9.5	18.5	3.1	387	11.0	22.9	0.689	0.067	0.5	-7.21	-50.4
30	19.31	19.46	UoxBC	7.83	264	18.4	27.5	5.8	272	24.7	568.0	3.220	0.054	0.8	-7.28	-47.3
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	-7.41	-46.3
32	20.66	20.81	ClSa	7.79	110	11.2	24.6	4.5	346	13.7	25.0	0.180	0.079	0.7	-7.32	-44.9
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	-7.20	-45.4
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	-7.17	-45.8
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	-7.42	-45.9
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	-7.31	-46.5
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	-7.32	-46.0
38	24.10	24.70	Ck	8.44	110	14.0	26.5	3.2	269	12.0	126.0	0.018	0.005	0.3	-7.19	-45.0
39	24.80	25.40	Ck	8.54	111	14.5	26.9	3.5	247	13.8	139.0	0.027	0.005	0.4	-7.39	-47.2
40	25.50	26.10	Ck	8.51	138	17.2	28.9	3.5	316	14.5	147.0	0.027	0.004	0.4	-7.07	-44.6
41	26.10	26.70	Ck	8.47	117	15.4	26.8	3.0	272	14.7	153.0	0.018	0.004	0.7	-7.17	-44.0
42	26.80	27.40	Ck	8.55	130	15.9	25.3	2.9	302	16.4	143.0	0.018	0.005	0.9	-6.00	-30.0
43	27.40	28.00	Ck	8.47	126	14.8	25.5	3.1	244	24.5	152.0	0.036	0.005	1.8	-8.00	-60.0
44	30.30	30.60	Ck	7.85	151	14.8	25.6	2.9	114	31.3	149.0	<0.009	0.019	2.2		

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

(b) Chemistry results from the monitoring of Borehole CLR1 and nearby sources

	Date	**pH**	**Ca**	**Mg**	**Na**	**K**	**HCO_3**	**Cl**	**SO_4**	**NO_2-N**	**TON**
			mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	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 obh)	19-Feb-03	7.61	187	32.7	25.3	6.85	424	37	228	<0.003	<0.8
Verge, Rede Lane (EA obh)	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 obh)	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

(c) CFC and stable isotope results from the monitoring of Borehole CLR1 and nearby sources

	Date	**CFC-12** pmol/l	**CFC-11** pmol/l	**$\delta^{18}O$** ‰	**$\delta^{2}H$** ‰	**$\delta^{13}C$-DIC** ‰
CLR1 shallow(till) piezometer	07-Feb-01			-7.07	-44.6	-17.86
CLR1 shallow(till) piezometer	03-Jul-01			-7.10	-46.2	-17.49
CLR1 shallow(till) piezometer	11-Sep-01			-7.20	-46.7	
CLR1 shallow(till) piezometer	19-Oct-01		4.21			
CLR1 shallow(till) piezometer	06-Nov-01			-6.58	-47.3	-17.05
CLR1 shallow(till) piezometer	04-Dec-01			-7.14	-48.0	-17.53
CLR1 shallow(till) piezometer	08-Jan-02			-6.27	-42.9	-17.39
CLR1 shallow(till) piezometer	06-Feb-02			-6.93	-46.2	-18.35
CLR1 shallow(till) piezometer	04-Mar-02			-7.00	-46.8	-18.06
CLR1 shallow(till) piezometer	09-Apr-02			-6.90	-43.5	-17.20
CLR1 shallow(till) piezometer	Jun-02			-7.83	-44.7	-18.03
CLR1 shallow(till) piezometer	Oct-02			-7.06	-46.0	-14.41
CLR1 shallow(till) piezometer	14-Nov-02			-7.14	-44.1	-17.83
CLR1 shallow(till) piezometer	16-Dec-02			-7.12	-44.2	-17.55
CLR1 deep (chalk) piezometer	07-Feb-01			-7.17	-44.0	-16.38
CLR1 deep (chalk) piezometer	03-Jul-01			-7.15	-44.4	-13.01
CLR1 deep (chalk) piezometer	11-Sep-01			-6.99	-47.9	
CLR1 deep (chalk) piezometer	06-Nov-01			-6.58	-45.6	-12.42
CLR1 deep (chalk) piezometer	04-Dec-01			-7.08	-47.1	-10.81
CLR1 deep (chalk) piezometer	08-Jan-02			-6.67	-44.0	-9.44
CLR1 deep (chalk) piezometer	06-Feb-02			-7.02	-47.8	-12.07
CLR1 deep (chalk) piezometer	04-Mar-02			-7.18	-48.0	-8.64
CLR1 deep (chalk) piezometer	09-Apr-02			-6.97	-43.8	-2.75
CLR1 deep (chalk) piezometer	14-Nov-02			-6.83	-46.4	-12.93
CLR1 deep (chalk) piezometer	16-Dec-02	3.43	4.65	-7.37	-44.7	-13.92
CLR1 deep (chalk) piezometer	20-Jan-03	2.68	3.91			
CLR1 deep (chalk) piezometer	20-Feb-03	2.59	4.40			

	Date	**CFC-12**	**CFC-11**	**$\delta^{18}O$**	**$\delta^{2}H$**	**$\delta^{13}C$-DIC**
		pmol/l	pmol/l	‰	‰	‰
CLR1 White Gas Piezometer	03-Jul-01			-7.05	-42.7	-13.57
CLR1 White Gas Piezometer	04-Mar-02			-7.16	-45.3	-15.04
CLR1 Blue Gas Piezometer	06-Feb-02			-7.17	-49.7	-19.6
Boulder Clay Ditch	06-Nov-01			-7.01	-42.9	-15.63
Boulder Clay Ditch	04-Dec-01			-6.59	-45.3	-16.48
Boulder Clay Ditch	08-Jan-02			-6.68	-44.2	-14.81
Boulder Clay Ditch	06-Feb-02			-6.37	-40.7	-16.92
Boulder Clay Ditch	06-Feb-02			-6.37	-40.7	-16.92
Boulder Clay Ditch	04-Mar-02			-6.94	-40.8	-15.11
Boulder Clay Ditch	Apr-02			-6.47	42.3	-15.29
Boulder Clay Ditch	Oct-02			-6.11	42.7	-13.06
Spring	07-Feb-01			-7.08	-45.3	-17.67
Spring	03-Jul-01			-7.18	-47.1	-16.85
Spring	11-Sep-01			-7.08	-48.8	
Spring	04-Dec-01			-6.97	-44.8	-17.42
Spring	08-Jan-02			-6.97	-45.5	-16.77
Spring	06-Feb-02			-7.09	-46.6	-17.98
Spring	09-Apr-02			-7.00	-47.6	-16.71
Spring	Jun-02			-7.14	-46.7	-14.71
Spring	Oct-02			-7.15	-46.9	-13.74

(d) Tritium results for porewaters and fracture water from Borehole CLR1

Porewater samples:

Sample	Depth range (m)		Tritium Activity	Error
	Top	Bottom	TU	±
CLR1	3.81	4.5	20.5	1
CLR1	7.5	8.7	15.6	0.8
CLR1	11.5	12.8	1.3	0.4
CLR1	17.9	19.5	1.4	0.4

Fracture water samples:

Sample	Depth m	Tritium Activity TU	Error ±
CLR1 Till	5.0	25.6	1.2
CLR1 Chalk	29.5	22.3	1.1

(e) Chemistry results for porewaters and fracture water from Borehole CW1

Porewaters:

Date	Rock[1]	Top mbgl	Base mbgl	Moisture content %	Sample type[2]	SEC µs/cm	pH	Ca mg/l	Cl mg/l	Fe µg/l	HCO_3 mg/l	K mg/l	Mg mg/l	Mn µg/l	Na mg/l	NH_4 mg/l	NO_2 mg/l	Si mg/l	SO_4 mg/l	Sr mg/l	TON mg/l
Dec-03	Till	1.1			U4			144				0	5.44	116	16.6			13.4	300	0.4	
Dec-03	Till	1.8			U4			141				0	13.4	44	21.2			13.2	525	0.5	
Dec-03	Till	2.4			U4			184				0	18.5	51	29.6			12.2	562	0.7	
Dec-03	Till	5.1			U4			1281				14.0	239	506	69.8			7.9	9450	6.5	
Dec-03	Till	5.9			U4			904				8.2	199	521	40.4			10.5	3642	6.3	
Dec-03	Till	15.2			U4			848				12.7	385	690	35.1			9.4	4875	20	
Dec-03	Till	24.1			U4			623				24.0	222	321	49.3			9.8	2832	14	
Dec-03	Till	28.1			U4			594				22.9	190	305	45.3			9.4	2484	14	
Dec-03	Till	29.3			U4			797				17.9	287	801	39.5			9.9	3633	18	
Mar-03	Ck	34.0	34.5	16.9	B	2060	7.9	409	59	<5	105	10.9	92.7	662	47.0	0.38	0.012	2.2	1140	7.2	<2
Mar-03	Ck	35.5	36.0	16.2	B	1092	8.2	188	51	<5	118	8.4	48.0	65	35.6	0.45	0.046	1.9	525	3.8	<2
Mar-03	Ck	36.0	36.5	14.1	B	1112	8.2	192	54	6	121	8.5	51.7	85	36.5	0.60	0.046	1.8	533	3.6	<2
Mar-03	Ck	36.5	37.0	26.1	U4	1200	7.9	213	51	51	283	8.7	63.0	146	36.0	0.71	0.003	5.8	504	4.4	<2
Mar-03	Ck	37.0	37.5	21.8	U4	1221	7.9	232	54	79	278	8.6	66.6	179	37.2	0.73	0.003	5.4	528	5.0	<2
Mar-03	Ck	38.0	38.5	26.9	B	1255	8.2	199	63	<5	133	9.2	70.6	45	40.4	0.55	0.017	3.6	591	4.6	<2
Mar-03	Ck	38.5	39.0	29.0	U4	1360	8.1	252	65	21	282	9.1	76.0	240	40.8	0.74	0.014	5.6	598	5.6	<2
Mar-03	Ck	39.0	39.5	25.0	U4	1270	8.1	236	65	18	198	10.1	72.1	145	41.5	0.73	0.004	3.6	607	4.6	<2
Mar-03	Ck	40.0	40.5	30.0	B	1165	8.2	194	60	6	140	8.5	54.0	129	37.6	0.53	0.026	1.8	523	2.8	<2
Mar-03	Ck	40.5	41.0	32.9	U4	1224	8.1	237	60	19	273	8.4	64.1	210	36.9	0.63	0.006	6.3	513	4.3	<2
Mar-03	Ck	41.0	41.5	28.2	U4	1216	8.1	229	59	123	282	8.5	59.7	185	36.1	0.63	0.004	6.1	498	4.2	<2
Mar-03	Ck	43.0	43.5	27.8	U4	1209	8.1	243	56	32.3	285	9.1	58.9	202	35.6	0.62	0.014	6.3	494	4.3	<2
Mar-03	Ck	44.5	45.0	33.4	U4	1217	8.0	250	48	20	286	7.9	59.2	192	36.7	0.57	0.003	8.4	521	4.4	<2
Mar-03	Ck	45.0	45.5	29.9	U4	1219	8.0	235	47	17	276	7.5	53.8	183	34.5	0.56	0.003	8.3	495	3.9	<2
Mar-03	Ck	46.5	47.0	36.0	U4	1179	8.0	198	40	21	267	7.5	52.7	150	33.3	0.53	0.002	8.2	492	3.6	<2
Mar-03	Ck	47.0	47.5	30.2	U4	1210	7.9	246	41	<5	290	6.8	53.5	5	34.3	0.53	0.003	8.4	492	3.9	<2

Porewaters continued:

Date	Rock[1]	Top	Base	Moisture content	Sample type[2]	SEC	pH	Ca	Cl	Fe	HCO_3	K	Mg	Mn	Na	NH_4	NO_2	Si	SO_4	Sr	TON
		mbgl	mbgl	%		µs/cm		mg/l	mg/l	µg/l	mg/l	mg/l	mg/l	µg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Mar-03	Ck	49.5	50.0	34.9	U4	1102	8.3	216	40	13	277	6.7	45.6	96	34.2	0.44	0.004	8.5	440	3.3	<2
Mar-03	Ck	50.0	50.5	31.8	U4	1069	8.0	219	40	8	249	6.0	45.4	53	33.6	0.47	0.005	8.6	439	3.4	<2
Mar-03	Ck	52.5	53.0	15.4	B	955	8.0	158	43	10	120	5.7	36.5	45	31.5	0.42	0.013	3.7	398	2.4	<2
Mar-03	Ck	53.5	54.0	32.7	B	927	7.9	152	44	<5	93	5.8	36.7	27	31.0	0.41	0.020	4.1	408	2.4	<2
Mar-03	Ck	56.0	56.5	20.8	B	953	7.8	152	63	<5	82	5.4	36.3	24	32.1	0.39	0.010	3.0	386	2.4	<2
Mar-03	Ck	62.0	62.5	29.7	B	918	8.1	143	47	<5	104	5.8	34.0	23	29.2	0.59	0.021	5.1	361	2.5	<2
Mar-03	Ck	63.0	64.0	37.7	B	1092	8.1	173	73	<5	136	4.9	44.5	10	32.3	0.47	0.005	2.2	408	2.6	<2
Mar-03	Ck	66.0	67.0	30.9	B	1018	8.3	165	44	7	198	4.9	41.3	49	31.6	0.59	0.010	12.0	358	3.1	<2
Mar-03	Ck	68.0	69.0	12.0	B	1095	8.2	179	67	<5	154	4.8	43.4	11	32.7	0.62	0.009	5.1	417	3.1	<2
Mar-03	Ck	70.0	70.5	32.1	U4	1051	8.2	199	41	11	350	5.7	44.5	17	32.1	0.50	0.005	13.6	343	3.7	<2
Mar-03	Ck	71.0	72.0	26.8	B	1122	8.2	177	70	5	146	4.4	43.3	9	34.6	0.52	0.011	6.2	421	2.9	<2
Mar-03	Ck	73.0	73.5	23.7	B	1044	8.0	169	67	<5	99	5.2	40.0	28	30.7	0.46	0.022	3.9	415	2.8	<2
Mar-03	Ck	75.0	75.5	36.0	B	1058	8.1	161	61	<5	134	5.2	41.4	24	34.0	0.49	0.016	6.5	395	2.7	<2
Mar-03	Ck	76.0	77.0	27.0	B	1002	8.1	157	45	<5	159	6.2	39.1	30	32.1	0.42	0.021	8.0	375	2.9	<2
Mar-03	Ck	79.0	80.0	29.9	B	985	8.1	153	46	<5	145	5.5	36.7	9	31.6	0.37	0.012	8.8	367	2.9	<2

Fracture water samples taken during drilling:

Date	Rock[1]	Depth	Notes	pH	Ca	Cl	Fe	HCO_3	K	Mg	Mn	Na	NH_4	NO_2-N	Si	SO_4	Sr	TON
		mbgl			mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Feb-03	Gr	35	Preferred gravel sample		182	105	<0.005	334	10.9	51.9	0.26	33.3	0.71	0.005	5.8	270	3.63	1
Feb-03	Ck	40	Near chalk surface sample	7.4	191	75	1.57	266	10.3	58.6	0.33	27.7	0.67	<0.0003	3.31	418	4.12	<0.8

Fracture water samples taken during pump testing (discharge rate = 0.5 l/s):

Date	Rock[1]	Top	Base	Water level (mbgl)	SEC	pH	Ca	Cl	Fe	HCO_3	K	Mg	Mn	Na	NH_4	NO_2-N	Si	SO_4	Sr	TON
		mbgl	mbgl		µs/cm		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	mg/l	mg/l	µg/l	mg/l	mg/l	mg/l	mg/l
Feb-03	Ck	46.2	51.4	25.24	1472		240	50	2.5	408	8.1	57.2	281	25.0	0.55	<3	8.2	464	4.3	<0.8
Feb-03	Ck	52	57	25.21	1624	6.7	246	50	3.1	427	8.3	59.7	263	35.5	0.57	<3	8.7	466	4.4	<0.8
Feb-03	Ck	52	57	25.21		6.5	250	50	3.1	413	8.5	61.0	270	27.0	0.60	<3	8.9	483	4.6	<0.8

1. Ck = Chalk, Gr = gravel
2. U4 = samples taken from a U100 core liner, B = cutting shoe samples (bagged)

(f) Stable isotope results for porewaters and fracture water from Borehole CW1

	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	$\delta^{13}C$-DIC ‰
Cowlinge P Test	-7.37	-49.0	-13.45
Cowlinge P Test 1	-7.34	-48.5	-12.80
Cowlinge P Test 2	-7.53	-51.2	-12.27
CW1 bailed 12 Feb	-6.97	-44.2	-13.85
CW1 bailed 13 Feb 0845	-7.05	-44.9	-12.55
CW1 bailed 13 Feb 1650	-7.09	-45.2	-13.62
CW1 bailed 14 Feb 0850	-7.01	-47.8	-12.32
CW1 Ck core 37 m	-7.33	-49.6	-11.21
CW1 Ck core 40 m	-7.40	-48.3	-11.50
CW1 Ck core 43 m	-7.12	-46.4	-11.43
CW1 Ck core 50 m	-7.33	-48.8	-7.27
CW1 Ck core 62 m	-7.30	-48.0	-9.24
CW1 Ck core 70 m	-7.47	-48.9	-10.46
CW1 Ck core 79 m	-7.50	-48.9	-8.21

(g) CFC and tritium results for porewaters and fracture water from Borehole CW1:

CFC data:

Sample	**CFC-12** pmol/l	**CFC-11** pmol/l
Cowlinge Pump Test 1a Sample 1	0.52	1.00
Cowlinge Pump Test 1b sample 1	0.63	0.76
Cowlinge Pump Test 1a Sample 2	0.45	0.56
Cowlinge Pump Test 1b sample 2	0.46	0.59
Cowlinge Pump Test 2a	0.54	0.61
Cowlinge Pump Test 2b	0.48	0.64
Cowlinge pumped piezo sample 1	0.94	1.20
Cowlinge pumped piezo sample 2	1.01	1.38

Tritium data:

Sample	**Depth from** m	**to** m	**Tritium** TU	**Error** ±
Porewater	5.05	5.5	1.5	0.3
Porewater	28.0	28.5	<1	
Porewater	36.0	38.5	<1	
Porewater	70.0	70.5	1	0.3
Pumped	Cowlinge Pump Test 1a		1.1	0.3

(h) Chemistry results for pumped samples from Environment Agency observation boreholes and CLR1

Borehole	Sample date	Pump depth (m)	Well depth (m)	NGR	Temperature ˚C	pH	SEC µS/cm	HCO$_3$ mg/l	Ca mg/l	Cl mg/l	K mg/l	Mg mg/l	Na mg/l	SO$_4$ mg/l	TON mg/l	NH$_4$-N µg/l	NO$_2$-N mg/l	Fe µg/l	Mn µg/l
CLR1 deep (Chalk)	20-Feb-03		30.8	471420 544770	10.3	6.52	1799	341.4	309	192	6.31	6.67	36	197	32	<9	0.005	57.1	5.1
CLR1- deep (Chalk)	20-Jan-03		30.8	471420 544770		7.13	1594	370.6	329	197	5.78	5.88	41	218	28.9	<9	<3	2.6	<0.9
Blacksmith's Hill	20-Feb-03		91.4	573700 240700	9.8	6.87	964	297.5	159	23	2.85	20.4	22.4	184	5.3	<9	4	16	3
Blacksmith's Hill	20-Jan-03		91.4	573700 240700		7.52	823	281.6	159	23	2.82	19.3	22.2	171	5.3	<9	<3	148	6
Mill House, Ridgewell	20-Feb-03	30	61	573290 240780		7.55	647	331	121	16	3.64	6.27	12.4	33.4	<0.2	<9	<3	248	346
Mill House, Ridgewell	20-Jan-03		61	573290 240780		7.53	654	312.1	125	15	4.61	6.45	12.2	35.8	<0.8	<9	<3	340	291
Rede Lane	21-Jan-03		150	582068 257440		9.69	156.8	42.06	3.24	21	9.2	1.16	20.4	0.5	<0.2	0.38	<3	<5	<2
Gainsford Hall, Toppesfield	21-Jan-03		61	572300 235000		7.01	1961	10.42	245	105	6.91	61.2	94	486	<0.2	0.29	<3		
Radwinter Road	18-Feb-03		60	559521 240683	9.7	7.26	1105	387.7	190	50	4.91	30.3	22	208	<0.8	0.33	<3	1630	108
Skippers Lane	19-Feb-03	37	110	564316 248471	9.7	10.4	942	13.1	67.1	53	56.9	8.97	60	325	<0.8	1.49	<3	16	<2
Thurlow Road	19-Feb-03	48	171	564228 251587		7.05	980	330.4	165	51	6.13	16.6	21.2	137	<0.8	0.14	<3	1480	49
Cowlinge EA	19-Feb-03	34		572007 255016		7.18	1168	407.8	187	37	6.85	32.7	25.3	228	<0.8	0.35	<3	4650	191

(i) CFC and stable isotope results for samples from Environment Agency and Anglian Water boreholes, and the River Stour

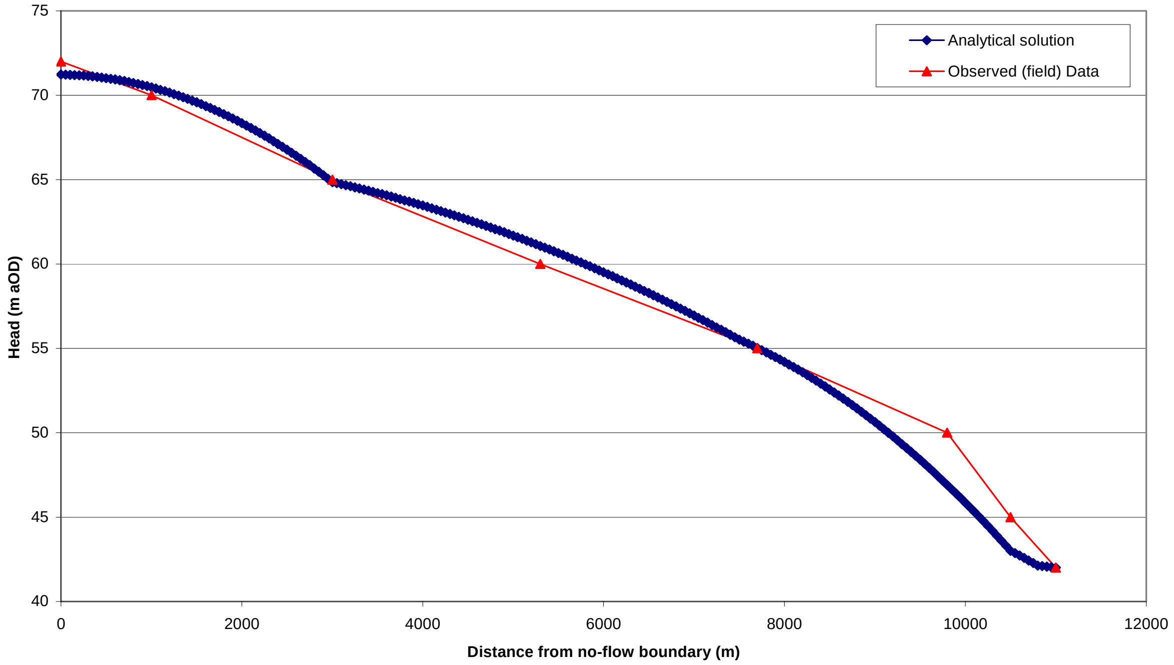
Sample	Date	CFC-12 pmol/l	CFC-11 pmol/l	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	$\delta^{13}C$ ‰
Blacksmith Hill	Apr-02			-6.61	-44.5	
Blacksmith Hill	Jun-02	3.05	4.88	-7.23	-45.4	-15.97
Blacksmith Hill	Aug-02	2.61	4.19			
Blacksmith Hill	Oct-02	2.21	4.35	-6.84	-42.8	-10.40
Blacksmith Hill	Nov-02	2.14	4.41	-6.48	-42.1	-10.91
Blacksmith Hill	Dec-02	2.25	3.45	-7.20	-44.6	-13.60
Blacksmith Hill	Jan-03			-7.02	-45.3	-13.97
Blacksmith Hill	Feb-03			-7.05	-47.9	-14.62
Mill House	Jun-02	3.50	0.79	-7.37	-47.2	-14.35
Mill House	Jul-02			-7.31	-47.3	
Mill House	Aug-02	0.40	0.97			
Mill House	Oct-02	2.51	0.40	-8.80	-57.4	-13.34
Mill House	Nov-02	2.56	4.92	-7.38	-46.5	-15.80
Mill House	Dec-02	3.02	1.13	-7.44	-47.7	-16.21
Mill House	Jan-03	1.57	2.05	-7.69	-48.9	-16.52
Mill House	Feb-03	0.77	1.35	-7.68	-50.9	-15.25
Great Wratting No. 1	Apr-02			-7.40	-47.0	-13.62
Great Wratting No. 1	Jun-02			-7.54	-49.7	-14.09
Great Wratting No. 1	Oct-02	30.5	24.5	-7.60	-49.8	-9.64
Wixoe	Apr-02			-7.25	-47.2	-9.09
Wixoe	Jun-02			-7.59	-48.2	-10.42
Rede Lane	Jan-03	1.75	0.55	-7.34	-47	-18.92
Gainsford Hall	Jan-03	0.45	0.28	-6.54	-42.9	-16.34
TL75/072	Feb-03	0.19	0.60	-7.25	-46.6	-10.91
Radwinter Rd	Feb-03	0.28	0.55	-7.18	-46.2	-10.77
Skippers Lane	Feb-03	1.97	0.34	-6.79	-43.9	-16.08
Thurlow Road	Feb-03	0.23	0.63	-6.85	-45.3	-10.36
River Stour	Oct-01			-6.21	-40.7	-14.91
River Stour	Nov-01			-6.99	-49.1	-15.87
River Stour	Dec-01			-7.11	-46.2	-15.82

River Stour	Jan-02			-7.01	-46.8	
River Stour	Feb-02			-6.90	-45.4	-17.47
River Stour	Mar-02			-7.09	-44.5	-15.50
River Stour	Apr-02			-6.77	-45.5	-15.35
River Stour	Jun-02			-7.03	-45.8	-15.98
River Stour	Oct-02	2.75	5.44	-6.86	-41.6	-13.36
River Stour	Nov-02			-7.05	-45.0	
River Stour	Jan-03			-7.37	-47.9	
River Stour	Feb-03			-6.98	-45.9	

Appendix 3

Spreadsheet model

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 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.



(Field data from contour plot of EA data for March 1999)

Zones in the model:

Length (m)	Location	Recharge (mm/a)	Transmissivity (m2/d)	Fixed Head (m aOD)
0	Interfluve	5	10	
3000	Interfluve	5	10	
4500	Interfluve	5	35	
3000	Interfluve	20	45	
290	Valley side in till	50	100	
200	Unconfined chalk	300	700	
10	River	300	700	42

X coordinate at left hand boundary = 0

Flow at left hand boundary = 0 m^3/d

Fixed head at RH Boundary42 m aOD

Recharge zones:

Zone	Value		
	mm/a	mm/d	m/d
1	5	0.013699	1.37E-05
2	5	0.013699	1.37E-05
3	20	0.054795	5.48E-05
4	50	0.136986	0.000137
5	300	0.821918	0.000822
6	300	0.821918	0.000822

Transmissivity zones:

Zone	Value
	m^2/d
1	10
2	35
3	45
4	100
5	700
6	700

Distance	T zone	Recharge zone					Head at end
			Flow	Cumulative Flow	Coefficients		Analytical solution
(m)			(m3/d)	(m3/d)	A	B	(m)
0	1	1	0	0	0	-71.22	71.22
50	1	1	0.000685	0.0006849	6.849E-05	-71.22	71.22
100	1	1	0.000685	0.0013699	0.000137	-71.22	71.21
150	1	1	0.000685	0.0020548	0.0002055	-71.21	71.20
200	1	1	0.000685	0.0027397	0.000274	-71.20	71.18
250	1	1	0.000685	0.0034247	0.0003425	-71.18	71.16
300	1	1	0.000685	0.0041096	0.000411	-71.16	71.14
350	1	1	0.000685	0.0047945	0.0004795	-71.14	71.11
400	1	1	0.000685	0.0054795	0.0005479	-71.11	71.09
450	1	1	0.000685	0.0061644	0.0006164	-71.09	71.05
500	1	1	0.000685	0.0068493	0.0006849	-71.05	71.02
550	1	1	0.000685	0.0075342	0.0007534	-71.02	70.98
600	1	1	0.000685	0.0082192	0.0008219	-70.98	70.94
650	1	1	0.000685	0.0089041	0.0008904	-70.94	70.89
700	1	1	0.000685	0.009589	0.0009589	-70.89	70.84
750	1	1	0.000685	0.010274	0.0010274	-70.84	70.79
800	1	1	0.000685	0.0109589	0.0010959	-70.79	70.73
850	1	1	0.000685	0.0116438	0.0011644	-70.73	70.67
900	1	1	0.000685	0.0123288	0.0012329	-70.67	70.61
950	1	1	0.000685	0.0130137	0.0013014	-70.61	70.54

Distance	T zone	Recharge zone					Head at end
			Flow	Cumulative Flow	Coefficients		Analytical solution
(m)			(m3/d)	(m3/d)	A	B	(m)
1000	1	1	0.000685	0.0136986	0.0013699	-70.54	70.47
1050	1	1	0.000685	0.0143836	0.0014384	-70.47	70.40
1100	1	1	0.000685	0.0150685	0.0015068	-70.40	70.32
1150	1	1	0.000685	0.0157534	0.0015753	-70.32	70.24
1200	1	1	0.000685	0.0164384	0.0016438	-70.24	70.15
1250	1	1	0.000685	0.0171233	0.0017123	-70.15	70.07
1300	1	1	0.000685	0.0178082	0.0017808	-70.07	69.98
1350	1	1	0.000685	0.0184932	0.0018493	-69.98	69.88
1400	1	1	0.000685	0.0191781	0.0019178	-69.88	69.78
1450	1	1	0.000685	0.019863	0.0019863	-69.78	69.68
1500	1	1	0.000685	0.0205479	0.0020548	-69.68	69.58
1550	1	1	0.000685	0.0212329	0.0021233	-69.58	69.47
1600	1	1	0.000685	0.0219178	0.0021918	-69.47	69.36
1650	1	1	0.000685	0.0226027	0.0022603	-69.36	69.25
1700	1	1	0.000685	0.0232877	0.0023288	-69.25	69.13
1750	1	1	0.000685	0.0239726	0.0023973	-69.13	69.01
1800	1	1	0.000685	0.0246575	0.0024658	-69.01	68.88
1850	1	1	0.000685	0.0253425	0.0025342	-68.88	68.75
1900	1	1	0.000685	0.0260274	0.0026027	-68.75	68.62
1950	1	1	0.000685	0.0267123	0.0026712	-68.62	68.48
2000	1	1	0.000685	0.0273973	0.0027397	-68.48	68.35
2050	1	1	0.000685	0.0280822	0.0028082	-68.35	68.20
2100	1	1	0.000685	0.0287671	0.0028767	-68.20	68.06
2150	1	1	0.000685	0.0294521	0.0029452	-68.06	67.91
2200	1	1	0.000685	0.030137	0.0030137	-67.91	67.76
2250	1	1	0.000685	0.0308219	0.0030822	-67.76	67.60
2300	1	1	0.000685	0.0315068	0.0031507	-67.60	67.44
2350	1	1	0.000685	0.0321918	0.0032192	-67.44	67.28
2400	1	1	0.000685	0.0328767	0.0032877	-67.28	67.11
2450	1	1	0.000685	0.0335616	0.0033562	-67.11	66.94
2500	1	1	0.000685	0.0342466	0.0034247	-66.94	66.77
2550	1	1	0.000685	0.0349315	0.0034932	-66.77	66.59
2600	1	1	0.000685	0.0356164	0.0035616	-66.59	66.41
2650	1	1	0.000685	0.0363014	0.0036301	-66.41	66.23
2700	1	1	0.000685	0.0369863	0.0036986	-66.23	66.04
2750	1	1	0.000685	0.0376712	0.0037671	-66.04	65.85
2800	1	1	0.000685	0.0383562	0.0038356	-65.85	65.66
2850	1	1	0.000685	0.0390411	0.0039041	-65.66	65.46
2900	1	1	0.000685	0.039726	0.0039726	-65.46	65.26
2950	1	1	0.000685	0.040411	0.0040411	-65.26	65.06
3000	1	1	0.000685	0.0410959	0.0041096	-65.06	64.85
3050	2	2	0.000685	0.0417808	0.0011937	-64.85	64.79
3100	2	2	0.000685	0.0424658	0.0012133	-64.79	64.73
3150	2	2	0.000685	0.0431507	0.0012329	-64.73	64.67
3200	2	2	0.000685	0.0438356	0.0012524	-64.67	64.61
3250	2	2	0.000685	0.0445205	0.001272	-64.61	64.54
3300	2	2	0.000685	0.0452055	0.0012916	-64.54	64.48
3350	2	2	0.000685	0.0458904	0.0013112	-64.48	64.41
3400	2	2	0.000685	0.0465753	0.0013307	-64.41	64.34
3450	2	2	0.000685	0.0472603	0.0013503	-64.34	64.28
3500	2	2	0.000685	0.0479452	0.0013699	-64.28	64.21

Distance	T zone	Recharge zone					Head at end
			Flow	Cumulative Flow	Coefficients		Analytical solution
(m)			(m3/d)	(m3/d)	A	B	(m)
3550	2	2	0.000685	0.0486301	0.0013894	-64.21	64.14
3600	2	2	0.000685	0.0493151	0.001409	-64.14	64.07
3650	2	2	0.000685	0.05	0.0014286	-64.07	63.99
3700	2	2	0.000685	0.0506849	0.0014481	-63.99	63.92
3750	2	2	0.000685	0.0513699	0.0014677	-63.92	63.85
3800	2	2	0.000685	0.0520548	0.0014873	-63.85	63.77
3850	2	2	0.000685	0.0527397	0.0015068	-63.77	63.70
3900	2	2	0.000685	0.0534247	0.0015264	-63.70	63.62
3950	2	2	0.000685	0.0541096	0.001546	-63.62	63.54
4000	2	2	0.000685	0.0547945	0.0015656	-63.54	63.46
4050	2	2	0.000685	0.0554795	0.0015851	-63.46	63.38
4100	2	2	0.000685	0.0561644	0.0016047	-63.38	63.30
4150	2	2	0.000685	0.0568493	0.0016243	-63.30	63.22
4200	2	2	0.000685	0.0575342	0.0016438	-63.22	63.14
4250	2	2	0.000685	0.0582192	0.0016634	-63.14	63.05
4300	2	2	0.000685	0.0589041	0.001683	-63.05	62.97
4350	2	2	0.000685	0.059589	0.0017025	-62.97	62.88
4400	2	2	0.000685	0.060274	0.0017221	-62.88	62.80
4450	2	2	0.000685	0.0609589	0.0017417	-62.80	62.71
4500	2	2	0.000685	0.0616438	0.0017613	-62.71	62.62
4550	2	2	0.000685	0.0623288	0.0017808	-62.62	62.53
4600	2	2	0.000685	0.0630137	0.0018004	-62.53	62.44
4650	2	2	0.000685	0.0636986	0.00182	-62.44	62.35
4700	2	2	0.000685	0.0643836	0.0018395	-62.35	62.26
4750	2	2	0.000685	0.0650685	0.0018591	-62.26	62.16
4800	2	2	0.000685	0.0657534	0.0018787	-62.16	62.07
4850	2	2	0.000685	0.0664384	0.0018982	-62.07	61.97
4900	2	2	0.000685	0.0671233	0.0019178	-61.97	61.88
4950	2	2	0.000685	0.0678082	0.0019374	-61.88	61.78
5000	2	2	0.000685	0.0684932	0.0019569	-61.78	61.68
5050	2	2	0.000685	0.0691781	0.0019765	-61.68	61.58
5100	2	2	0.000685	0.069863	0.0019961	-61.58	61.48
5150	2	2	0.000685	0.0705479	0.0020157	-61.48	61.38
5200	2	2	0.000685	0.0712329	0.0020352	-61.38	61.28
5250	2	2	0.000685	0.0719178	0.0020548	-61.28	61.18
5300	2	2	0.000685	0.0726027	0.0020744	-61.18	61.07
5350	2	2	0.000685	0.0732877	0.0020939	-61.07	60.97
5400	2	2	0.000685	0.0739726	0.0021135	-60.97	60.86
5450	2	2	0.000685	0.0746575	0.0021331	-60.86	60.75
5500	2	2	0.000685	0.0753425	0.0021526	-60.75	60.65
5550	2	2	0.000685	0.0760274	0.0021722	-60.65	60.54
5600	2	2	0.000685	0.0767123	0.0021918	-60.54	60.43
5650	2	2	0.000685	0.0773973	0.0022114	-60.43	60.32
5700	2	2	0.000685	0.0780822	0.0022309	-60.32	60.20
5750	2	2	0.000685	0.0787671	0.0022505	-60.20	60.09
5800	2	2	0.000685	0.0794521	0.0022701	-60.09	59.98
5850	2	2	0.000685	0.080137	0.0022896	-59.98	59.86
5900	2	2	0.000685	0.0808219	0.0023092	-59.86	59.75
5950	2	2	0.000685	0.0815068	0.0023288	-59.75	59.63
6000	2	2	0.000685	0.0821918	0.0023483	-59.63	59.51
6050	2	2	0.000685	0.0828767	0.0023679	-59.51	59.39

Distance	T zone	Recharge zone	Flow	Cumulative Flow	Coefficients		Head at end Analytical solution
(m)			(m3/d)	(m3/d)	A	B	(m)
6100	2	2	0.000685	0.0835616	0.0023875	-59.39	59.27
6150	2	2	0.000685	0.0842466	0.002407	-59.27	59.15
6200	2	2	0.000685	0.0849315	0.0024266	-59.15	59.03
6250	2	2	0.000685	0.0856164	0.0024462	-59.03	58.91
6300	2	2	0.000685	0.0863014	0.0024658	-58.91	58.78
6350	2	2	0.000685	0.0869863	0.0024853	-58.78	58.66
6400	2	2	0.000685	0.0876712	0.0025049	-58.66	58.53
6450	2	2	0.000685	0.0883562	0.0025245	-58.53	58.41
6500	2	2	0.000685	0.0890411	0.002544	-58.41	58.28
6550	2	2	0.000685	0.089726	0.0025636	-58.28	58.15
6600	2	2	0.000685	0.090411	0.0025832	-58.15	58.02
6650	2	2	0.000685	0.0910959	0.0026027	-58.02	57.89
6700	2	2	0.000685	0.0917808	0.0026223	-57.89	57.76
6750	2	2	0.000685	0.0924658	0.0026419	-57.76	57.62
6800	2	2	0.000685	0.0931507	0.0026614	-57.62	57.49
6850	2	2	0.000685	0.0938356	0.002681	-57.49	57.36
6900	2	2	0.000685	0.0945205	0.0027006	-57.36	57.22
6950	2	2	0.000685	0.0952055	0.0027202	-57.22	57.08
7000	2	2	0.000685	0.0958904	0.0027397	-57.08	56.95
7050	2	2	0.000685	0.0965753	0.0027593	-56.95	56.81
7100	2	2	0.000685	0.0972603	0.0027789	-56.81	56.67
7150	2	2	0.000685	0.0979452	0.0027984	-56.67	56.53
7200	2	2	0.000685	0.0986301	0.002818	-56.53	56.39
7250	2	2	0.000685	0.0993151	0.0028376	-56.39	56.24
7300	2	2	0.000685	0.1	0.0028571	-56.24	56.10
7350	2	2	0.000685	0.1006849	0.0028767	-56.10	55.96
7400	2	2	0.000685	0.1013699	0.0028963	-55.96	55.81
7450	2	2	0.000685	0.1020548	0.0029159	-55.81	55.67
7500	2	2	0.000685	0.1027397	0.0029354	-55.67	55.52
7550	3	3	0.00274	0.1054795	0.002344	-55.52	55.40
7600	3	3	0.00274	0.1082192	0.0024049	-55.40	55.28
7650	3	3	0.00274	0.1109589	0.0024658	-55.28	55.15
7700	3	3	0.00274	0.1136986	0.0025266	-55.15	55.03
7750	3	3	0.00274	0.1164384	0.0025875	-55.03	54.89
7800	3	3	0.00274	0.1191781	0.0026484	-54.89	54.76
7850	3	3	0.00274	0.1219178	0.0027093	-54.76	54.62
7900	3	3	0.00274	0.1246575	0.0027702	-54.62	54.48
7950	3	3	0.00274	0.1273973	0.0028311	-54.48	54.34
8000	3	3	0.00274	0.130137	0.0028919	-54.34	54.19
8050	3	3	0.00274	0.1328767	0.0029528	-54.19	54.04
8100	3	3	0.00274	0.1356164	0.0030137	-54.04	53.89
8150	3	3	0.00274	0.1383562	0.0030746	-53.89	53.74
8200	3	3	0.00274	0.1410959	0.0031355	-53.74	53.58
8250	3	3	0.00274	0.1438356	0.0031963	-53.58	53.42
8300	3	3	0.00274	0.1465753	0.0032572	-53.42	53.25
8350	3	3	0.00274	0.1493151	0.0033181	-53.25	53.09
8400	3	3	0.00274	0.1520548	0.003379	-53.09	52.92
8450	3	3	0.00274	0.1547945	0.0034399	-52.92	52.74
8500	3	3	0.00274	0.1575342	0.0035008	-52.74	52.57
8550	3	3	0.00274	0.160274	0.0035616	-52.57	52.39
8600	3	3	0.00274	0.1630137	0.0036225	-52.39	52.20

Distance	T zone	Recharge zone	Flow	Cumulative Flow	Coefficients		Head at end Analytical solution
(m)			(m3/d)	(m3/d)	A	B	(m)
8650	3	3	0.00274	0.1657534	0.0036834	-52.20	52.02
8700	3	3	0.00274	0.1684932	0.0037443	-52.02	51.83
8750	3	3	0.00274	0.1712329	0.0038052	-51.83	51.64
8800	3	3	0.00274	0.1739726	0.0038661	-51.64	51.44
8850	3	3	0.00274	0.1767123	0.0039269	-51.44	51.24
8900	3	3	0.00274	0.1794521	0.0039878	-51.24	51.04
8950	3	3	0.00274	0.1821918	0.0040487	-51.04	50.84
9000	3	3	0.00274	0.1849315	0.0041096	-50.84	50.63
9050	3	3	0.00274	0.1876712	0.0041705	-50.63	50.42
9100	3	3	0.00274	0.190411	0.0042314	-50.42	50.21
9150	3	3	0.00274	0.1931507	0.0042922	-50.21	49.99
9200	3	3	0.00274	0.1958904	0.0043531	-49.99	49.77
9250	3	3	0.00274	0.1986301	0.004414	-49.77	49.55
9300	3	3	0.00274	0.2013699	0.0044749	-49.55	49.33
9350	3	3	0.00274	0.2041096	0.0045358	-49.33	49.10
9400	3	3	0.00274	0.2068493	0.0045967	-49.10	48.87
9450	3	3	0.00274	0.209589	0.0046575	-48.87	48.63
9500	3	3	0.00274	0.2123288	0.0047184	-48.63	48.39
9550	3	3	0.00274	0.2150685	0.0047793	-48.39	48.15
9600	3	3	0.00274	0.2178082	0.0048402	-48.15	47.91
9650	3	3	0.00274	0.2205479	0.0049011	-47.91	47.66
9700	3	3	0.00274	0.2232877	0.0049619	-47.66	47.41
9750	3	3	0.00274	0.2260274	0.0050228	-47.41	47.16
9800	3	3	0.00274	0.2287671	0.0050837	-47.16	46.91
9850	3	3	0.00274	0.2315068	0.0051446	-46.91	46.65
9900	3	3	0.00274	0.2342466	0.0052055	-46.65	46.39
9950	3	3	0.00274	0.2369863	0.0052664	-46.39	46.12
10000	3	3	0.00274	0.239726	0.0053272	-46.12	45.85
10050	3	3	0.00274	0.2424658	0.0053881	-45.85	45.58
10100	3	3	0.00274	0.2452055	0.005449	-45.58	45.31
10150	3	3	0.00274	0.2479452	0.0055099	-45.31	45.03
10200	3	3	0.00274	0.2506849	0.0055708	-45.03	44.75
10250	3	3	0.00274	0.2534247	0.0056317	-44.75	44.47
10300	3	3	0.00274	0.2561644	0.0056925	-44.47	44.18
10350	3	3	0.00274	0.2589041	0.0057534	-44.18	43.89
10400	3	3	0.00274	0.2616438	0.0058143	-43.89	43.60
10450	3	3	0.00274	0.2643836	0.0058752	-43.60	43.31
10500	3	3	0.00274	0.2671233	0.0059361	-43.31	43.01
10550	4	4	0.006849	0.2739726	0.0027397	-43.01	42.87
10600	4	4	0.006849	0.2808219	0.0028082	-42.87	42.73
10650	4	4	0.006849	0.2876712	0.0028767	-42.73	42.58
10700	4	4	0.006849	0.2945205	0.0029452	-42.58	42.43
10750	4	4	0.006849	0.3013699	0.0030137	-42.43	42.28
10800	4	4	0.006849	0.3082192	0.0030822	-42.28	42.12
10850	5	5	0.041096	0.3493151	0.000499	-42.12	42.10
10900	5	5	0.041096	0.390411	0.0005577	-42.10	42.07
10950	5	5	0.041096	0.4315068	0.0006164	-42.07	42.04
11000	6	6	0.041096	0.4726027	0.0006751	-42.04	42.00

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.

BERRIDGE, N.G., BRISTOW, C.R., ELLISON, R.A., HEATH, M.J., MILLS, S.R., MILLWARD, D., MOORLOCK, B.S.P., PATTISON, J., SMITH, A., YOUNG, B. AND ZALASIEWICZ. 1991, Sudbury Geological Map Sheet 206, British Geological Survey.

COX, S.J. 2002. Recharge through drift: A modelling investigation into recharge pathways through the Lowestoft Till of East Anglia, with special reference to sand lenses and fractures. MSc dissertation University of Reading.

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. Hydrogeology Journal 9, 60–78.

GRISAK, G.E. AND CHERRY, J.A. 1975. Hydrologic characteristics and response of fractured till and clay confining a shallow aquifer. Canadian Geotechnical Journal 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), Royal Society of Canada Special Publication 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. Journal of Geology 60, 303–329.

HOSSAIN, D. 1992. Prediction of permeability of fractured tills. Quarterly Journal of Engineering Geology 25, 331–342.

INESON, J. 1962. A hydrogeological study of the permeability of the Chalk. Journal of the Institute of Water Engineering Science 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.

JACKSON, C.R. 2001. The development and validation of the object-oriented quasi three-dimensional regional groundwater model ZOOMQ3D. British Geological Survey Internal Report IR/01/144.

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. Quarterly Journal of Engineering Geology 14, 87–96.

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

MANSOUR, M.M. AND HUGHES, G.A. 2004. Application of numerical modelling to investigate recharge to the Chalk aquifer beneath thick till deposits in East Anglia. British Geological Survey Technical Report, IR/04/127.

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.

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.

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.

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.

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), Geological Society of London Special Publication 130, 129–141.

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

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

WOODLAND, A.W. 1946. Water supply from underground sources of Cambridge–Ipswich District – General discussion. Geological Survey of Great Britain Wartime Pamphlet No 20, Part X, 89pp.