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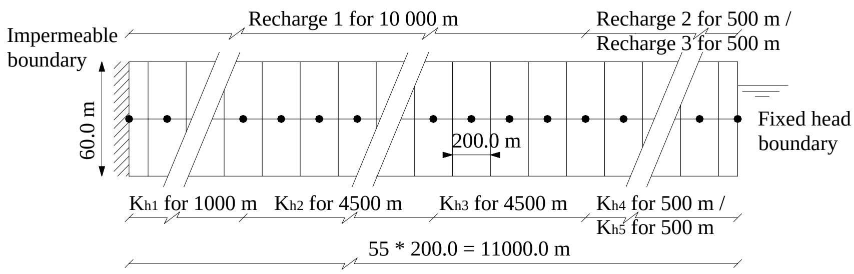
Application of Numerical Modelling to Investigate Recharge To the Chalk Aquifer Beneath Thick Till Deposits in East Anglia

Groundwater Systems and Water Quality Programme

Internal Report IR/04/127



BRITISH GEOLOGICAL SURVEY

GROUNDWATER SYSTEMS AND WATER QUALITY PROGRAMME

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Application of Numerical Modelling to Investigate Recharge To the Chalk Aquifer Beneath Thick Till Deposits in East Anglia

Mansour M M, Hughes A G.

Keywords

Chalk; till-deposits; numerical modelling; ZOOMQ3D; time lag.

Front cover

Illustration of the numerical representation of the conceptual model.

Bibliographical reference

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British Geological Survey offices

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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

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Summary

The importance of the Chalk aquifer as a groundwater source and the uncertainty associated with the occurrence of recharge to the Chalk when it is overlain by thick till deposits has led to the development of a project to investigate the Chalk-till groundwater system. An area in East Anglia, where the Chalk is mainly covered by the till-deposits but still exposed in some places especially at the river valleys, has been selected for investigation. This study involves drilling cored boreholes, monitoring groundwater levels, sampling Chalk and till groundwaters and porewaters and the development of a conceptual model of Chalk-till groundwater hydrogeology (Marks et al., 2004). This report discusses the application of numerical modelling to validate the conceptual model built by Marks et al. (2004). This is achieved by determining the likely recharge rates and transmissivity distribution required to reproduce the groundwater heads observed in the study area. A one-dimensional groundwater model has been constructed and both steady state and time-variant modelling are undertaken.

A one-dimensional model that extends 11 km starting from the river Stour to the south is considered. This model includes a 1 km of exposed Chalk next to the river and 10 km of till-deposits covered Chalk. A fixed head is considered at the end where the river is located while an impermeable boundary is imposed at the other end.

The steady state modelling showed that recharge rates of 5 mm/a through the till and 300 mm/a over the exposed Chalk were required to produce the observed groundwater heads. A transmissivity value of between 10 and 50 m2/d was used under the till and a transmissivity value of greater than 400 m2/d was used in the valley.

Under time variant conditions, the numerical results are compared to the groundwater head fluctuations recorded at two observation wells. The first is approximately 1000 m away from the river bank and drilled in the exposed part of the Chalk, and the second is approximately 9000 m away from the river bank and drilled in the covered part of the Chalk. The use of constant recharge under the till and seasonally varying the recharge over exposed part of the Chalk produced reasonable match between the numerical and observed results at the first observation well when the parameter distribution for the steady state model is used. However, this parameter distribution could not reproduce the observed fluctuations in the groundwater heads at the second observation well drilled in the covered part of the Chalk. A small, approximately 1%, seasonal component of recharge under the till was required to produce the observed groundwater head fluctuations. This is justified by calculating seasonal changes in the vertical hydraulic gradients in the system. While simple calculations showed that there should be a lag time between the groundwater hydrographs at the two observation wells, the field hydrographs at these two observation wells do not show any time lag between the occurrence of the peaks or the troughs. This is further evidence for some degree of seasonality in the recharge under the till.

1 Introduction

The British Geological Survey (BGS) has undertaken a study to investigate recharge rates and mechanisms through till to the underlying Chalk aquifer. An area in East-Anglia was selected for this research. The Chalk has low matrix permeability due to small pore apertures but has a moderate to high bulk permeability due to fractures. The till, which overlies extensive area of the Chalk, has a very low matrix permeability that significantly limits recharge. However, field investigations have shown that recharge is higher than can be explained by matrix permeability alone and, therefore, it is presumed that the till is fractured (Marks et al., 2004). It is assumed that these fractures increase the overall permeability of the till and create pathways for recharge to reach the Chalk. The study involved drilling investigation boreholes to identify the main geological units, to determine the porewater chemistry of the till and to monitor water level responses within the till and the Chalk to recharge. A conceptual model of the Chalk-till groundwater system was also developed. This involved the quantification of recharge components and an analysis of the properties of the Chalk. The conceptual model divides the Chalk aquifer into two domains. The first domain is characterised by low transmissivity Chalk, less than 50 m^2/d, and covered by the till. The second domain is characterised by exposed Chalk in the valleys where transmissivities are much higher and usually exceed 250 m^2/d.

A simple spreadsheet model was developed to simulate the piezometric surface in the Chalk based on an analytical solution under steady-state conditions. Although this spreadsheet model gives valuable information about the transmissivity of the Chalk and the recharge rates, it does not simulate time-variant groundwater heads. The time-variant results offer additional information, which if interpreted and compared to the observed field data, can improve the understanding of the groundwater system. In the current study, a numerical finite-difference groundwater flow model, ZOOMQ3D (Jackson, 2001), is used to investigate the Chalk-till groundwater system described by Marks et al. (2004). The additional features that can be incorporated in the numerical model, such as the simulation of the time-variant flow and the switching from confined to unconfined conditions allow a better spatial representation of the system and improve the understanding of the Chalk-till groundwater interaction.

The aim of the work is to use numerical modelling to determine the likely recharge rates and transmissivity distribution required to reproduce the observed groundwater heads. Emphasis is placed on adjusting the recharge rates and transmissivity values within physically justifiable ranges to investigate recharge to the Chalk-till system.

2 Description of the Area. Geology and Hydrogeology

The study area is located between the River Stour in the south, the River Granta in the southeast and the River Kennet in the north (Figure 1). The topography is of a gently sloping plateau dissected by river valleys. The region is mainly rural and arable landuse predominates. The area receives an average rainfall of approximately 600 mm a^{-1} and the evapo-transpiration is estimated to be in the order of 500 mm a^{-1}. The Chalk Formation, which is a major aquifer, is overlain by superficial deposits mainly till. The till, also known as the Boulder Clay, can exceed 30 m in thickness but thins towards the main river valleys where the Chalk becomes exposed.

The Chalk transmissivity is less than 50 m^2/d, and often lower, beneath the till-covered interfluves. However, within the main river valleys Chalk transmissivity is much higher, usually greater than 250 m^2/d and can sometimes exceed 1000 m^2/d. These higher transmissivities are due to the development of solution-enhanced fractures.

The till in East-Anglia is a clay rich deposit with subordinate lenses of sand and gravel. A large number of clasts of Chalk and flint occur within this till. Worldwide, many tills are known to be fractured (Klinck et al. 1996, Gerber et al. 2001, Van der Kamp 2001, etc.) and these fractures may be hydrogeologically significant as they could enhance the quantity and rate of recharge.

A water table within the till can exist and, in the centre of the interfluve, it may be within a few metres of ground surface. The piezometric surface of the Chalk starts from the water level at the river and rises up to a maximum of approximately 20 m above the river water level as shown in Figure 2.

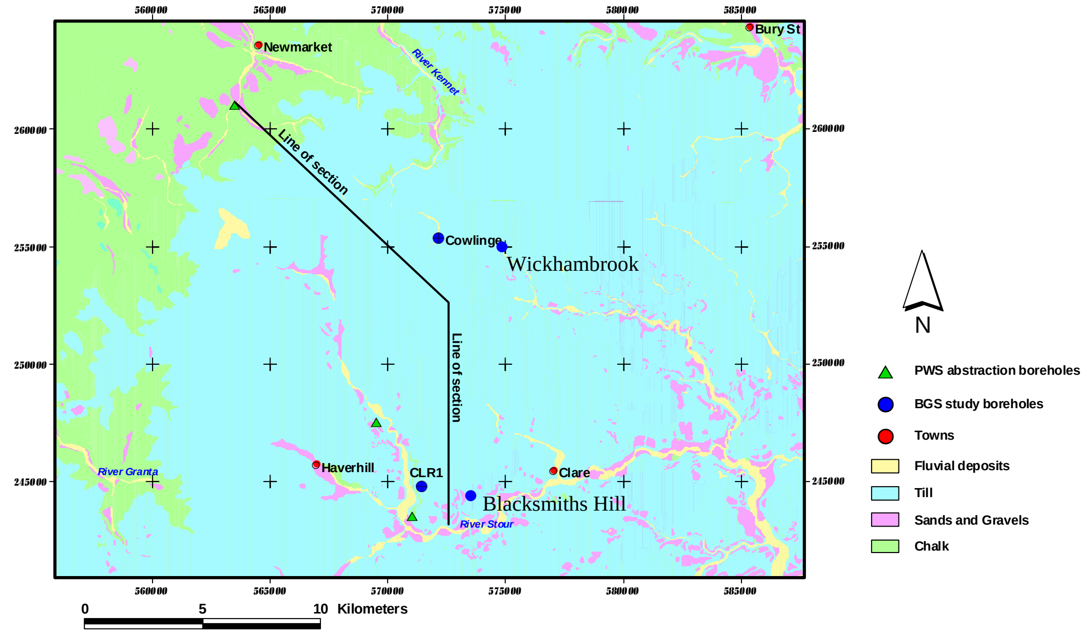


Figure 1 Plan view of the study area (After Marks et al. 2004).

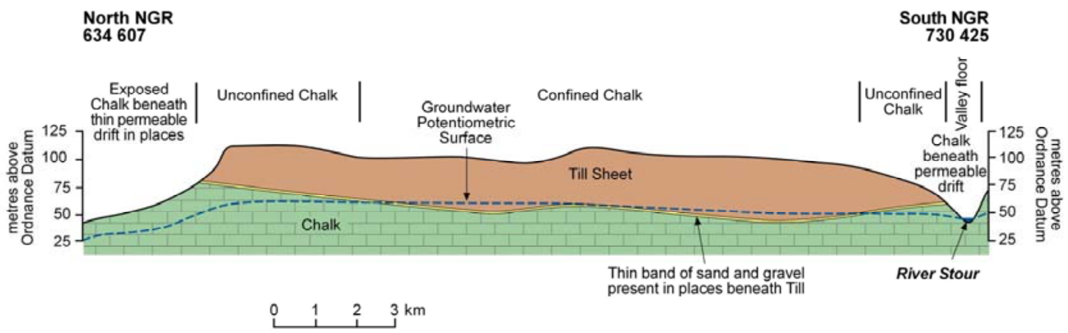


Figure 2 Geological section A-A (After Marks et al. 2004)

3 Observed Groundwater Heads

The observed regional groundwater head values within the Chalk are derived from the hydrogeological maps of the area (Institute of Geological Sciences and Anglian Water Authority, 1981). Head variation in the groundwater system is driven by seasonality in recharge. The groundwater fluctuation within the Chalk is recorded at two observation wells, Blacksmiths Hill and Wickhambrook, which are located approximately 1 km and 9 km from the river respectively. The hydrograph for Blacksmiths Hill observation well, which is drilled in the unconfined part of the Chalk, has an annual groundwater fluctuation of about 2.5 m to 4.5 m (Figure 3). The hydrograph for Wickhambrook observation well, which is drilled where the Chalk is confined by the till, has an annual groundwater fluctuation of only about 0.3 m (Figure 3).

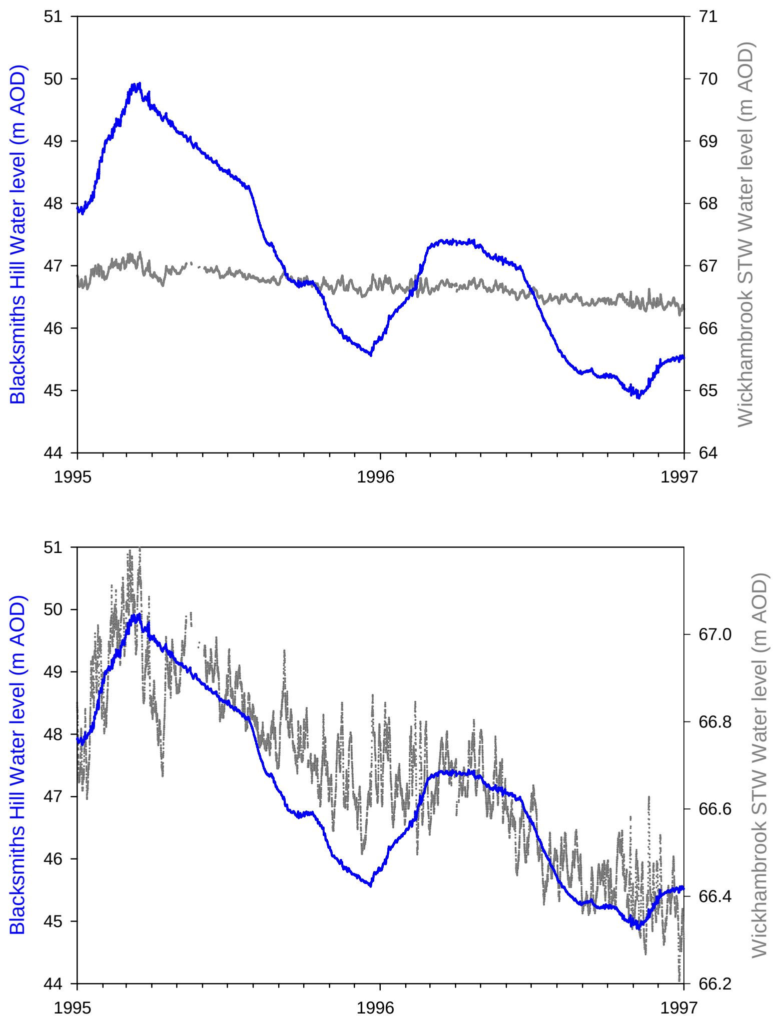


Figure 3 Groundwater hydrographs at Blacksmiths Hill and Wickhambrook observations wells (After Marks et al. 2004).

4 Conceptual Model of Groundwater Flow

To represent the groundwater system, a cross-section from the River Stour in the south to the groundwater divide approximately 11 km further north was considered. The conceptual model, Figure 4, focuses on the Chalk layer only. The relatively low permeability of the till restricts the recharge to the Chalk and, as a consequence, increase the volume of runoff available for recharge at the edge of the till sheet. The effects of the till are included in the conceptual model by considering that this layer provides limited but constant amount of recharge to the Chalk beneath it and by increasing the amount of recharge applied over the exposed part of the Chalk in the valleys. When time-variant conditions are investigated, the seasonal variations of the recharge are assumed to have a direct influence on the exposed part of the Chalk while the recharge beneath the till is constant. The conceptual model is illustrated in Figure 4.

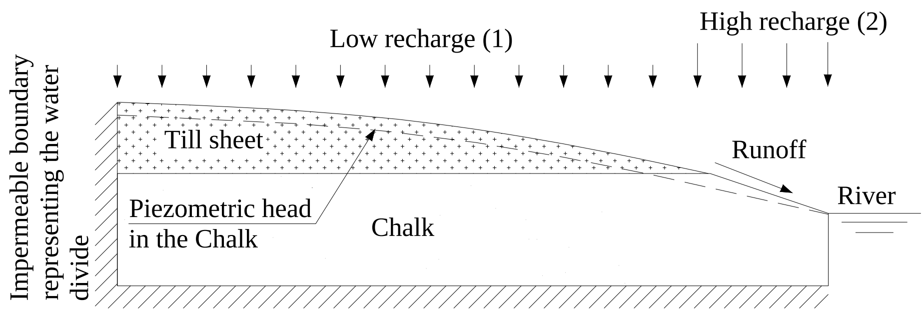


Figure 4 Conceptual model for simulating the groundwater profile in the Chalk

5 Numerical Model

The numerical groundwater flow model ZOOMQ3D (Jackson, 2001), is used to simulate groundwater flow in the aquifer system described above. The model uses a Cartesian mesh to solve the governing equation of the groundwater flow using a finite-difference approach. The features of this model relevant to this investigation are its capability to represent time-variant problems and to allow the switch between confined and unconfined conditions during the runtime at a given location. The latter mechanism is based on the elevation of the top of the aquifer and the groundwater head at a model node. This allows a better spatial representation of the piezometric surface in the Chalk under the till and in the river valleys.

The model represents a vertical slice through the conceptual model of the Chalk (Figure 4) and consists of a single layer. Assuming that the groundwater divide does not change location with time, it is represented by an impermeable boundary condition that is imposed at the north end of the conceptual model section (left hand side of Figure 5). A fixed head boundary is considered at the south end of the section (right hand side of Figure 5) to represent the river. The vertical slice is split horizontally into five zones for each of which a hydraulic conductivity value is specified. The numerical model calculates the transmissivity automatically by multiplying the hydraulic conductivity value by the saturated aquifer thickness.

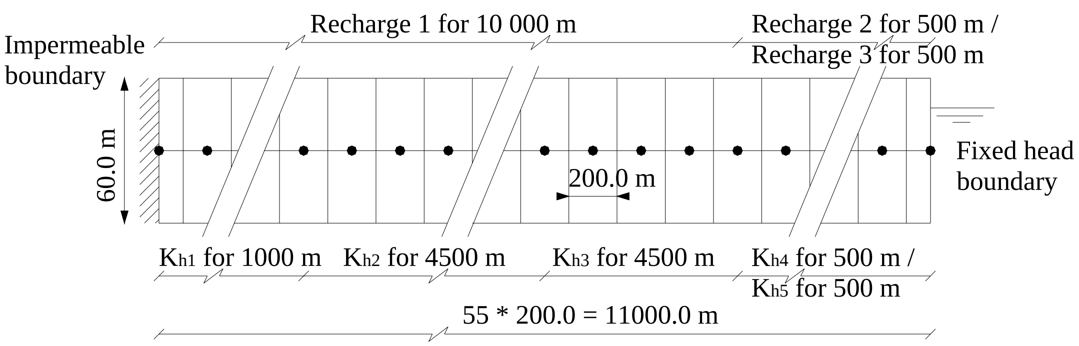


Figure 5 Numerical representation of the conceptual model.

6 Steady-State Modelling to Investigate Chalk Hydraulic Properties and Recharge Rates

This section describes the use of the model to estimate the hydraulic conductivity values and recharge rates that are required to produce a numerical piezometric surface similar to that observed in the Chalk. The transmissivity values and the recharge rates applied in the spreadsheet model used by Marks et al. (2004) are considered as the starting point for this study. Since the numerical model requires the hydraulic conductivity values rather than the transmissivity values, the initial values of the hydraulic conductivities are determined by dividing the transmissivity values produced by the spreadsheet model by the saturated thickness. Marks et al. (2004) used recharge values of 5 mm a^{-1} and 500 mm a^{-1} over the Chalk beneath the interfluves and in the river valleys respectively. They also suggest the use of hydraulic conductivity values of 0.05 m/d, 0.33 m/d and 0.82 m/d for the first 1000 m, the second 4500 m and the third 4500 m Chalk intervals measured from the northern impermeable boundary respectively, and the use of hydraulic conductivity values of 11.1 m/d and 1.9 m/d over the first and the second 500 m Chalk intervals north of the river respectively (Table 1). The use of these values in the numerical model produces a groundwater profile that is slightly lower than that observed, as shown in Figure A.2b of Appendix A. Using these aquifer parameters, the numerical model shows that an average recharge value of 900 mm a^{-1} must be applied in the river valleys to produce a good match between the numerical and field groundwater profiles as shown in Figure A.2c of Appendix A. This recharge value is greater than the rainfall; however, it may indicate that runoff from the till is recharging the Chalk on the valley sides.

Table 1 Hydraulic conductivity distribution over the Chalk aquifer zones as suggested by Marks et al. (2004)

Zone	Distance from the left boundary (m)	Hydraulic conductivity (m/d)
1	0 to 1000	0.05
2	1000 to 5500	0.33
3	5500 to 10000	0.82
4	10000 to 10500	1.9
5	10500 to 11000	11.1

Although the till sheet could transfer large amounts of runoff to the exposed Chalk in the valleys, recharge values in excess of 500 mm a^{-1} are believed to be unrealistic. The total recharge to the Chalk at the valleys is not expected to be more than 300 mm a^{-1} as shown in the time-variant study discussed later in the report. The reduction of the applied recharge rates over the river valleys, however, should be complemented by a reduction of the hydraulic conductivity values to elevate the groundwater profile to the position observed in the field. Several runs are carried out to estimate the hydraulic conductivities of the aquifer zones. These are presented in Appendix A.

It has been found that the representation of the vertical slice considered by the numerical model by six permeability zones with the following characteristics produce a good match between the numerical and field groundwater profiles. The first and the second zones stretch over two 1000 m intervals starting from the impermeable boundary and have hydraulic conductivity values of 0.05 m/d and 0.2 m/d respectively. The third zone stretches from the end of the second zone a distance of 3000 m and has a hydraulic conductivity of 0.3 m/d, the fourth zone stretches from the end of the third zone a distance of 5000 m and has a hydraulic conductivity of 0.8 m/d and the last two zones stretch over the last two 500 m intervals and have hydraulic conductivity values of 1.1 m/d and 6.0 m/d respectively (Table 2). These values produce steady-state groundwater profiles illustrated in Figure 6.

Table 2 Hydraulic conductivity distribution over the Chalk aquifer zones as suggested by this study.

Zone	Distance from the left boundary (m)	Hydraulic conductivity (m/d)
1	0 to 1000	0.05
2	1000 to 2000	0.2
3	2000 to 5000	0.3
4	5000 to 10000	0.8
5	10000 to 10500	1.1
6	10500 to 11000	6.0

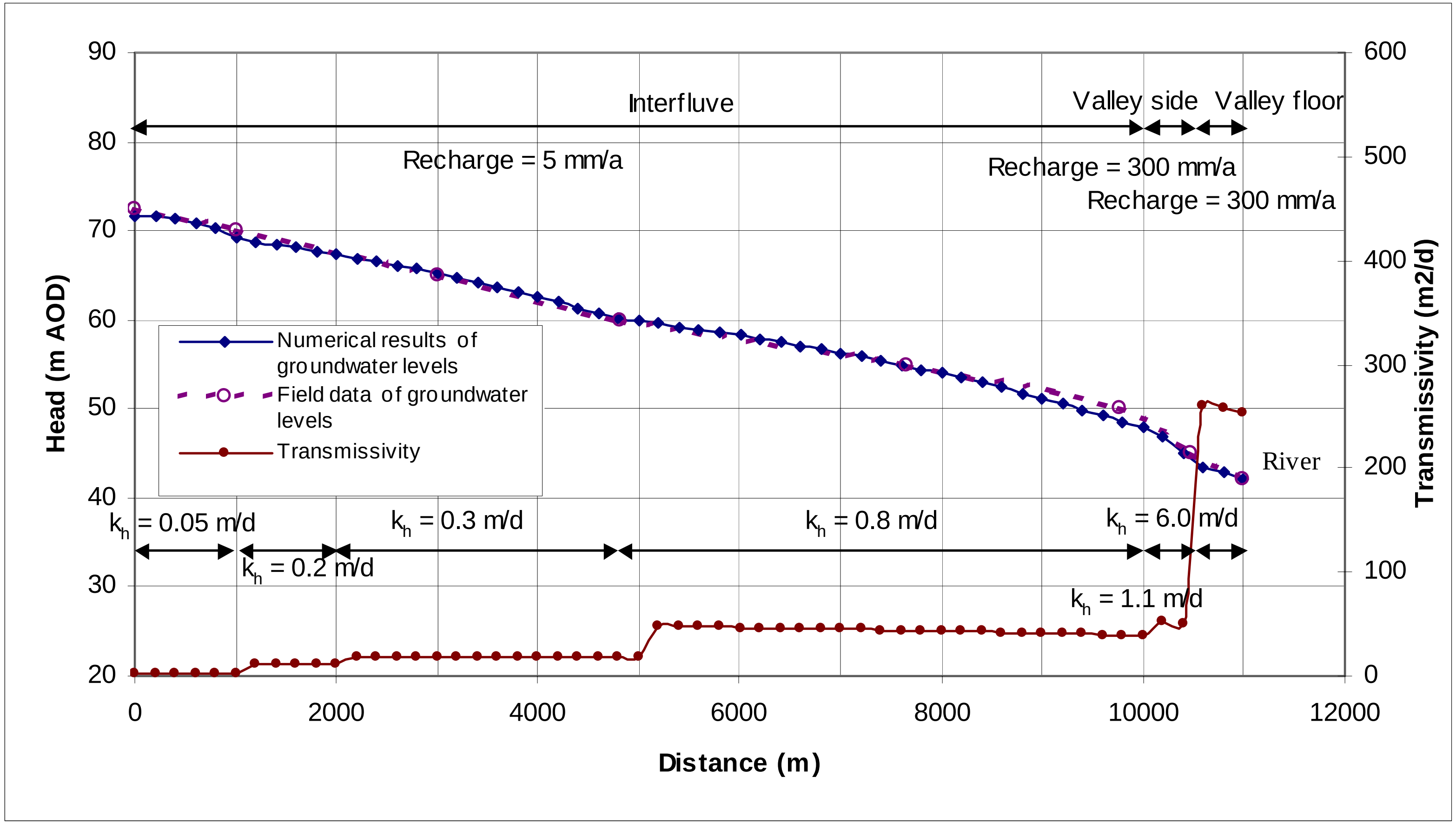


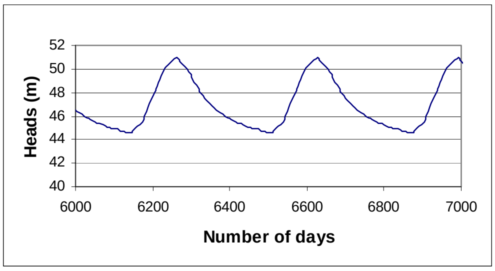
Figure 6 Head and transmissivity distribution for the final steady-state model.

7 Further Investigations Under Time Variant Conditions

The groundwater hydrographs for the two observation wells at Blacksmiths Hill and Wickhambrook allow further investigation into the Chalk-till groundwater system. The groundwater head in the Chalk fluctuates between 2.5 m and 4.5 m each year at the Blacksmiths Hill observation borehole but only between 0.25 m and 0.4 m per year at the Wickhambrook observation borehole. It was assumed that the recharge through the till is constant with time and that the small variation in the groundwater heads observed at Wickhambrook observation well is a response to the fluctuation of the groundwater heads in the valley.

To test this assumption, a time-variant model is considered in which a recharge rate of 500 mm a^{-1} is applied over the unconfined Chalk for six months of the year. A value of 500 mm a^{-1} is used to represent a relatively high recharge rate resulting from rainfall and runoff water. A constant recharge rate of 5 mm a^{-1} is applied uniformly over the till covered Chalk. The 500 mm a^{-1} recharge rates are distributed approximately normally over the six months and the 5 mm a^{-1} recharge rates are applied constantly at all time. In the first run, the Chalk is assumed to have a specific storage of 10-6 m^{-1} and a specific yield varying from 1% under the interfluves to 3% in the valley. The initial conditions for this simulation are obtained from the results of the steady-state model discussed in the previous section. The annual cycle of recharge is applied repeatedly until the system reaches a state of dynamic balance. This state is defined as the stage where the storage change over an annual cycle is zero. Generally the ratio between transmissivity and storage coefficient, termed diffusivity, defines the period of time required for a system to reach dynamic balance. The Chalk is a high diffusivity aquifer and consequently the model reaches a dynamic balance after a relatively short period of time.

The application of 500 mm a^{-1} recharge over the unconfined Chalk causes the groundwater head at the location of Blacksmiths Hill, to fluctuate between 45 m and 51 m as illustrated in Figure 7. The magnitude of this fluctuation is higher than that observed at this borehole. The annual groundwater fluctuation at Wickhambrook, although it has not reached dynamic balance, is about a few millimetres, which is much lower than that observed. Three possible approaches can be taken to reduce the groundwater fluctuation at the Blacksmiths Hill observation well. The first is by increasing the hydraulic conductivity, but this would alter the match between the numerical and observed groundwater profiles discussed in the previous section. The second is by increasing the value of the storage coefficient of the aquifer. However, the specific yield of 3% used in the model is already a high value and increasing this further would reduce the fluctuation observed at Wickhambrook observation well. The third option is to reduce the recharge rate applied over the exposed part of the Chalk. The latter option is the most plausible and agrees with best fit obtained with the previous steady-state modelling.



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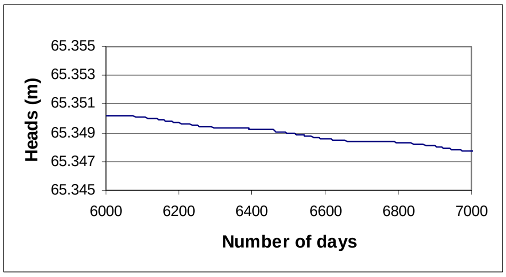
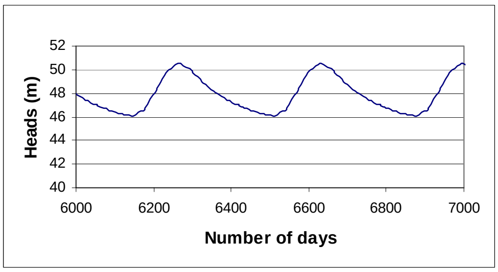


(b)

Figure 7 Modelled groundwater head fluctuations in the Chalk. (a) Blacksmiths Hill observation borehole drilled in the valley Chalk and (b) Wickhambrook observation borehole with 500 mm a^{-1} recharge.

Reducing the recharge value to 300 mm a^{-1} over the unconfined Chalk produces numerical groundwater head fluctuations at Blacksmiths Hill that are within the observed field range, as shown in Figure 8. However, this requires that the specific storage is set to a value of 1.67×10^{-7} m^{-1} and the specific yield is set to a value of 0.05% for the Chalk under the interfluves and to values of 4% and 3% for the first and the second 500 m Chalk intervals from the river respectively. The groundwater head at Wickhambrook observation well, however, does not show any response to the fluctuations created in the valley. Reducing the specific yield of the first and the second 500 m Chalk intervals from the river to 1% and 0.5% respectively brought the groundwater fluctuations at Wickhambrook observation well to an acceptable value of 0.25 m but created large groundwater fluctuations at Blacksmiths Hill as shown in Figure 9.

The failure of the numerical model to produce water level responses at both observation wells suggests that there is a problem or lack of understanding in the conceptual model. In the conceptual model, the observed seasonal water level fluctuation at Wickhambrook is a response to a change in head, due to recharge within the unconfined part of the Chalk. This assumption is questioned here.



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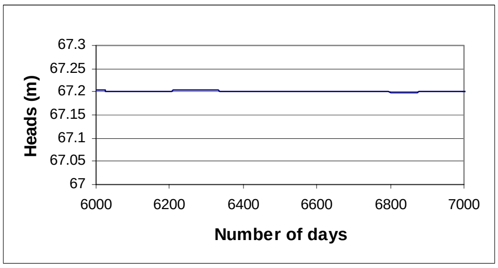
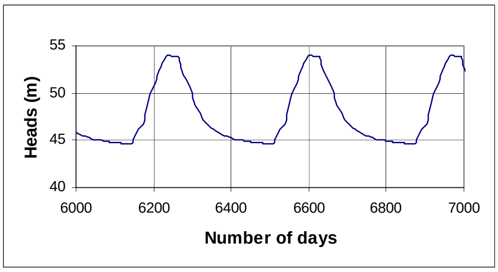
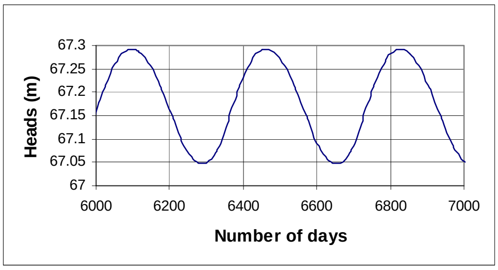


(b)

Figure 8 Modelled groundwater head fluctuations in the Chalk. (a) Blacksmiths Hill observation borehole drilled in the valley Chalk and (b) Wichambroock observation borehole with 300 mm a^{-1} recharge.



(a)



(b)

Figure 9 Modelled groundwater head fluctuations in the Chalk. (a) Blacksmiths Hill observation borehole drilled in the valley Chalk and (b) Wickhambrook observation borehole with 300 mm a^{-1} recharge and after reducing the specific yield in the unconfined Chalk.

Furthermore, if the groundwater fluctuations at the Wickhambrook borehole are caused by the groundwater fluctuations in the unconfined Chalk, there should be a time lag between the occurrence of the peak groundwater heads at Blacksmiths Hill and Wickhambrook observation wells. The output from the numerical model shows that peak water levels occur at Blacksmiths Hill borehole at 6250 days and that the response to this fluctuation is observed after 6450 days at the Wickhambrook borehole. This is a time lag of about 200 days (Figure 9).

The time required for any head perturbation occurring at a source point to be transferred through the aquifer and reach a second point located at a distance d from the source is given by the following analytical solution (U.S. Army Corps of Engineers, 1999):

$$t_{lag} = d\sqrt{\frac{PS}{4\pi T}}$$

Where

P is the period of the stage fluctuation. (T)

S is the storage coefficient. (Dimensionless)

T is the transmissivity. (L^2/T)

d is the distance between the source of fluctuation and the observation well. (L)

If an average transmissivity value of 35 m^2/d and an average storage coefficient of 0.05% are considered to represent the general characteristics of the Chalk, the above equation produces a time lag of 163 days. This is close to and confirms the occurrence of the lag observed in the numerical results. This time lag, however, is not observed in the field results as shown in Figure 3. Field data indicate that the peaks and the troughs of the groundwater fluctuations at both observation wells occur almost at the same time. The absence of the time lag between the field results at these observation wells is an indicator that the groundwater fluctuations observed within the unconfined Chalk are not the main cause of the groundwater fluctuations at Wickhambrook observation well. The failure to properly simulate these groundwater fluctuations using this conceptual model means that another mechanism must be identified to explain the groundwater system behaviour.

Field data indicate that the water table within the till sheet rises by approximately one metre in the wet season. Conversely, Figure 3 shows that the piezometric head in the confined Chalk rises by approximately 20 cm only. Figures 10a and 10b illustrate an approximate location of the water table in the till and the piezometric head in the Chalk during the wet and dry seasons respectively. The relatively large groundwater head movement in the till compared to the groundwater head movement in the Chalk, as illustrated in Figures 10a and 10b, provides a steeper vertical gradient during the recharge season which may lead to additional recharge water reaching the Chalk during this season.

If the locations of the water table in the till and the piezometric head in the Chalk shown in Figure 10b are considered to be representative of their positions in the dry season, the head difference of 15 m causes a vertical hydraulic gradient calculated at the top of the Chalk equal to $(25-10)/25 = 0.6$. During the wet season, the head difference increases to a value of 15.8 m if the locations of the water table in the till and the piezometric head in the Chalk are those shown in Figure 10a. The distance over which this gradient is applied is 26 m in this case. The vertical hydraulic gradient is, therefore, equal to $(26-10.2)/26 = 0.608$ in the wet season. This indicates that the head gradient calculated in the wet season is 1.33 % greater than the gradient calculated in the dry season and this should lead to approximately 1.33 % increase in the recharge reaching the confined Chalk.

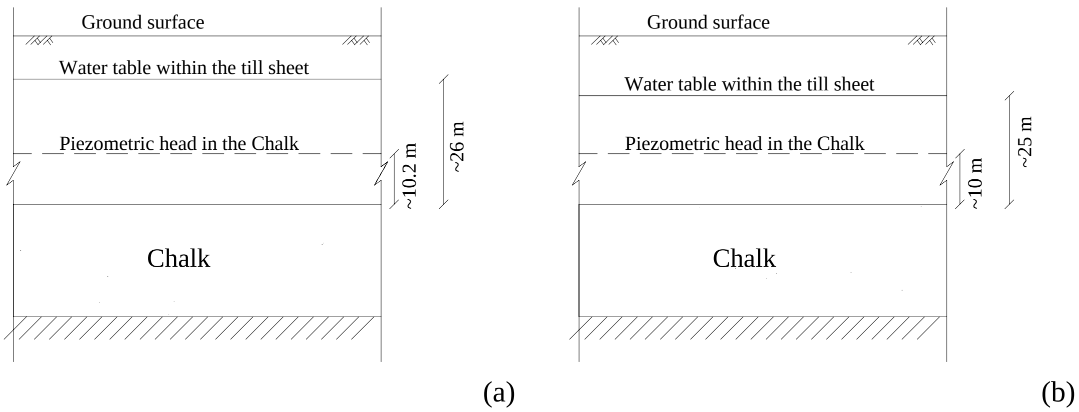
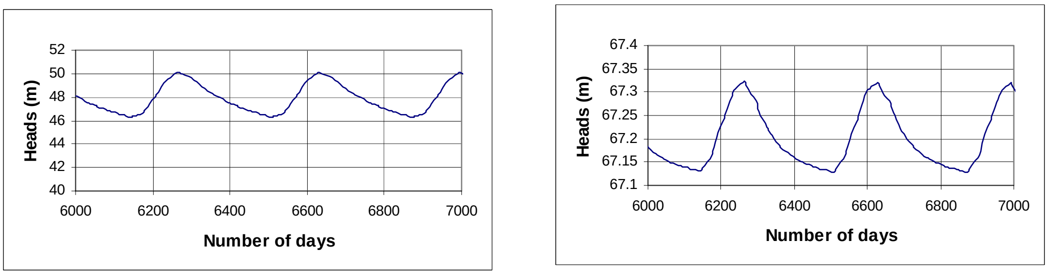


Figure 10 Seasonal changes in the vertical hydraulic gradient in the till. (a) Wet season case and (b) dry season case.

The numerical model is adjusted so that the constant recharge value applied to the confined Chalk is reduced to 4.95 mm a^{-1} and an amount of seasonally varying recharge of 0.05 mm a^{-1} is added to this part. The total amount of recharge applied in the wet season is approximately 1% greater than the amount of recharge applied in the dry season. The specific storage is set to a value of 1.67×10^{-6} m^{-1} and the specific yield values are set to 0.5% and 4% in the confined and unconfined Chalk respectively. The numerical results at Blacksmiths Hill and Wickhambrook observation wells are shown in Figures 11a and 11b respectively. These figures show that the magnitude of the groundwater fluctuations at both observation wells is similar to the observed field data. In addition, there are no significant time lags between the peaks and the troughs of the simulated groundwater head values at the observation wells.



(a) (b)

Figure 11 Modelled groundwater head fluctuations in the Chalk. (a) Blacksmiths Hill observation borehole drilled in the valley Chalk and (b) Wickhambrook observation borehole after modifying the specific storage and specific yield.

8 Summary

This report has described the modelling of groundwater flow in a Chalk aquifer overlain by till. The aim was to attempt to quantify the recharge through the till. A one-dimensional model was constructed of a slice through a Chalk valley. Various recharge rates through the till to the Chalk were applied to reproduce observed groundwater gradients and head fluctuations. To accomplish this both steady-state and time-variant modelling was undertaken.

The steady-state modelling showed that to reproduce the groundwater gradients a low recharge rate (5 mm a^{-1}) was required through the till and a high recharge rate (300 mm a^{-1}) was required over the unconfined Chalk in the valley. The latter is thought to be the result of both direct recharge from rainfall and indirect recharge from runoff from adjacent till covered areas. A transmissivity value of between 10 and 50 m^2/d was used under the till and a transmissivity value greater than 250 m^2/d was used in the valley.

Time-variant modelling showed that using a constant recharge under the till and seasonally varying recharge over the unconfined Chalk could not reproduce the observed fluctuations in the groundwater heads. By adjusting the storage coefficient, either the head fluctuation in the Chalk in the valley or the head fluctuation in the Chalk under the till could be reproduced. A small (1%) seasonal component of recharge under the till was required to produce the observed groundwater head fluctuations. This small seasonal change in the recharge value is justified on the basis of changes in the vertical gradient in the till taken from observation well data. The hydrographs of the Chalk groundwater head recorded at two observation wells that are approximately 8000 m apart, one in the valley and the other under the till, did not show any lag in their response. This provides further evidence for some degree of seasonality in the recharge under the till.

Appendix A

Several runs have been undertaken to estimate the recharge values over the Chalk. In this appendix the steps followed to reach the desired solution are presented. In the first set of runs five different permeability zones are considered to represent the aquifer. In the first run of this set, the hydraulic conductivities of the different aquifer zones are determined by dividing the transmissivity values used in the Spreadsheet model (Marks et al., 2004) by the observed field groundwater head values. In the subsequent runs, the hydraulic conductivity values are changed and the resulting groundwater heads are investigated.

Figure A.1 shows the first numerical representation of the vertical slice considered in the model. Table A.1 details the aquifer hydraulic conductivity values implemented in the model in this set of runs.

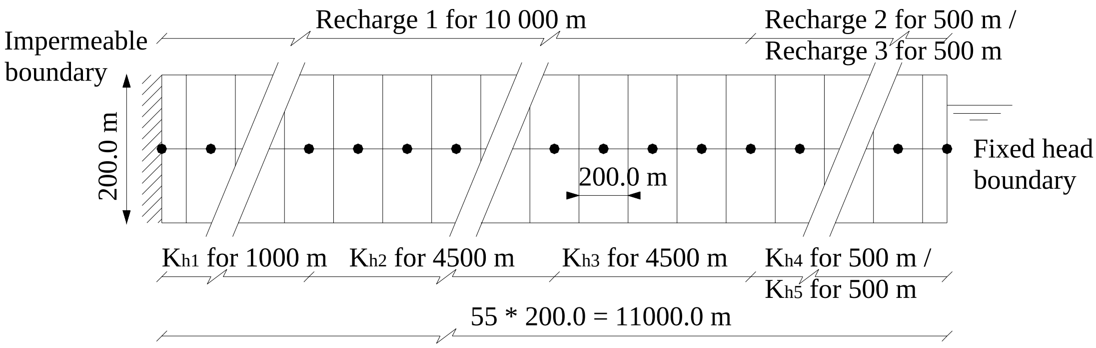


Figure A.1 Numerical representation of the vertical slice. Case 1: The aquifer is represented by five hydraulic conductivity zones.

Table A.1 Aquifer characteristics of the different undertaken runs in case 1 where the aquifer is represented by five hydraulic conductivity zones.

	Kh1 (m/d)	Kh2 (m/d)	Kh3 (m/d)	Kh4 (m/d)	Kh5 (m/d)	Rech 1 (mm/a)	Rech 2 (mm/a)	Rech 3 (mm/a)
Run 1	0.05	0.33	0.82	1.89	11.1	5	1000	1500
Run 2	0.05	0.33	0.82	1.89	11.1	5.84	500	500
Run 3	0.05	0.33	0.82	1.89	10	5	800	1000
Run 4	0.05	0.33	.82	1.5	7.5	5	500	500

Figures A.2a, A.2b, A.2c and A.2d show the groundwater head profile resulting from runs 1, 2, 3 and 4 respectively. Figure A.3a, A.3b, A.3c and A.3d show the variation of the groundwater heads with time at two nodes located at distances of 1000 m and 9000 m from the river and resulting from runs 1, 2, 3 and 4 respectively.

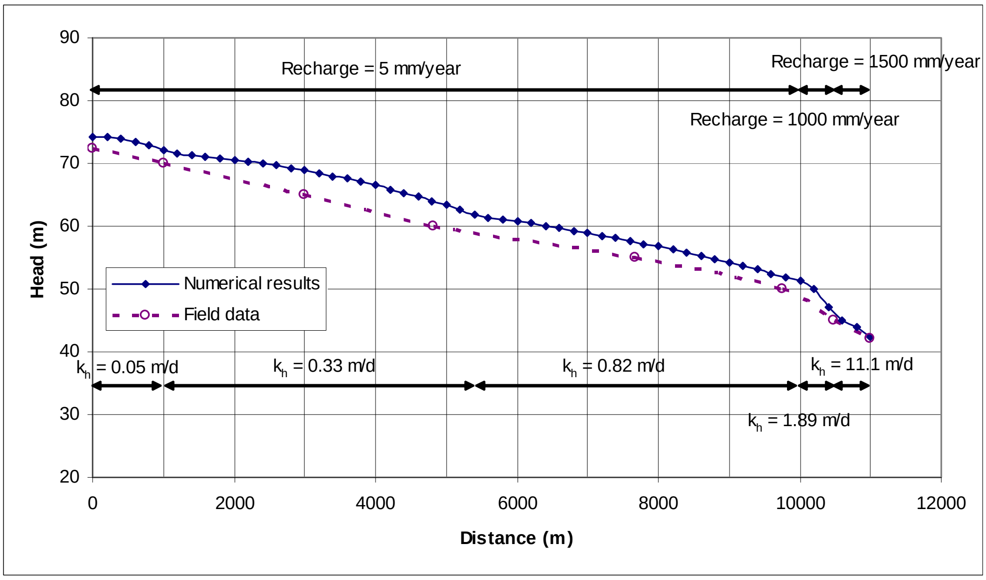


Figure A.2a Groundwater profile resulting from Run 1

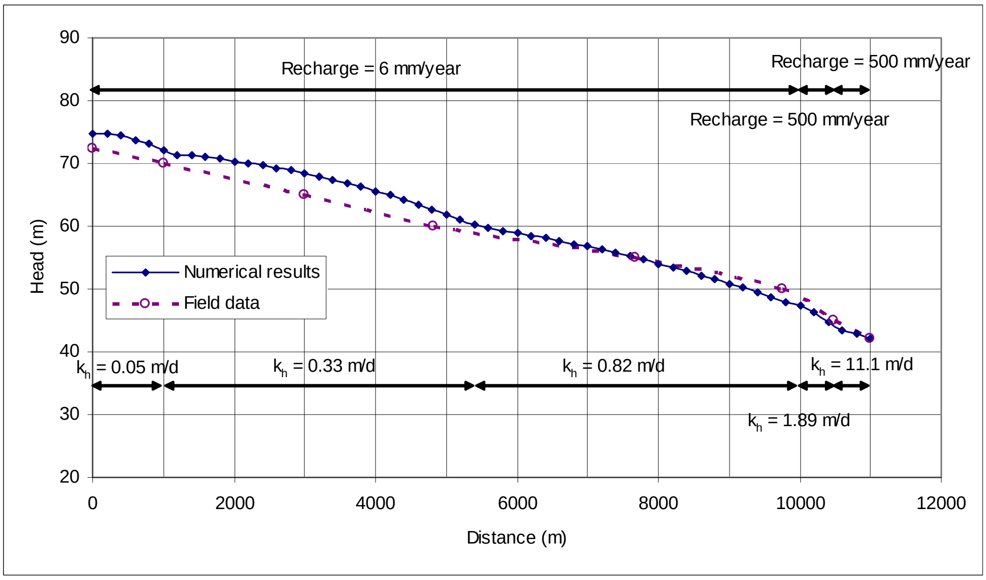


Figure A.2b Groundwater profile resulting from Run 2

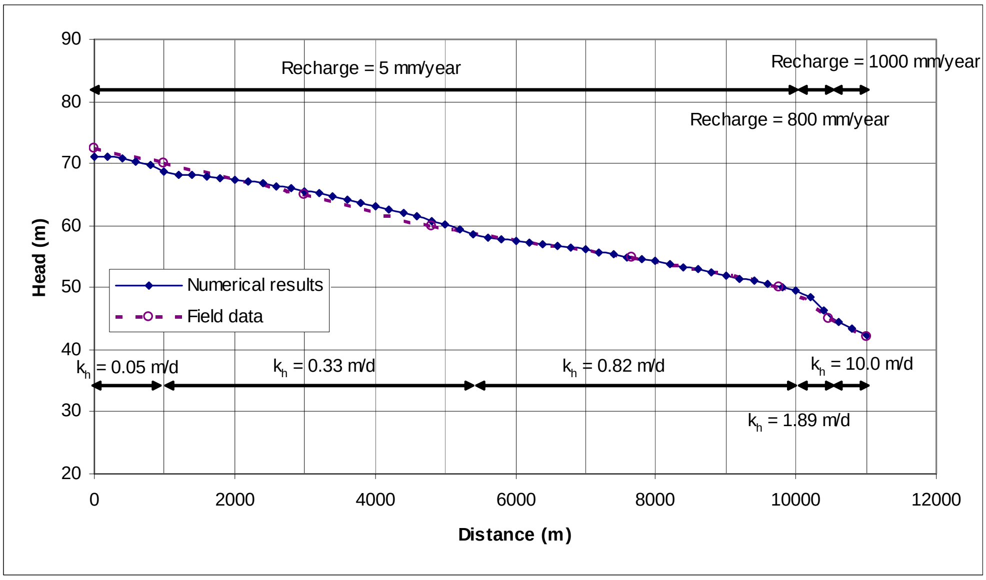


Figure A.2c Groundwater profile resulting from Run 3

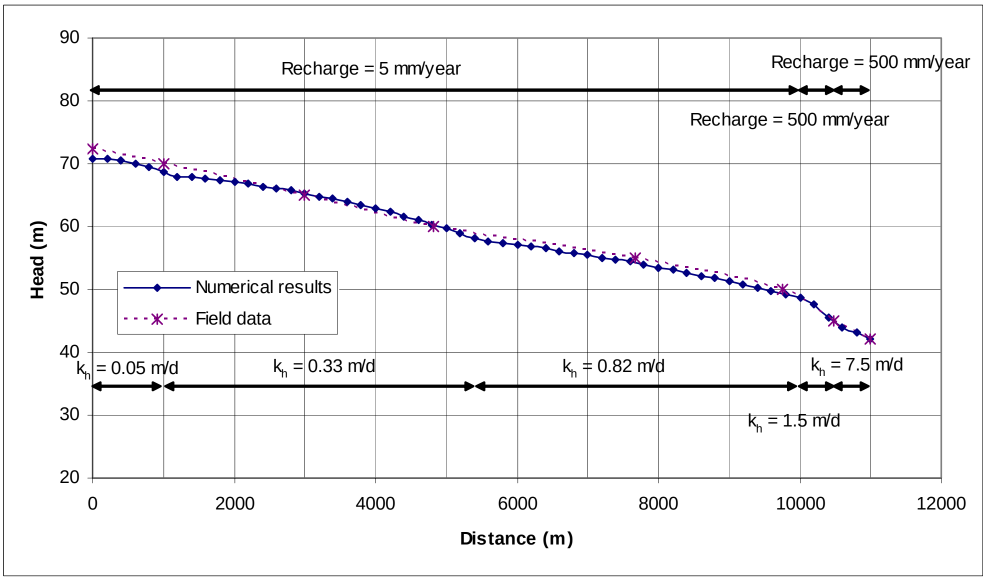
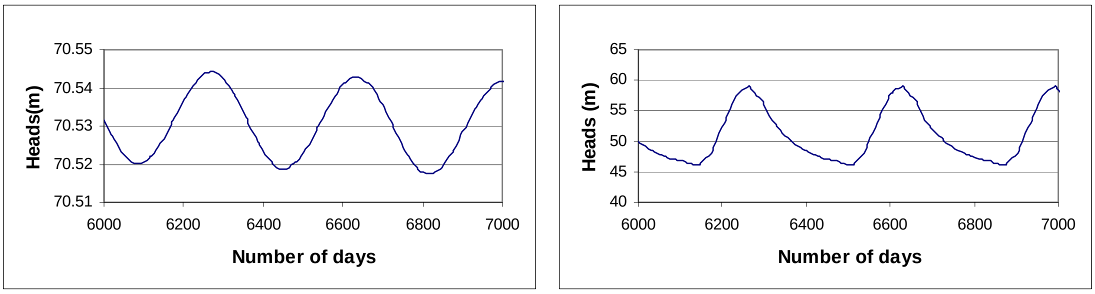


Figure A.2d Groundwater profile resulting from Run 4



(1) (2)

Figure A.3a Groundwater fluctuation with time at: 1) 9000m from the river and 2) 1000 m from the river. Results from Run 1.

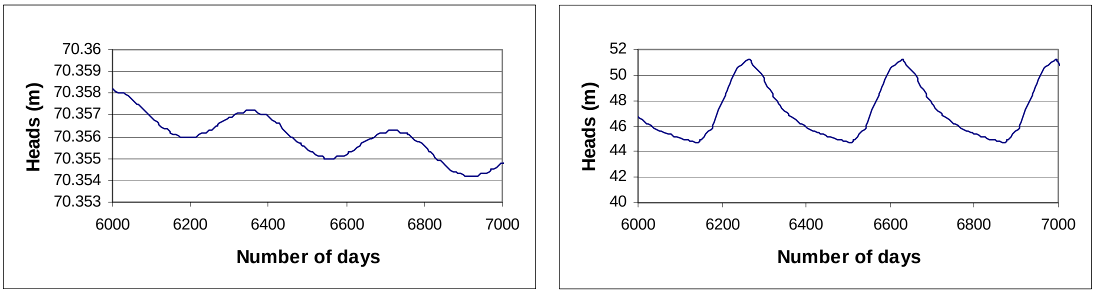


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Figure A.3b Groundwater fluctuation with time at: 1) 9000m from the river and 2) 1000 m from the river. Results from Run 2.

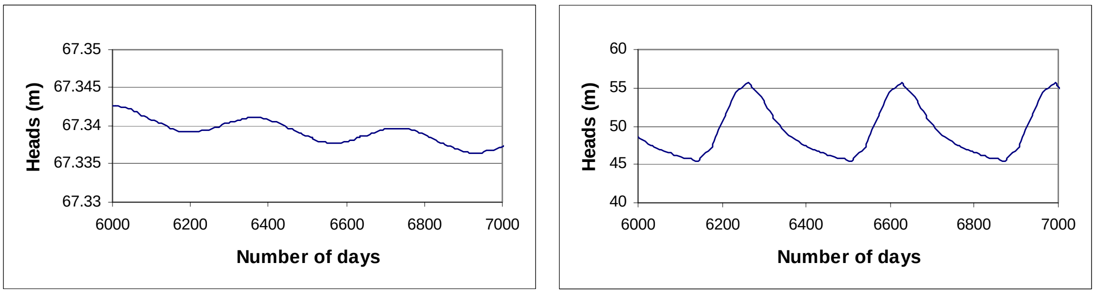

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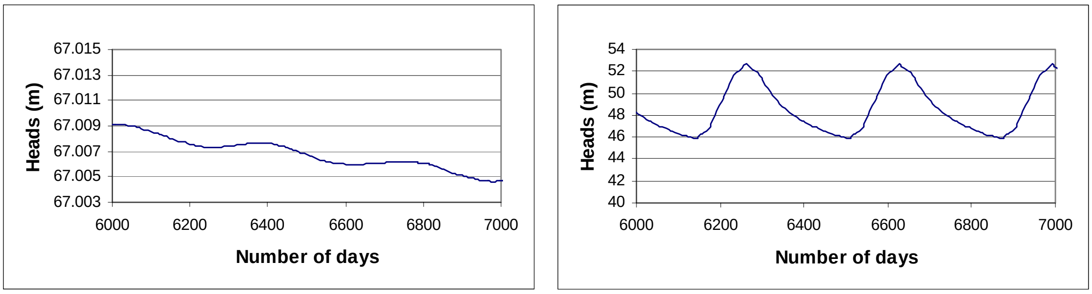
Figure A.3c Groundwater fluctuation with time at: 1) 9000m from the river and 2) 1000 m from the river. Results from Run 3.



(1) (2)

Figure A.3d Groundwater fluctuation with time at: 1) 9000m from the river and 2) 1000 m from the river. Results from Run 4.

In the second set of runs, the representation of the observed groundwater heads is improved by splitting the aquifer into six permeability zones. The best hydraulic conductivity values for these zones and the applied recharge rates over them are given in Table A.2. The comparison between the numerical and observed groundwater heads is given in Figure A.4. This part shows the additional five runs undertaken under time-variant conditions to simulate the groundwater fluctuations with time. The hydraulic conductivity values of the aquifer zones given in Table A.2 are used in the following runs. The variations of the specific yield and specific storage values are given in Tables A.3a to A.3e. These tables also show the variations of the applied recharge rates. The results of these runs are given Figures A.5a to A.5e.

Table A.2 the hydraulic conductivity values of the six Chalk aquifer zones and the applied recharge rates.

Distance from Impermeable boundary (m)	0-1000	1000-2000	2000-5000	5000-10000	10000-10500	10500-11000
Recharge	5 mm a^{-1}				300 mm a^{-1}	
Hydraulic conductivity (m/d)	0.05	0.2	0.3	0.8	1.1	6.0

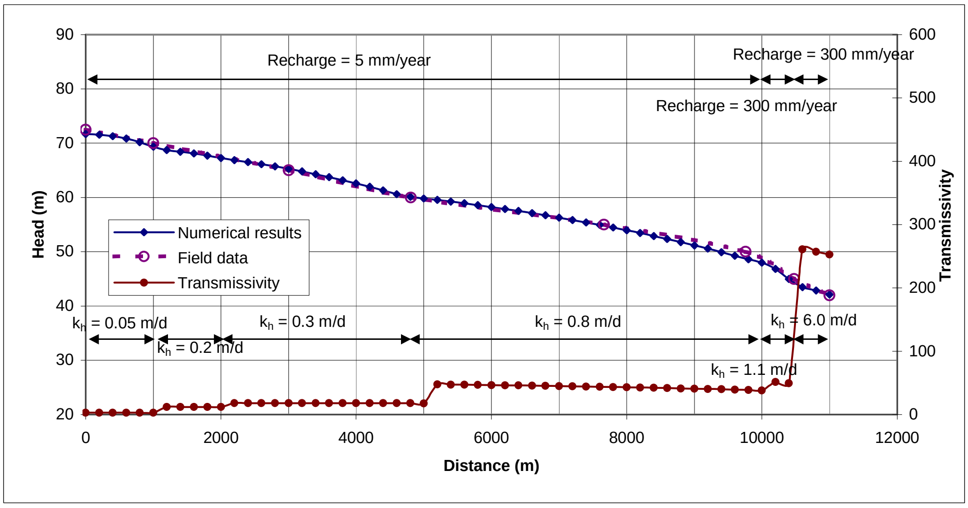
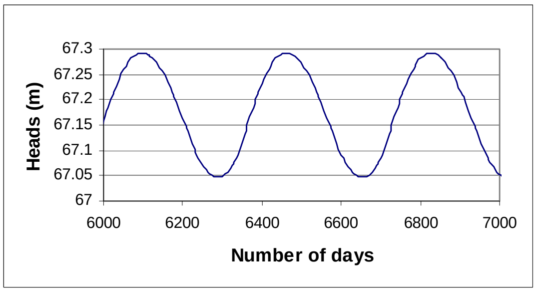
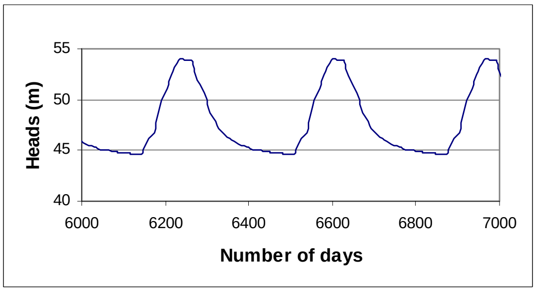


Figure A.4 Comparison between numerical and observed Groundwater profiles

Table A.3a Storage coefficients and applied recharge rates used in the first time-variant run.

Distance from Impermeable boundary (m)	0 10000	10500	11000
Recharge	Constant 5 mm a^{-1}	Var. 300 mm a^{-1}	Var. 300 mm a^{-1}
Specific storage (m^{-1})	$1.67*10^{-7}$	$1.67*10^{-7}$	$1.67*10^{-7}$
Specific yield	0.0005	0.005	0.01



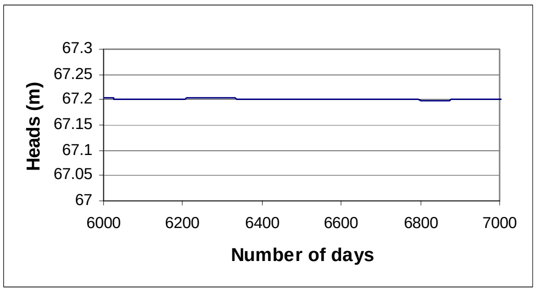


(1) (2)

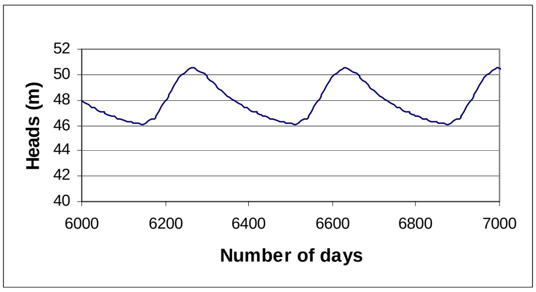
Figure A.5a Groundwater fluctuation with time at: 1) 9000m from the river and 2) 1000 m from the river. Results from the first time-variant run.

Table A.3b Storage coefficients and applied recharge rates used in the second time-variant run.

Distance from Impermeable boundary (m)	0 10000	10000 10500	10500 11000
Recharge	Constant 5 mm a^{-1}	Var. 300 mm a^{-1}	Var. 300 mm a^{-1}
Specific storage (m^{-1})	$1.67*10^{-7}$	$1.67*10^{-7}$	$1.67*10^{-7}$
Specific yield	0.0005	0.03	0.04



(1)

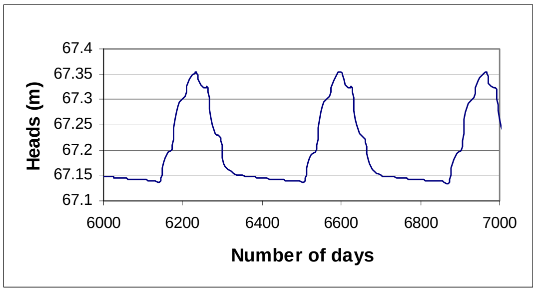


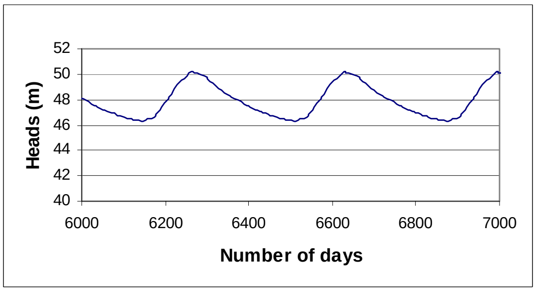
(2)

Figure A.5b Groundwater fluctuation with time at: 1) 9000m from the river and 2) 1000 m from the river. Results from the second time-variant run.

Table A.3c Storage coefficients and applied recharge rates used in the third time-variant run.

Distance from Impermeable boundary (m)	0 10000	10500	11000
Recharge	Constant 4.964 mm a^{-1} + Var. 0.036 mm a^{-1}	Var. 300 mm a^{-1}	Var. 300 mm a^{-1}
Specific storage (m^{-1})	$1.67*10^{-7}$	$1.67*10^{-7}$	$1.67*10^{-7}$
Specific yield	0.0005	0.04	0.04



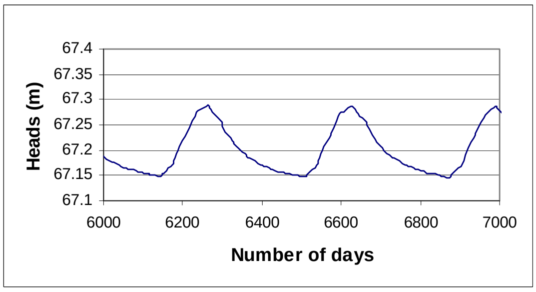


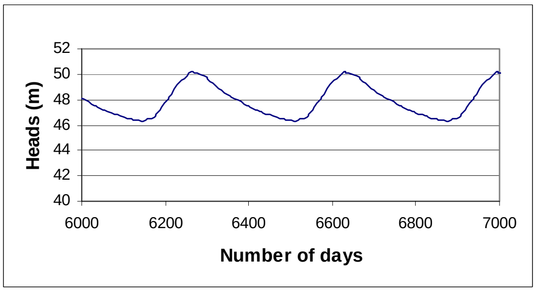
(1) (2)

Figure A.5c Groundwater fluctuation with time at: 1) 9000m from the river and 2) 1000 m from the river. Results from the third time-variant run.

Table A.3d Storage coefficients and applied recharge rates used in the fourth time-variant run.

Distance from Impermeable boundary (m)	0 10000	10500	11000
Recharge	Constant 4.964 mm a^{-1} + Var. 0.036 mm a^{-1}	Var. 300 mm a^{-1}	Var. 300 mm a^{-1}
Specific storage (m^{-1})	$1.67*10^{-6}$	$1.67*10^{-6}$	$1.67*10^{-6}$
Specific yield	0.0005	0.04	0.04



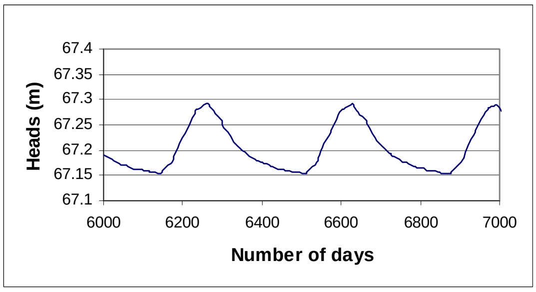


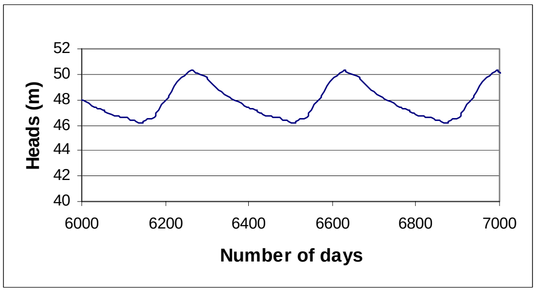
(1) (2)

Figure A.5d Groundwater fluctuation with time at: 1) 9000m from the river and 2) 1000 m from the river. Results from the fourth time-variant run.

Table A.3e Storage coefficients and applied recharge rates used in the fifth time-variant run.

Distance from Impermeable boundary (m)	0 10000	10500	11000
Recharge	Constant 4.964 mm a^{-1} + Var. 0.036 mm a^{-1}	Var. 300 mm a^{-1}	Var. 300 mm a^{-1}
Specific storage (m^{-1})	$1.67*10^{-6}$	$1.67*10^{-6}$	$1.67*10^{-6}$
Specific yield	0.005	0.03	0.05





(1) (2)

Figure A.5e Groundwater fluctuation with time at: 1) 9000m from the river and 2) 1000 m from the river. Results from the fifth time-variant run.

References

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

U.S. Army Corps of Engineers. *Engineering and Design, Groundwater Hydrology*. Manual No. 1110-2-1421. Washington, DC.

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.

Gerber, R.E., Boyce, J.J. 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

Institute of Geological Sciences and Anglian Water Authority, 1981. Hydrogeological map of southern East Anglia. NERC, Keyworth.

Marks, R.J., Lawrence, A.R., Whitehead, E.J., Cobbing, J.E., Darling, W.G. and Hughes, A.G. 2004. Recharge to the Chalk aquifer beneath thick till deposits in East Anglia. *British Geological Survey Internal Report,* IR/04/007

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

Van Der Kamp, G. 2001. Methods for determining the in situ hydraulic conductivity of shallow aquitards – an overview. *Hydrogeology Journal* 9, 5-16