ANALYSIS OF AQUIFER PUMPING TESTS WITHIN GLACIAL SAND AND GRAVEL USING FUNCTION.XLS

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ABSTRACT

Pumping tests can be carried out to assess the behaviour of a particular well, to determine the impact of pumping on neighbouring wells and watercourses, or to determine the hydraulic properties of an aquifer such as the transmissivity (and related hydraulic conductivity) and storage coefficient.

Aquifer pump tests have been carried out at a proposed sand and gravel quarry site in Essex to inform a Hydrogeological Impact Appraisal (HIA) and the design of dewatering operations. Analysis of the pump tests was carried out using traditional methods; including the Cooper-Jacob method (Kruseman and de Ridder, 1990), and using Function.xls (Hunt, 2008). Function.xls is a freely available Microsoft Excel® spreadsheet that enables user defined functions to derive aquifer parameters from pump tests by matching theoretical curves with observed data. These aquifer parameters can then be used to model groundwater behaviour.

This paper compares the results obtained using the traditional methods against the use of Function.xls for a step discharge test, and two constant discharge tests.

The results of the pump test showed a complex aquifer system, with distinctly different responses to pumping observed both spatially and temporally. These results showed that the standard linear model solutions were not appropriate in this hydrogeological setting. Possible explanations for the different responses including the transition from confined to unconfined conditions and hydrogeological discontinuities are examined in this paper using geological cross sections as well as the pump test results and analyses.

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Pp. 91-104 in Hunger, E. and Brown, T.J. (Eds.)
Proceedings of the 18th Extractive Industry Geology Conference 2014 and technical meeting 2015,
EIG Conferences Ltd, 250pp.
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INTRODUCTION

Pumping Tests

A pumping test involves pumping water from a well and measuring the response (lowering of head) within the pumped well and, if possible, in neighbouring observation wells. By recording the lowering of the groundwater levels in these wells it is possible to estimate characteristics about the pumped well and the hydraulic properties of the aquifer.

Pumping tests may be carried out for a number of different reasons and there are a large number of methods that can be used to analyse the results obtained (Kruseman and de Ridder, 1990). BS ISO 14686:2003 'Hydrometric determinations — Pumping tests for water wells — Considerations and guidelines for design, performance and use' (British Standards, 2003), gives three reasons;

- to assess the hydraulic behaviour of a well and so determine its ability to yield water,
- to determine the hydraulic properties of the aquifer or aquifers, and
- to determine the effects of pumping upon neighbouring wells.

A series of pumping tests were carried out at a potential sand and gravel quarry site, near Chelmsford in Essex. The aim was to determine the hydraulic properties of the aquifer within the sand and gravel deposits. The hydraulic properties of the aquifer were required for two principal reasons;

- to enable requisite dewatering rates for the mineral extraction operations to be estimated, and
- to inform a Hydrogeological Impact Appraisal (HIA) that was being undertaken in line with the Environment Agency's guidance document; Hydrogeological Impact Appraisal for Dewatering Abstractions (Environment Agency, 2007).

Function.xls

Function.xls (Hunt,2008) is a freely available Microsoft excel spreadsheet that enables user defined functions to be derived to model groundwater behaviour if aquifer characteristics and parameters are known, or alternatively to derive aquifer parameters from pump tests by matching theoretical curves with observed data (Hunt, 2005). Within the spreadsheet are solutions to the various 'well functions' commonly used to describe aquifer behaviour including:

- Theis (confined or unconfined if drawdowns are not a significant portion of the saturated aquifer thickness),
- Hantush (leaky),
- Boulton (delayed yield),
- Neuman (unconfined)

Following the completion of the pumping tests at the site, the data obtained was analysed using Function.xls to derive the aquifer parameters. For completeness, the results achieved using this method were compared with the more traditional graphical methods such as the Theim-Dupuit, Eden Hazel and Cooper-Jacob methods as detailed in Kruseman and de Ridder (1990).

SITE BACKGROUND

Site Description

The site is located to the north east of Chelmsford and consists of arable fields and areas of recent woodland planting. The site is situated in an area that has historically been worked for glacial sand and gravel deposits, with former workings located to the immediate west of the site and an active quarry some 500m to the east which is planned to extend to the area to the north of the site in the future.

Planning permission has been obtained for the recovery of sand and gravel from the site which is approximately 11.7Ha in area and contains an estimated 200,000 cubic metres (325,000 tonnes) of mineral.

Published Geology

The British Geological Survey (BGS) 1:50,000 scale geological map of the area, Sheet 241, Chelmsford (BGS, 1975), indicates that the site is underlain by natural, superficial drift deposits of the Lowestoft Formation (Boulder Clay) which overlies the target mineral of drift Fluvioglacial Deposits (Glacial Sand and Gravel). These units overlie the solid London Clay Formation. The Institute of Geological Sciences (IGS) publication 'The sand and gravel resources of the country around Terling, Essex' (Eaton, 1973) shows the same geological sequence and states that the site is within an area categorised as 'continuous or almost continuous spreads of mineral beneath overburden'. The Boulder Clay (overburden to the mineral) is described as 'brown or grey sandy clay containing more or less frequent pellets and larger fragments of chalk together with a fairly wide variety of erratics'. The Glacial Sand and Gravel is referred to as the Chelmsford Gravel and comprises 'medium flint gravels and pebbly sands'. Within the site, the thickness of the sand and gravel ranges from being absent at the south to a maximum of just over 8m in the central areas. The thickness of overburden is variable, but typically in the range of 5 to 9m.

Hydrogeology

The Environment Agency (EA) website indicates that the site is not situated within any Source Protection Zones and is situated over unproductive strata; drift deposits and solid geology with low permeability that have negligible significance for water supply or river base flow. This classification apparently ignores the Glacial Sand and Gravel between the Boulder Clay and London Clay.

Mineral exploration boreholes had been drilled historically by flight auger within the site area, (Figure 1; RMC 1986 boreholes) but prior to the boreholes installed as part of the pumping test (Figure 1; Geotechnics Ltd 2011 boreholes), no other groundwater monitoring boreholes had been installed on the site. Groundwater investigations had been undertaken in the area to the north and east of the site and a single borehole had been installed to the south east of the site. To the north and east, five boreholes had been installed with piezometers (two of which are shown on Figure 1; Hanson boreholes 2009). Groundwater levels typically indicated unconfined aquifer conditions with an average saturated mineral thickness of 3.36m compared to an average total mineral thickness of 5.54m. Groundwater level data indicated groundwater flow generally in a north to north westerly direction. However, some 500m to the east, a separate report for ongoing quarrying operations there indicated that groundwater flowed in a south easterly direction. It is unclear whether that quarry was pumped. The unconfined conditions reported to the north also contrast with the groundwater conditions encountered in the borehole located 175m to the south east of the site where groundwater levels were observed to rise within the borehole by around 1.9m when the Glacial Sand and Gravel deposits were struck, indicating sub-artesian confined aquifer conditions.

Therefore, prior to the pumping test there was considerable uncertainty surrounding the hydrogeological regime in the vicinity of the site and to what extent dewatering would be required and what impacts dewatering could have.

GROUND INVESTIGATION

Boreholes Installed

A total of fourteen boreholes were drilled in advance of the pumping test. Of these, eight were installed with 50mm diameter standpipes as monitoring boreholes and one borehole, the abstraction borehole (ABH7) was installed with 100mm diameter casing. (Figure 1; Geotechnics Ltd 2011 boreholes.)

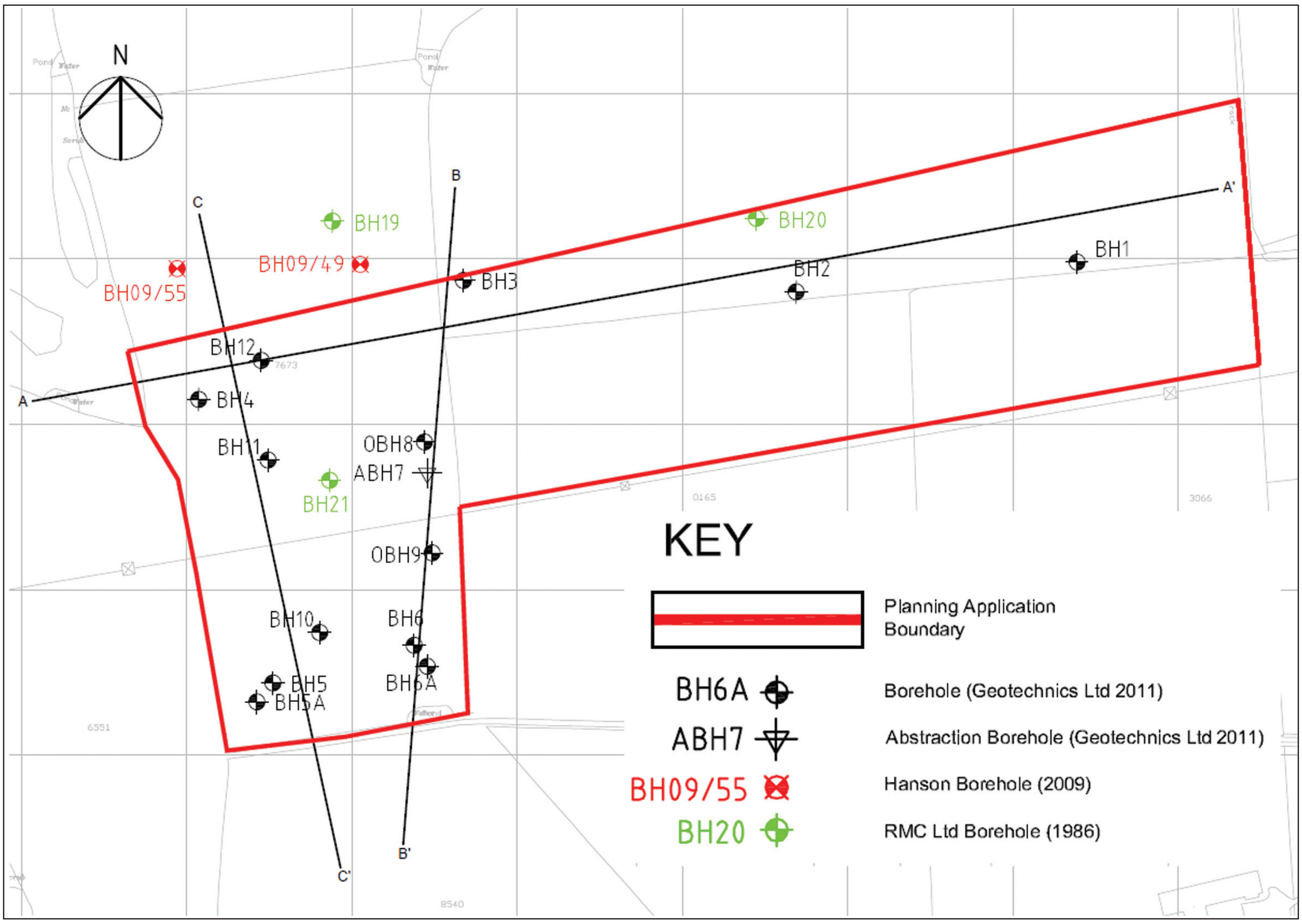


Figure 1. *Site and borehole location plan with lines of cross section (corresponding cross sections shown on Figures 2, 3 and 4). (Scale, gridlines are at 100m spacings).*

All boreholes proved the inferred geological sequence of overburden (Boulder Clay), overlying Glacial Sand and Gravel, overlying London Clay. Three cross sections; A-A' (Figure 2), B-B' (Figure 3) and C-C' (Figure 4) (lines of section shown on Figure 1) showed considerable variations in the thickness of the sand and gravel deposits which appeared to thin to the east and west of the site.

Groundwater Levels

Monitoring undertaken in the installed boreholes showed very little variation in groundwater levels with the exception of BH4 (Figures 2 and 4), which was later shown to be hydraulically separated from the other monitoring boreholes. The pre-pumping test groundwater levels are presented in Table 1.

The lack of variation in the measured groundwater levels made it difficult to determine a clear groundwater flow pattern. Groundwater elevation contour maps produced were inconclusive, suggesting a clear hydraulic gradient towards the east due to the difference in groundwater levels between BH1 and BH2. However at the western side of the site, the difference between BH6A and BH5A suggested the opposite i.e. a hydraulic gradient towards the west.

Borehole	m AOD
BH1	45.27
BH2	45.61
BH3	45.60
BH4	**46.15**
BH5A	45.57
BH6A	45.78
ABH7	45.54
OBH8	45.62
OBH9	45.63

Table 1. *Pre-pumping test groundwater levels.*

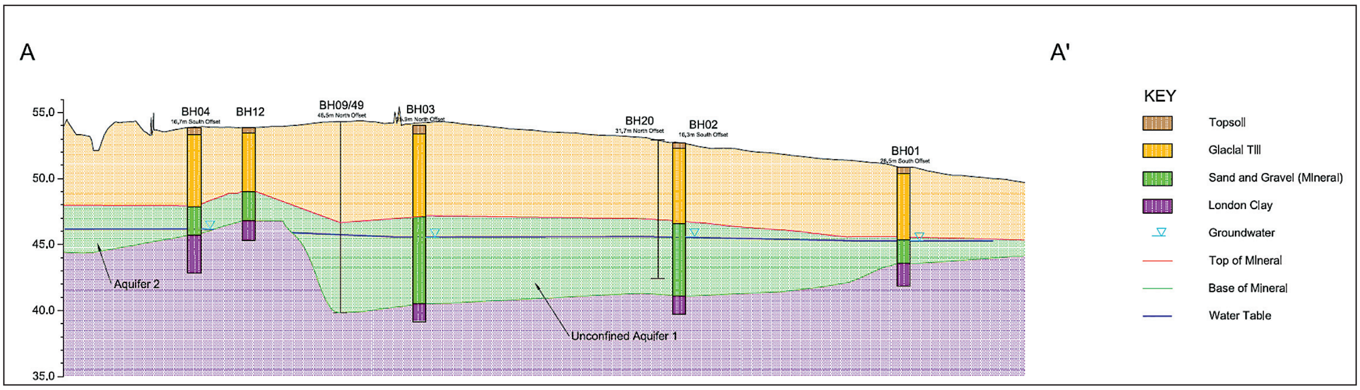


Figure 2. *Cross section A-A'. (Line of section shown on Figure 1, Scale: Horizontal 1:2500, Vertical 1:250).*

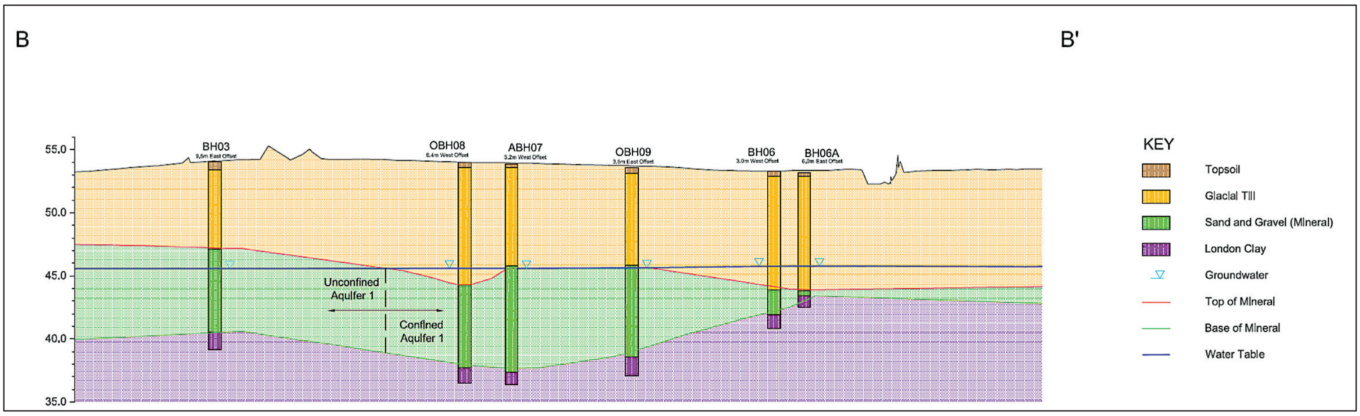


Figure 3. *Cross section B-B'. (Line of section shown on Figure 1, Scale: Horizontal 1:1250, Vertical.1:250).*

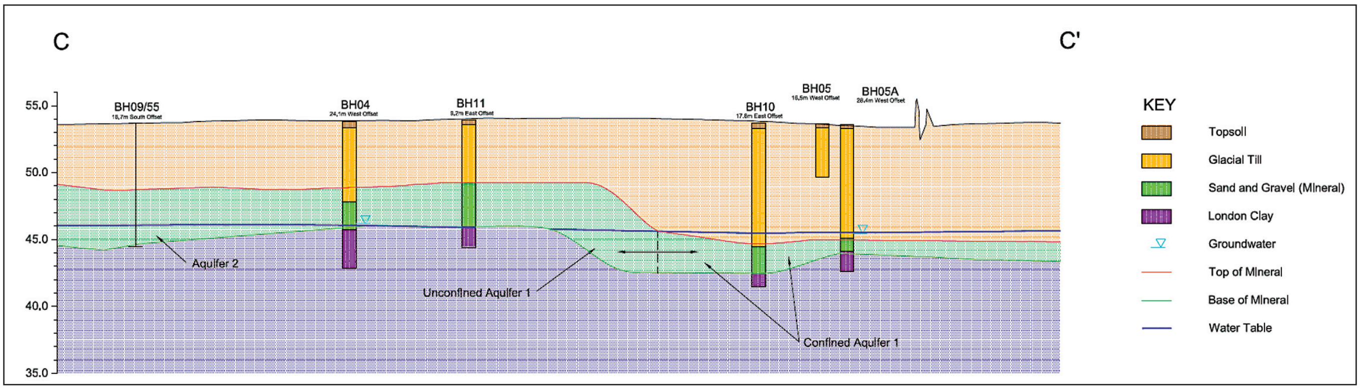


Figure 4. *Cross section C-C'. (Line of section shown on Figure 1, Scale: Horizontal 1:1250, Vertical 1:250)).*

PUMPING TESTS

Three tests were carried out during the investigation comprising:

1. Equipment test
   Found that the planned maximum discharge rate of 15 litres per second was not achievable by the pump due to hydraulic losses. A discharge rate of 13 litres per second was achieved and therefore the maximum rate for the subsequent tests was reduced.
2. Step discharge test
   Run for 100 minutes per step at discharge rates of 2.5, 5, 7.5, 10 and 12.5 litres per second.
3. Constant rate discharge test
   Run for 48 hours at 10 litres per second.

Step Discharge Test

The measured responses to the step drawdown test in the abstraction borehole (ABH7), and the two closest observation boreholes (OBH8 and OBH9, shown on Figure 1), located 18.9m north and 48.2 m south of the abstraction borehole respectively, are shown in Figure 5.

The results were analysed using Function.xls to estimate the aquifer parameters 'T' (Transmissivity) and 'S' (Storage Coefficient) from the test by matching theoretical curves with the observed data.

Based on the borehole logs for the site which showed groundwater levels in the abstraction and observation boreholes to be semi confined (i.e. above the base level of the confining Boulder Clay layer) the Boulton (delayed

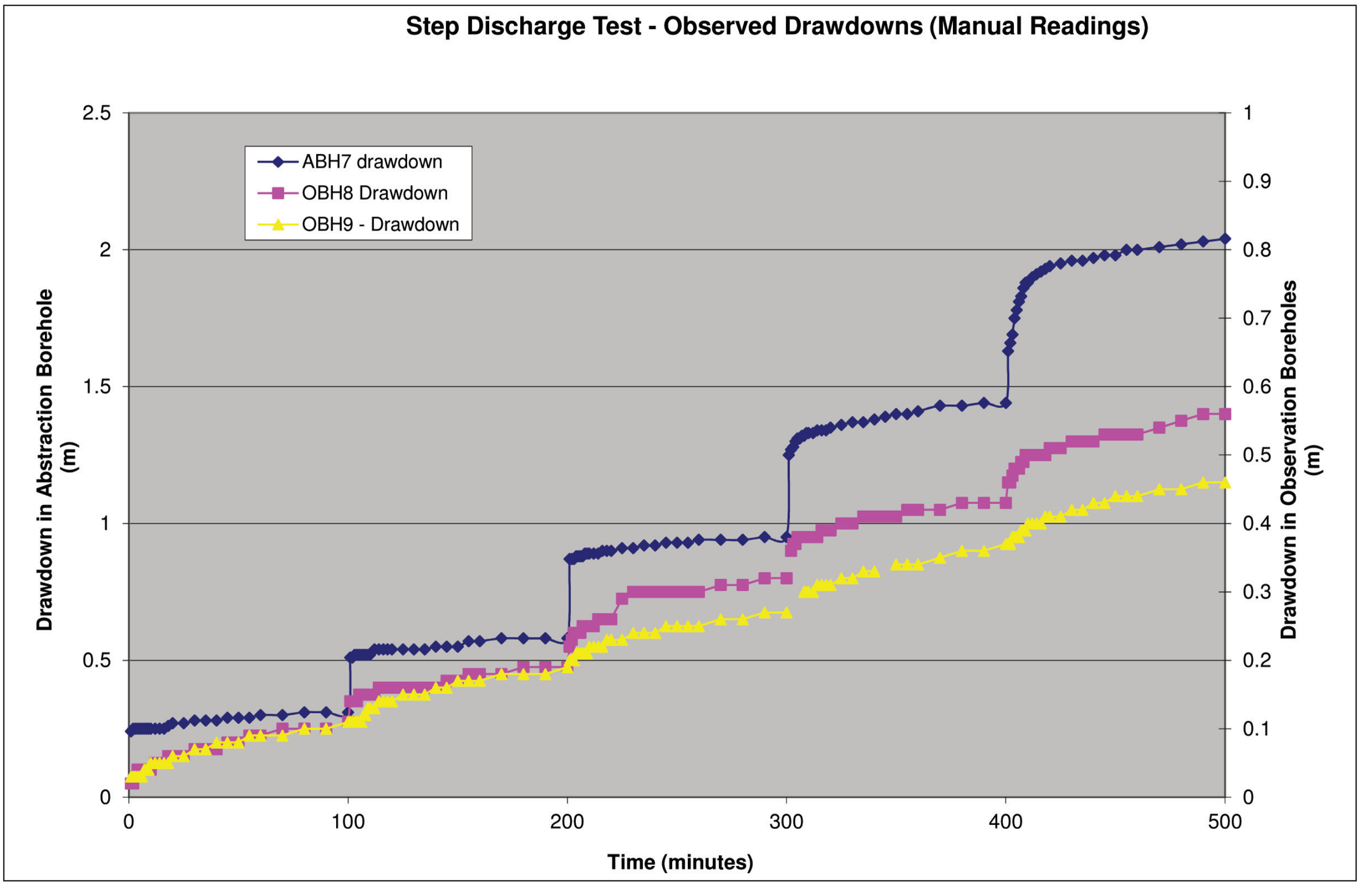


Figure 5. *Step discharge test: measured drawdowns (from manual readings) in abstraction and observation boreholes.*

yield) solution was used to try to fit the pump test data. (For the constant rate test (see below), other solutions including the Theis, Hantush and Neuman well functions were tried with very little difference observed between the 'best fit' for any of the four well functions.) The conceptual model for a Boulton type delayed yield aquifer response comprises an aquitard overlying a confined aquifer as shown in Figure 6.

Hunt (2008) describes the observed response in a Boulton type aquifer. Immediately after well abstraction begins the pumped aquifer behaves as a confined aquifer. At intermediate times however, water starts to move downward through the aquitard to recharge the pumped aquifer, and during this period the aquifer response is described closely by the Hantush solution for flow to a well in a leaky aquifer. Unlike the Hantush solution, though, the Boulton solution allows the free surface in the aquitard to move downward as water is drained from the aquitard into the pumped aquifer. Thus, at larger times piezometric levels in the aquitard and in the pumped aquifer approach each other, and the aquifer

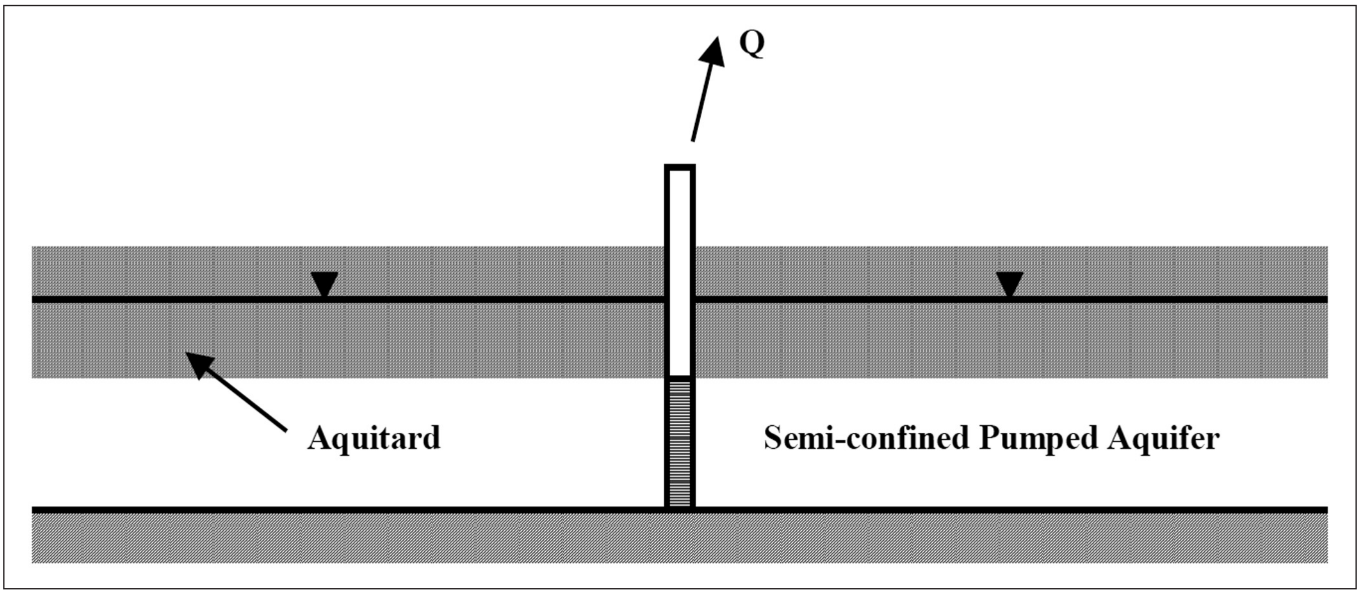


Figure 6. *Conceptual Model for a Boulton type delayed yield aquifer (from Hunt, 2008).*

response becomes similar to the response predicted with the Theis solution for an unconfined aquifer. If the permeability of the aquitard is very low, then the solution approaches the Theis solution.

The method of fitting the field data to the model comprises making initial estimates of the relevant parameters (Transmissivity (T) and Storage Coefficient (S)) and using the Excel Add-on function 'Solver' to undertake iterations to determine the fit that minimises the variance between the observed data and the model.

Figures 7 and 8 show both the results from the hand held water level meters and the automated data loggers plotted against the matched points derived using Function.xls.

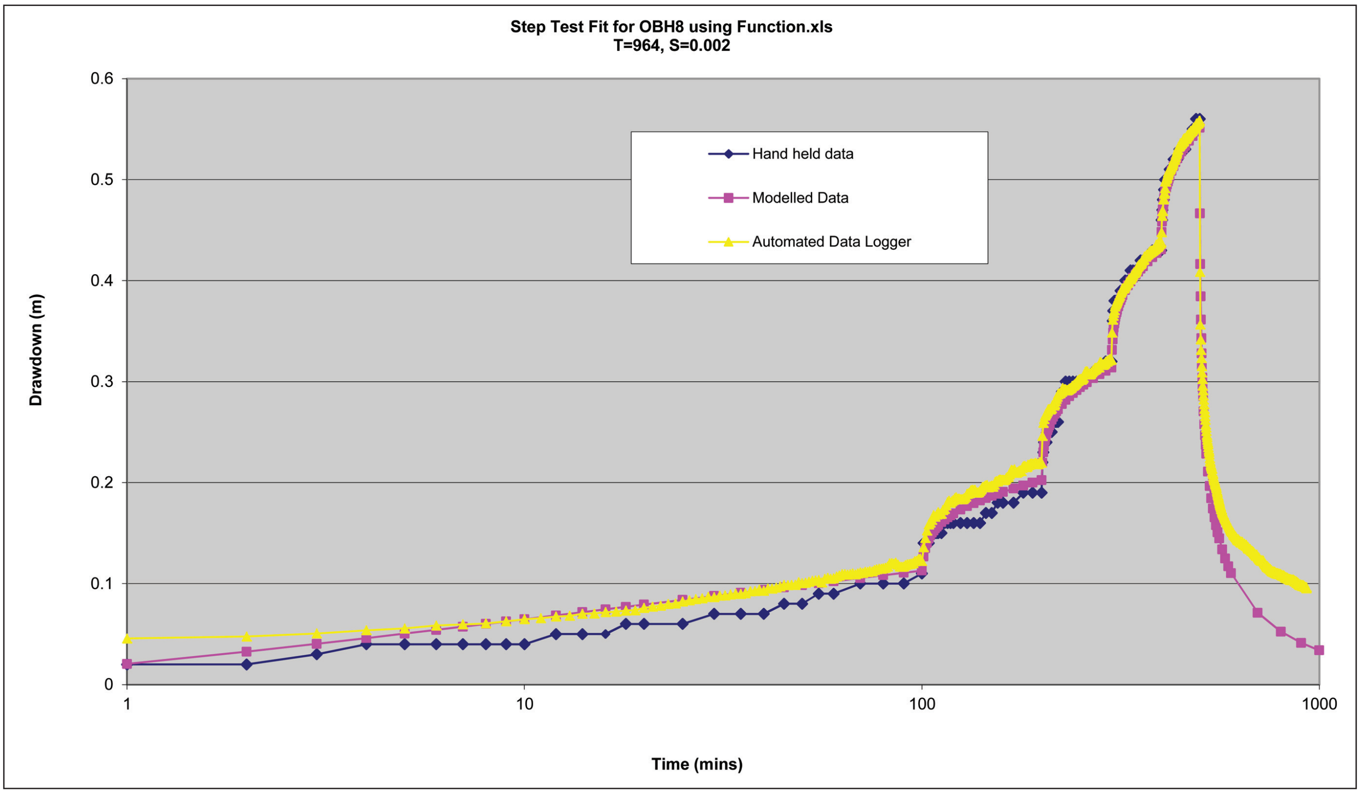


Figure 7. *Plot of the 'modelled' drawdown against the measured response in OBH8.*

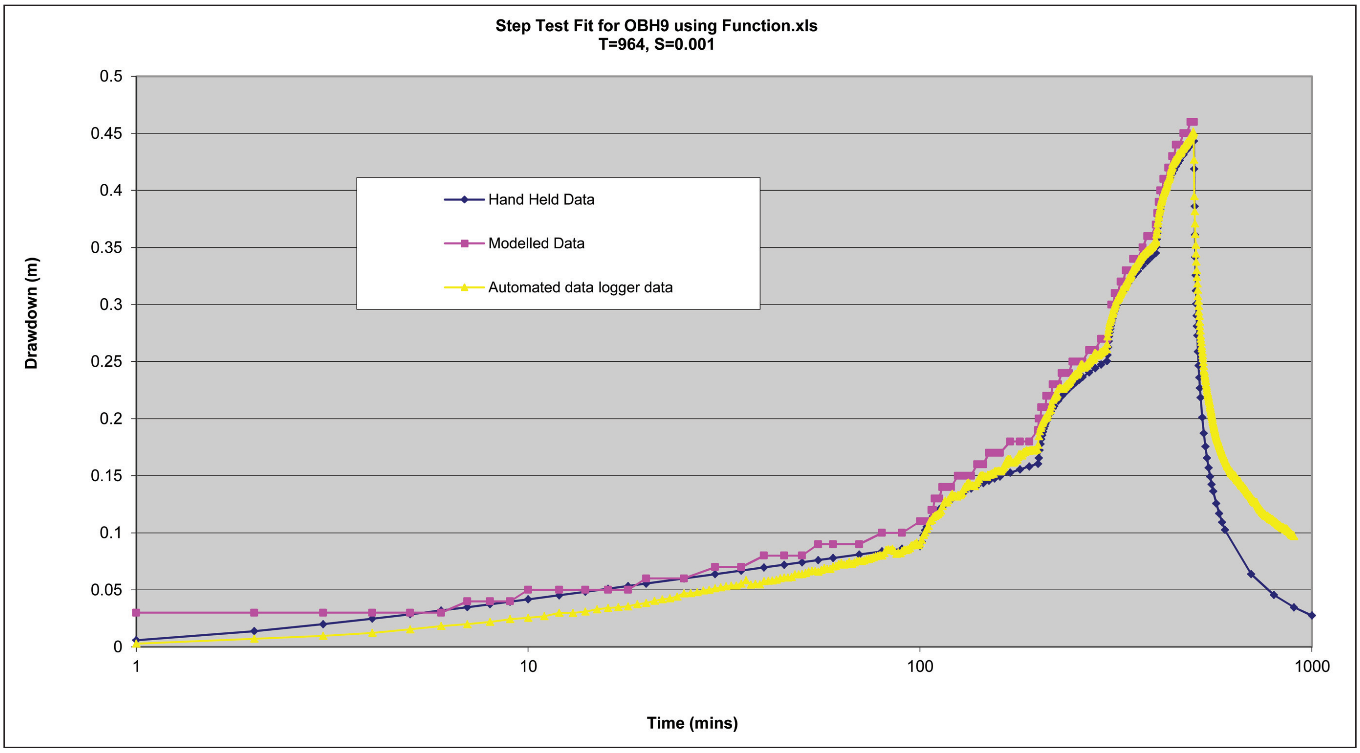


Figure 8. *Plot of the 'modelled' drawdown against the measured response in OBH9.*

For the solutions shown in Figures 7 and 8, Solver was allowed to vary the Storage Coefficient (S) for both OBH8 and OBH9 to find the best fitting Transmissivity for both observation boreholes. As shown on Figures 7 and 8, a Transmissivity of 964m2/d was determined to be the best fit for both observation boreholes with Storage Coefficients of 0.002 and 0.001 respectively. Other simulations were run to find the best overall fit for Storage Coefficient and individual fit for each borehole (Table 2).

Observation Borehole	Fitting Constraints	Transmissivity (m^2/day)	Storage Coefficient (dimensionless)
OBH8	Best Fit	848.5	0.0036
OBH9	Best Fit	1124	0.00048
OBH8 and OBH9	Best Fit (same T and S)	964	0.0014
OBH8 and OBH9	Best Fit (same T, varying S)	964	0.002 (OBH8) 0.001 (OBH9)

Table 2. *Modelled Parameters from Function.XLS analysis of the step drawdown test.*

The results were also reviewed using traditional analytical methods for analysing step drawdown tests such as the Hantush-Bierschenk and the Eden Hazel methods. These traditional analytical methods are typically used to determine the expected long term drawdown in the abstraction borehole, although a rough estimate of the Transmissivity is possible with the Eden Hazel method.

The predicted drawdowns using these methods were acceptable i.e. they did not indicate the abstraction borehole would be fully depleted during the proposed two day constant rate test and therefore the constant rate test could proceed. The estimate of Transmissivity using the Eden Hazel method was 580 m^2/day, which was slightly lower than the estimates derived using Function.xls.

Date of constant discharge test	8 July 2011 to 10 July 2011
Duration of constant discharge test	48 hours (2 days)
Water level in the abstraction borehole (ABH7) before test	8.58m below ground level (mbgl) (45.3m AOD)
Abstraction rate	10.5 litres per second (average from 43 measurements)
Discharge location	A dry pond, ~250m north of abstraction
Groundwater recovery following test	Groundwater recovered to 8.9mbgl after 24 hrs
Background influences:	- Rainfall. Aquifer underlies significant deposits of low permeability Boulder Clay, rainfall unlikely to have even a minor influence. - Equipment Failure. None
Observation Boreholes **BH1, BH2, BH3, BH4, BH5A, BH6A, OBH8, OBH9**	Automated data loggers installed in abstraction borehole (ABH7) and the 8 No. monitoring boreholes. ABH7, OBH8 and OBH9 monitored manually at frequent intervals. Remaining boreholes monitored prior to test commencing and 5 times during test.

Table 3. *Details of constant rate pumping test.*

Constant Rate Test

Test details

Two constant rate tests were undertaken; however the first test was aborted due to a mechanical breakdown after a few hours. The aquifer was allowed to recover prior to the second test commencing. Details of the test are presented in Table 3.

Groundwater observations

The groundwater levels recorded in each borehole during the test are presented in Figure 9. A reduction in groundwater levels (i.e. a positive drawdown) was recorded in all boreholes except borehole BH4, in which groundwater levels rose marginally during the duration of the test suggesting that BH4 may not be in hydraulic connection to the abstraction borehole ABH7. BH4 is located 145m from the abstraction borehole, significantly closer than some of the boreholes that did show a response (e.g. BH2 located 249m away). As shown in the cross section A-A' in Figure 2, there is a local ridge within the London Clay which is shown by the base of the sand and gravel in BH12 being above the groundwater level. The fact that no drawdown response was measured in BH4 (on the other side of this ridge) would appear to confirm that the aquifer in this area is not continuous.

Figure 9 shows, by the end of the 48hr pumping period, 'transient steady state' conditions appear to have been met in the four closest monitoring boreholes (OBH8, OBH9, BH3 and BH6A) with drawdown against log time data plotting on parallel straight lines for the 'late time' data. The early time and mid time responses varied significantly across these four boreholes, although the responses for OBH8 and OBH9 showed very similar patterns.

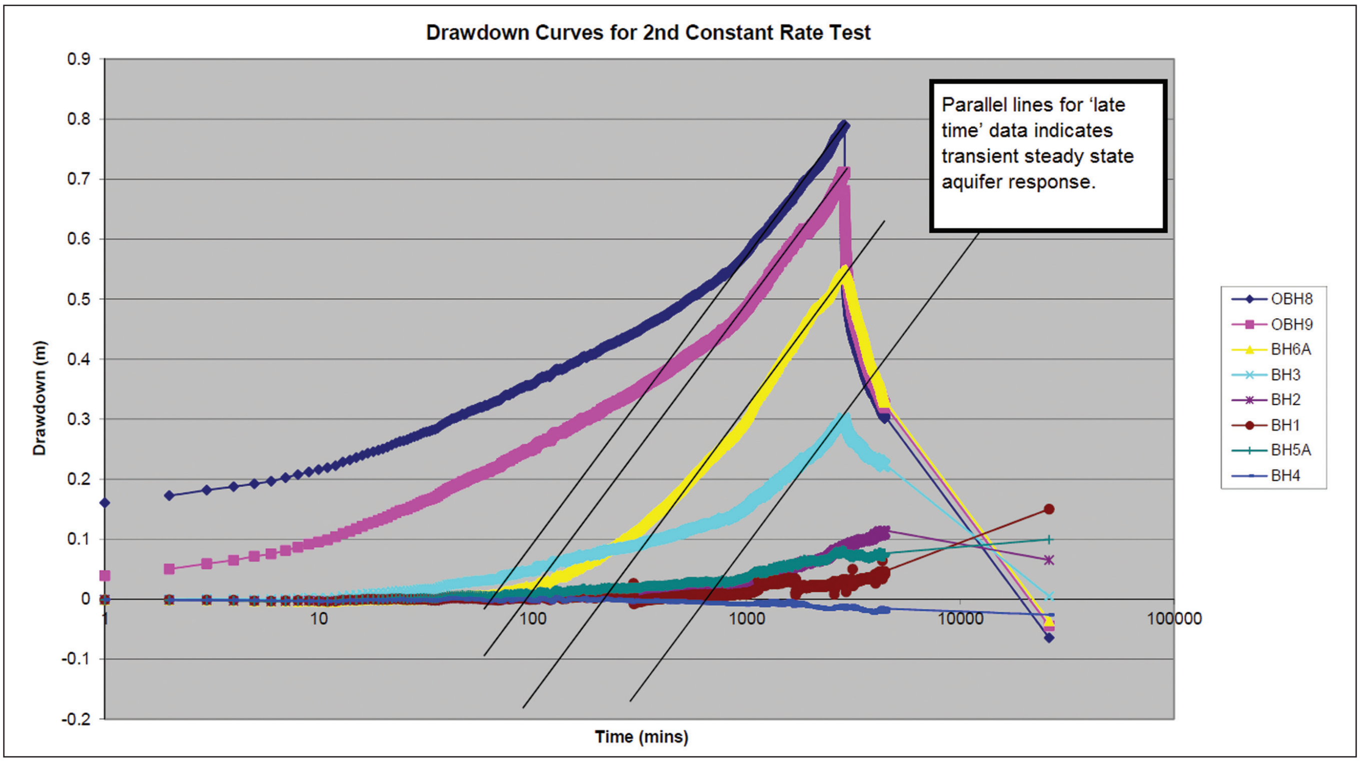
Interpretation – Transient Steady State (Theim-Dupuit)

As transient steady state conditions were met in four of the monitoring boreholes, the Theim-Dupuit (unconfined aquifer) method (Kruseman and de Ridder,1990) was used to estimate the aquifer transmissivity.

Boreholes OBH8 and BH3 are located 18.9 and 118.6m to the north of the abstraction borehole (ABH7) respectively. As they are on approximately the same flow line towards ABH7 they were paired for the Theim-Dupuit analysis. Similarly OBH9 and BH6A were paired as they are located 48.2 and 116.8m to the south of ABH7. The results of the Theim- Dupuit calculations are summarised in Table 4.

Observation Boreholes	Transmissivity (m^2/day)
OBH8 and BH3	536
OBH9 and BH6A	746

Table 4. *Transmissivity calculated from transient steady state (Theim-Dupuit).*



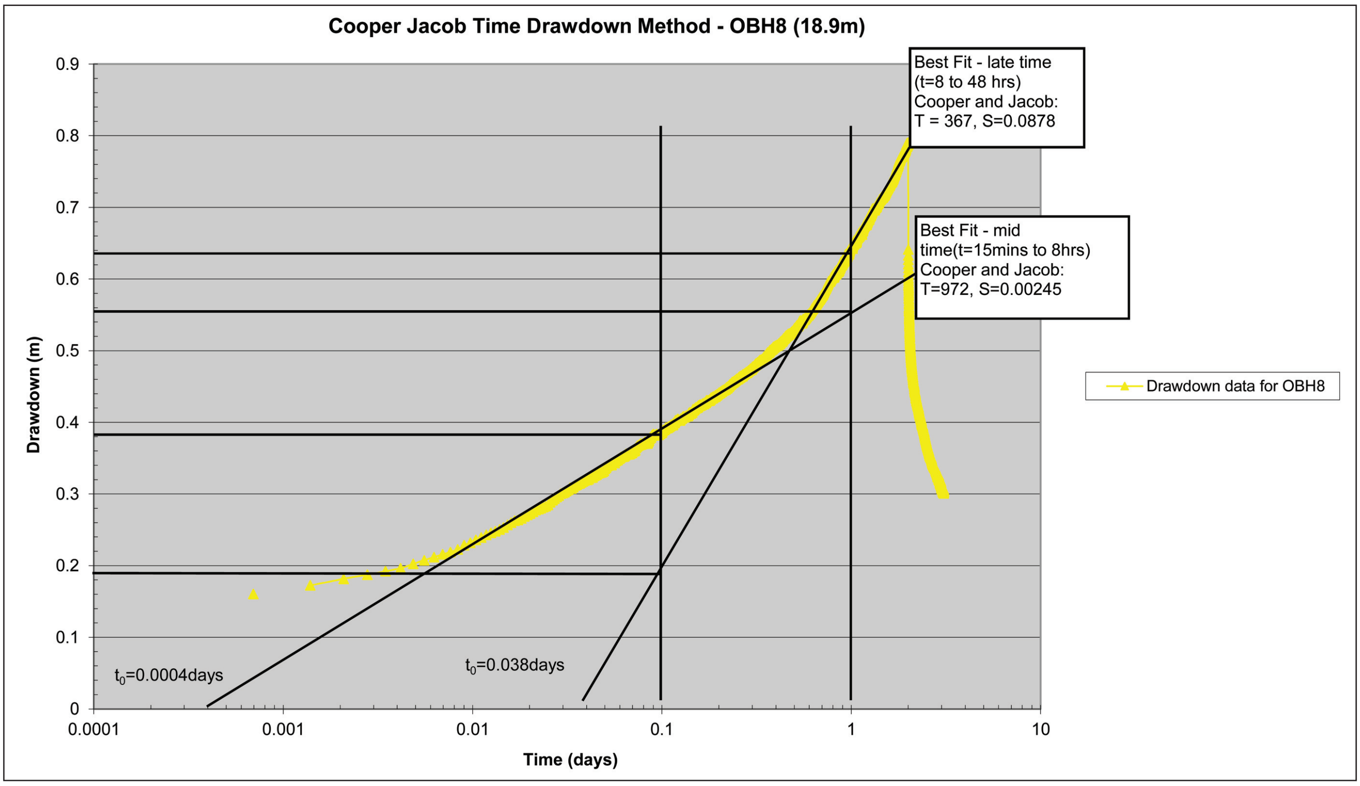
Parallel lines for 'late time' data indicates transient steady state aquifer response.

Figure 9. *Groundwater observations during constant rate pumping test.*

Interpretation: Time Drawdown Method (Cooper-Jacob)

Figure 10 shows the drawdown against log time response curve for the observation borehole OBH8. As can be seen on the graph, there are two sections of the response curve that plot on straight lines, these being the mid time data (t=15 minutes to t=8hrs) and a much steeper late time response curve (t=8 hours to t=48hrs).

The values of transmissivity and storage coefficient have been calculated based on slope and y axis intercept values as per the Cooper-Jacob method. The increasing slope of the drawdown/log time graph results in significantly lower transmissivity values being calculated for the late time data (367m²/day) than for the mid time data (972m²/day). There may be a number of explanations for this and these are discussed later in the paper.



Best Fit - late time (t=8 to 48 hrs) Cooper and Jacob: T = 367, S=0.0878

Best Fit - mid time(t=15mins to 8hrs) Cooper and Jacob: T=972, S=0.00245

Figure 10. *Constant rate pumping test. Cooper-Jacob time drawdown method for OBH8. Yellow line gives the observed groundwater response data.*

The increasing slope also results in a large change of storage coefficient from 0.00245 to 0.0878. A possible explanation for this (given the geological cross sections and groundwater levels monitored prior to the start of the test) is that the initial aquifer response is dominated by a confined aquifer type elastic response, whilst at late time, the aquifer has become unconfined and the storage coefficient approaches the effective porosity of the aquifer matrix.

Interpretation: Theis Solutions for OBH8 (Function.xls)

Function.xls was used to fit the response data from OBH8 to theoretical model curves. The semi-log plot of drawdown against time (Figure 11), shows that excellent fits could be achieved for the different time segments of the pump test by using Solver to minimise the variance between the observed and the model data points. The resulting calculated aquifer parameters are very similar to those calculated graphically using the Cooper-Jacob time drawdown method.

From Figure 11 it can be seen that the shape of the observed response curve overall (yellow) is significantly different from the shape of the Theis response curves. To test if this was simply down to the change in storage coefficient, an assessment was made using function.xls and the Neuman solution (Neuman, 1972).

The Neuman solution for unconfined aquifers includes two values of storage coefficient which represent the early time elastic response and the late time specific yield response. Using Function.xls, the Neuman solution was used to try to obtain a better fit to the data. However, as shown in Figure 12, whilst a marginally better solution is achievable, it still does not accurately model the aquifer response.

Interpretation: Image wells and the principle of superposition using Function.xls

Kruseman and de Ridder (1990) discuss the use of image wells to enable the analysis of bounded aquifer systems. If an abstraction borehole is known to be bounded then image wells and the principle of superposition can be used to simulate the observed aquifer response.

One of the key advantages of using Function.xls over traditional techniques to analyse the pump test data is that all of the equations used are linear, with coefficients that do not change with time. Therefore, the principles/techniques of superposition and time translation can always be used, which means that concepts such as bounded systems can rapidly be assessed.

To see whether or not the observed behaviour could be modelled using image wells, Function.xls was used to model the predicted drawdowns that would occur if additional abstraction boreholes (i.e. image wells) were added. The Excel add-on Solver was used to determine the optimum distance the image wells should be placed from the observation well and to obtain the best fit for each borehole for the mid-time data.

Using the image wells, excellent fits to the data were obtained as shown in Figures 13 and 14, and very similar estimates of the transmissivity and storage coefficient were determined for both the observation borehole responses (OBH8 and OBH9).

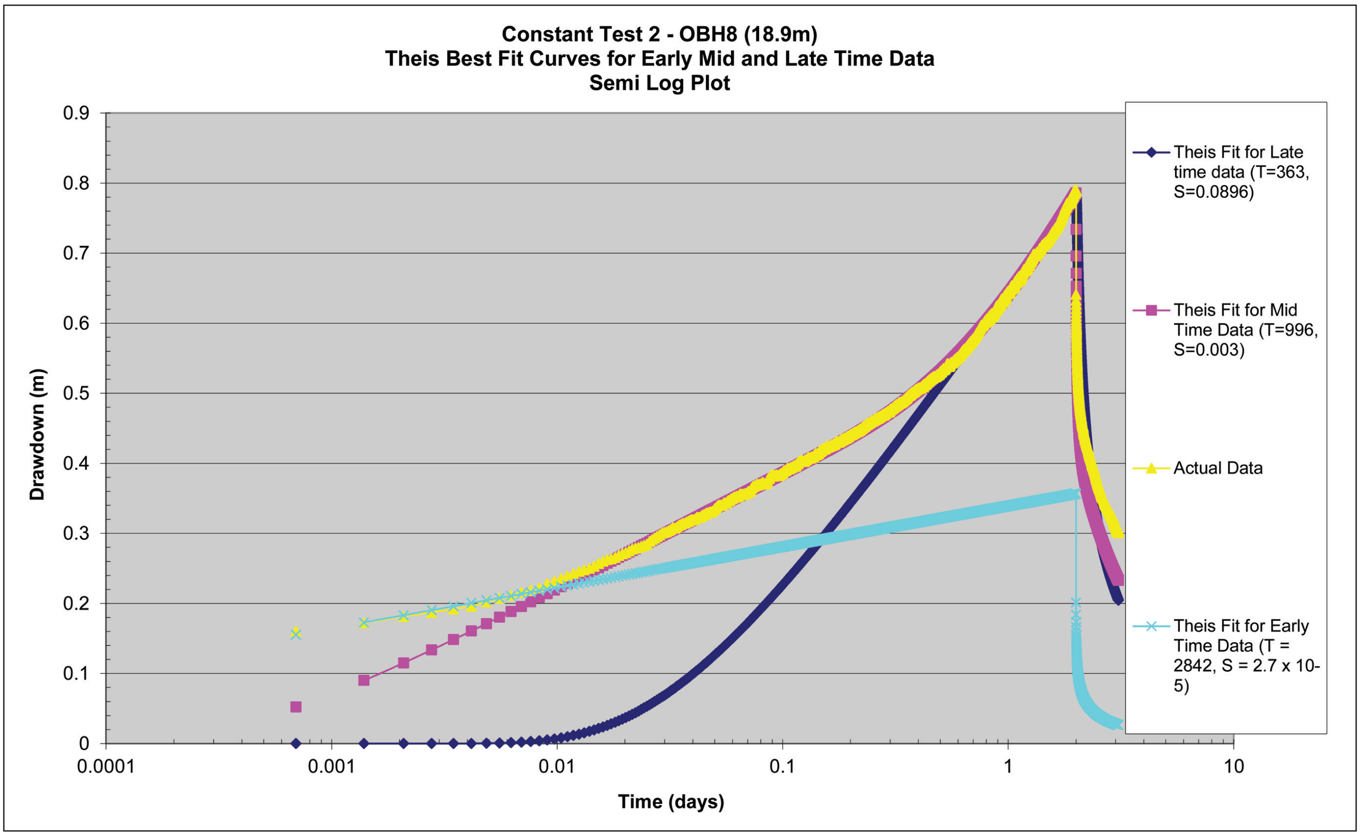


Figure 11. *Constant rate pumping test. Curve fitting using Theis solution in Function.xls. Yellow line gives the observed groundwater response data, the light blue, pink and dark blue lines give the Theis fit for early time, mid time and late time data respectively.*

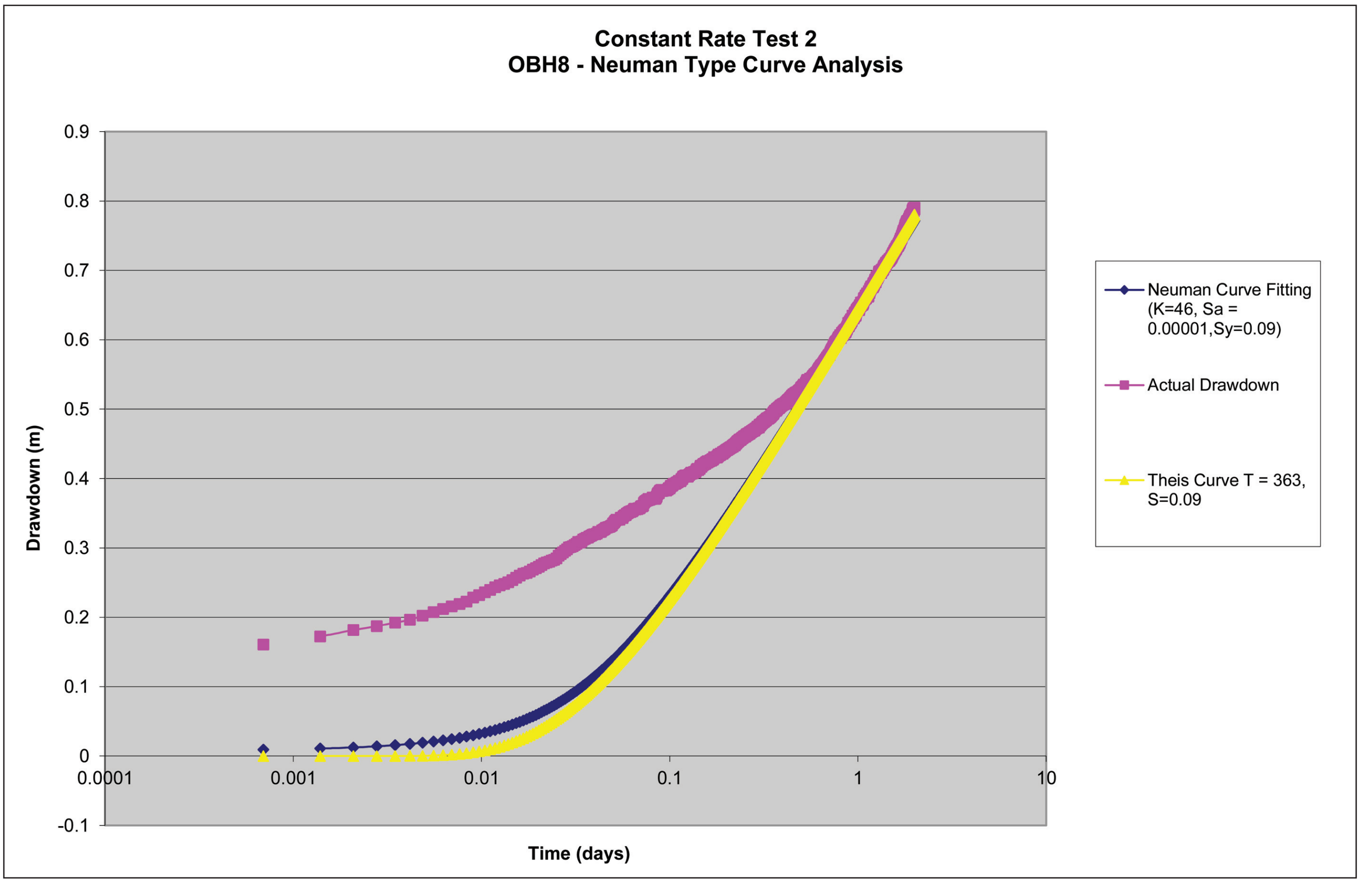


Figure 12. *Constant rate pumping test. Curve fitting using Neuman solution in Function.xls. Pink line gives the observed groundwater response data.*

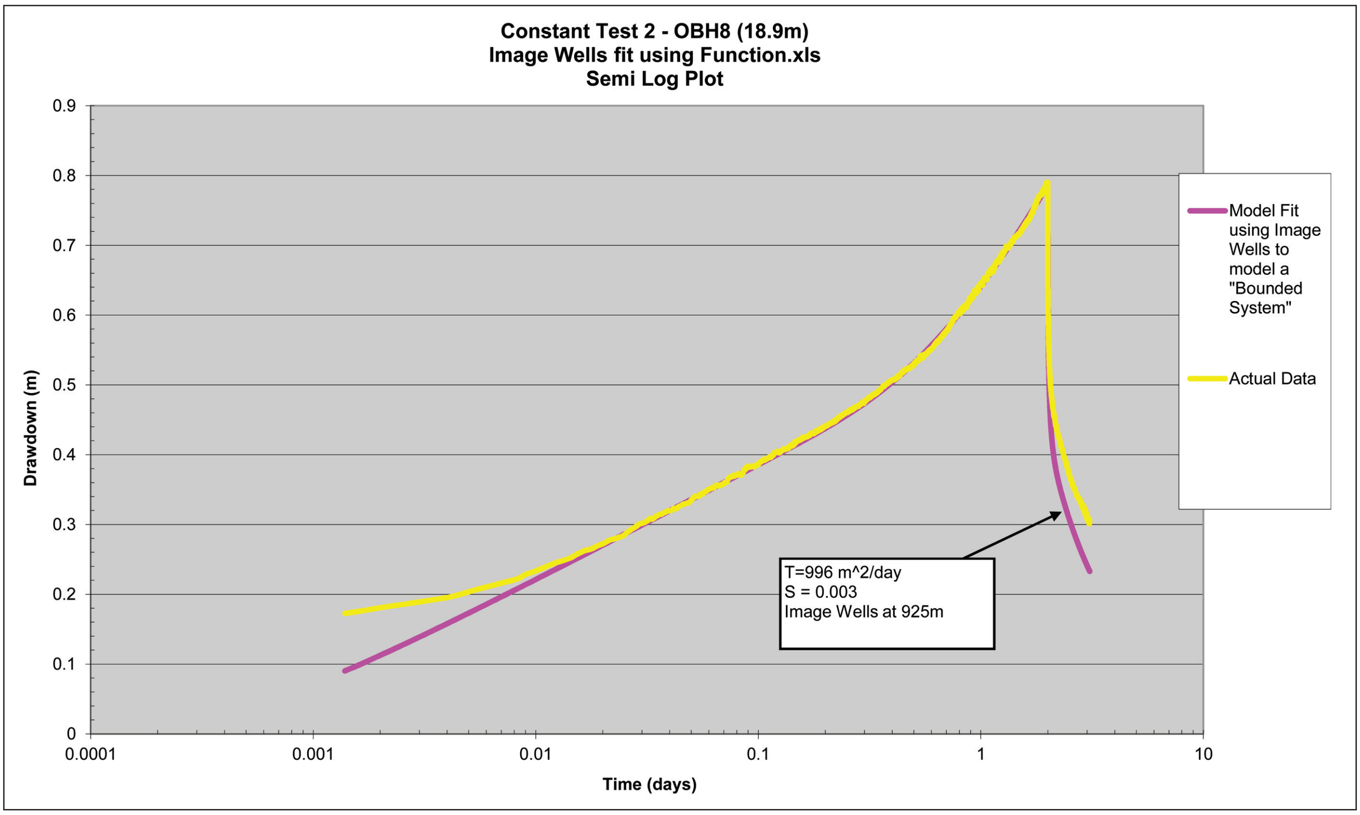


Figure 13. *Constant rate pumping test. Analysis of OBH8 using image wells to fit late time response. Yellow line gives the observed groundwater response data.*

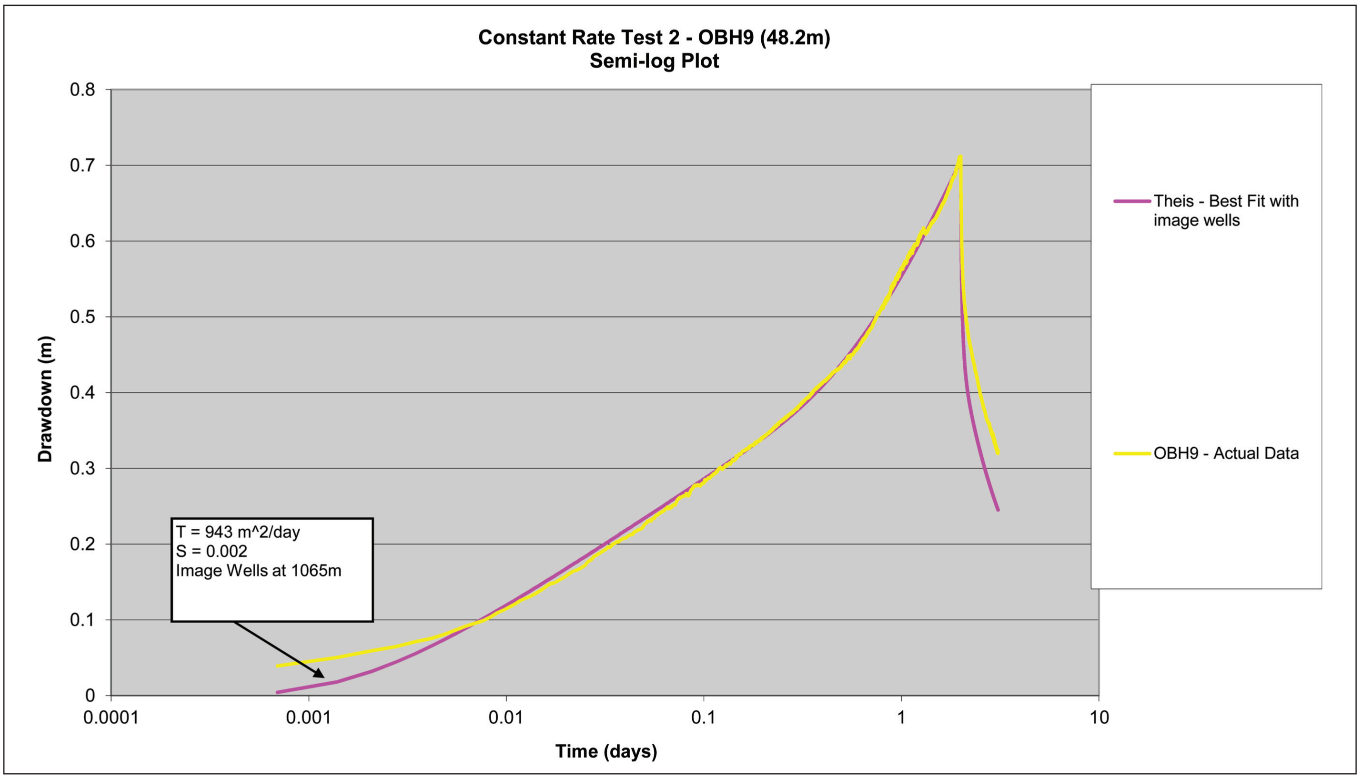


Figure 14. *Constant rate pumping test. Analysis of OBH9 using image wells to fit late time response Yellow line gives the observed groundwater response data.*

The excellent fit to the measured data using the image well concept indicates that the presence of physical barriers within the aquifer system (i.e. limits in the lateral extent of the aquifer) could potentially explain the drawdown response that was measured (some other possible explanations are postulated below). As shown in the cross section A-A' in Figure 2, there is a local ridge within the London Clay which is shown by the base of the sand and gravel in BH12 being above the groundwater level.

GEOLOGICAL AND HYDROGEOLOGICAL INTERPRETATION

Hydrogeological Conceptual Model

Three hydrogeological cross-sections based on the borehole logs obtained during the ground investigation and groundwater level monitoring data related to the interpretation described above are presented as Figures 2 to 4. The lines of section are shown on Figure 1.

As detailed above, no drawdown of groundwater was detected in BH4 during any of the various pump tests. This is despite BH4 being significantly closer (145m) to the abstraction borehole ABH7 than other boreholes (BH1, over 400m; BH2, 250m; and BH5A, 170m) which did show a noticeable drawdown during the tests. The lack of a response indicates that the groundwater within the sand and gravel in BH4 is not in hydraulic connection with the groundwater in the remainder of the monitoring boreholes. Further evidence of a hydraulic separation is provided by the borehole logs for BH11 and BH12, in which the elevation of the base of the sand and gravel deposits is significantly higher than in the majority of the other boreholes.

The sand and gravel deposits are saturated throughout their full depth within BH5A, BH6A, BH10, OBH8, OBH9 and the abstraction borehole ABH7, with rest groundwater levels being above the top of the sand and gravel deposits by up to 1.6m indicating confined (or sub artesian) aquifer conditions. In the remaining boreholes, groundwater levels were significantly below the top of the sand and gravel indicating that the aquifer in these areas is unconfined.

Based on the borehole logs and this interpretation, a plan showing the hydrogeological interpretation is presented in Figure 15. This shows the site to be broken into three different hydrogeological units:

- Aquifer 1 (Confined/sub artesian): Located under the southern section of the site and includes boreholes BH5A, BH6A, BH10, OBH8, OBH9 and the abstraction borehole ABH7.
- Aquifer 1 (Unconfined): Located under the central and north eastern part of the site and includes boreholes BH1, BH2 and BH3.
- Aquifer 2: Located under the north western section of the site, includes boreholes BH4, BH11 and BH12. The pump test was undertaken within Aquifer 1 with no measured response in Aquifer 2. Therefore Aquifer 2 is not discussed further.

Aquifer 1:Aquifer Thickness

In ABH7, OBH8 and OBH9 the thickness of the sand and gravel aquifer is between 6 and 8m. To the south and west of these boreholes the thickness of the aquifer reduces significantly, to around 2m in the vicinity of boreholes BH10 and BH6 and 1m in the vicinity of BH5A.

In the unconfined section, proved saturated thicknesses

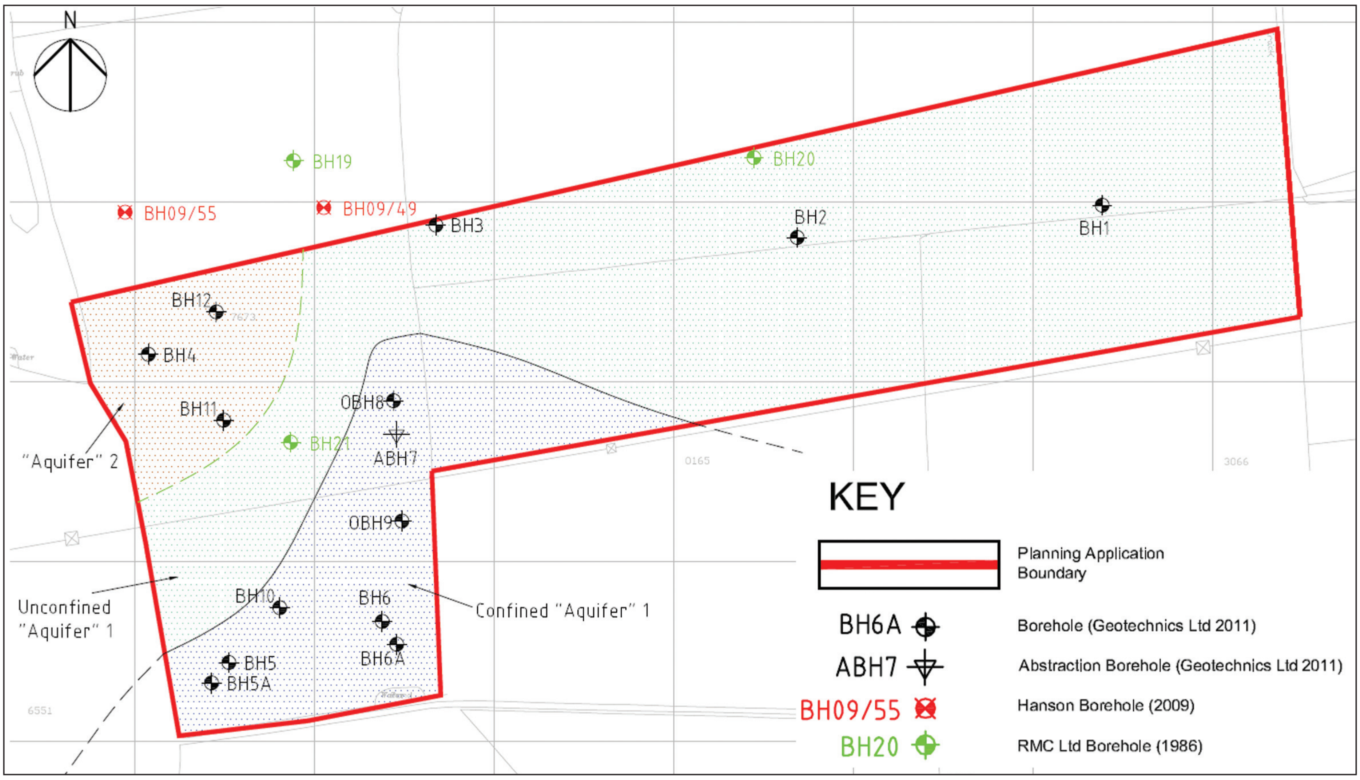


Figure 15. *Interpretation of aquifers within the site boundary (Scale, gridlines are at 100m spacings).*

range from 1.8m in BH1 to 6m in BH3, with the thickness of both the sand and gravel mineral deposit and associated saturated thickness reducing from west to east.

Aquifer 1: Transmissivity

The various estimates of transmissivity based on different analytical techniques and from observations in different boreholes ranged from around 340 to 1000m^2/day. In general, the 'short time' transmissivity values derived using the step test and early parts of the constant rate test were typically higher (median = 896 m^2/day than the values derived using late time data from the constant rate rest (median = 404 m^2/day). Possible reasons for this are discussed below.

Transmissivity is defined as the Hydraulic Conductivity (K) multiplied by the aquifer thickness (D). As detailed in the 'Aquifer Thickness' section, based on the boreholes drilled, the maximum aquifer thickness of between 6 and 8m is in the vicinity of the abstraction borehole ABH7 and the closest monitoring boreholes OBH8, OBH9 and BH3. In the initial phases of the pump test (when the cone of depression is limited in its lateral extent), the aquifer response will be a reflection of the aquifer thickness and hydraulic conductivity local to the abstraction borehole. As the aquifer thickness is greatest in the vicinity of ABH7 it follows that relatively high values of transmissivity have been determined for the short time response, especially when the boreholes OBH8, OBH9 and BH3 are used as the observation boreholes. As the pump test continues the cone of depression spreads into areas where there is less water available (to the south the confined aquifer thins to approximately 1m thick, to the north east the unconfined thickness reduces to 1.8m and to the north west there is the physical barrier between the abstraction and BH4).

For boreholes OBH8 and OBH9, the effect of the reduction in available water can be modelled using image wells to simulate a physical aquifer boundary.

Aquifer 1: Storage Coefficient

The various estimates of storage coefficient based on different analysis techniques and from observations in different boreholes ranged from 0.0014 to 0.09. In general, the 'short time' storage coefficients derived using the step test and early parts of the constant rate test were typically an order of magnitude lower (median = 0.0025) than the values derived using late time data from the constant rate test (median = 0.024).

The storage coefficient is defined as the volume of water released from storage per unit surface area, per unit decline in head (Kruseman and de Ridder, 1990). Typical values for a confined aquifer are $1x10^{-4}$ to $1x10^{-5}$. In an unconfined aquifer water is released by dewatering of the aquifer and a typical storage coefficient for an unconfined aquifer is 0.1 (Hunt, 2008).

The abstraction borehole was located within part of the aquifer where confined conditions were present at the start of the test. However during the test the resulting drawdown in the abstraction borehole (and observation boreholes) meant that unconfined conditions were progressively encountered as the test proceeded.

Therefore it is considered likely that the increase in storage coefficient may be due simply to the fact that as the pump test progressed and drawdown in the aquifer increased, a larger section of the aquifer was unconfined.

Linearity of the Conceptual Hydrogeological Model

The key finding of the constant rate pump test was that the rate of change in the drawdown against log time curve for the nearby monitoring boreholes OBH8 and OBH9 appeared to increase as the pump test progressed (see Figures 10, 14 and 15 in particular). This observation can be explained by the presence of hydraulic barriers, and, the theoretical match shown in Figures 14 and 15 that was produced using the principle of image wells to model the effect of a bounded aquifer.

However, whilst this relationship is able to accurately match the drawdown during pumping, the relationship is not so effective at matching the rebound following shut down. This is best demonstrated in Figure 16 below, which is identical to Figure 13, except a linear rather than log scale for time is used.

Figure 16 shows the theoretical solution almost perfectly matches the observed drawdown up until the time when the pump is shutdown (t=2 days). After 24hrs of recovery the predicted residual drawdown (modelled using the principle of superposition) is around 0.23m whilst the actual residual drawdown is around 30% higher at 0.31m. Similar relationships were observed for other monitoring boreholes.

The lack of linearity can be explained by the conceptual hydrogeological model of the relatively thin sand and gravel aquifer. Linearity is only achieved when the various parameters have coefficients that do not change with time. The linearity of the various hydrogeological solutions (Theis, Hantush etc) to the fundamental mathematical differential equations is obtained by introducing the term transmissivity (T = KD) to neglect changes in D (and hence T) caused by calculated changes in hydraulic head (h). This linear approximation is generally valid if calculated changes in 'h' for an unconfined aquifer are small compared with the saturated aquifer thickness, D. In the immediate vicinity of the abstraction borehole, this is likely to be a valid approximation; however as the cone of depression spreads to areas where the saturated aquifer thickness is very low to begin with, then this approximation will break down.

Another explanation for the lack of a linear response (i.e. use of superposition to model pump shut down not accurately representing field data) is due to the storage coefficient for the recovery (S) being different from the storage coefficient during the pump test. Based on the conceptual hydrogeological model for the site, one reason for this could be that the test began in ABH7 under confined or sub artesian conditions, but finished in unconfined conditions. Confined conditions are generally characterised by very low storage coefficients as water is released by the elastic expansion of water in the aquifer due to reduced pressure. As the pump test progressed and groundwater levels were drawn down to below the level of the overburden, water would have been released from storage within the pore space and a storage coefficient or effective porosity would be applicable. At shut down, this process is reversed, i.e. initially water will flow back into the pore space so the effective porosity soon after shut down will be high and will reduce again once confined conditions start to be encountered.

The final conceptual explanation is simply that the glacial sand and gravel aquifer is of a very limited, finite extent (i.e. a sealed system) and therefore will not recover to the pre-test levels.

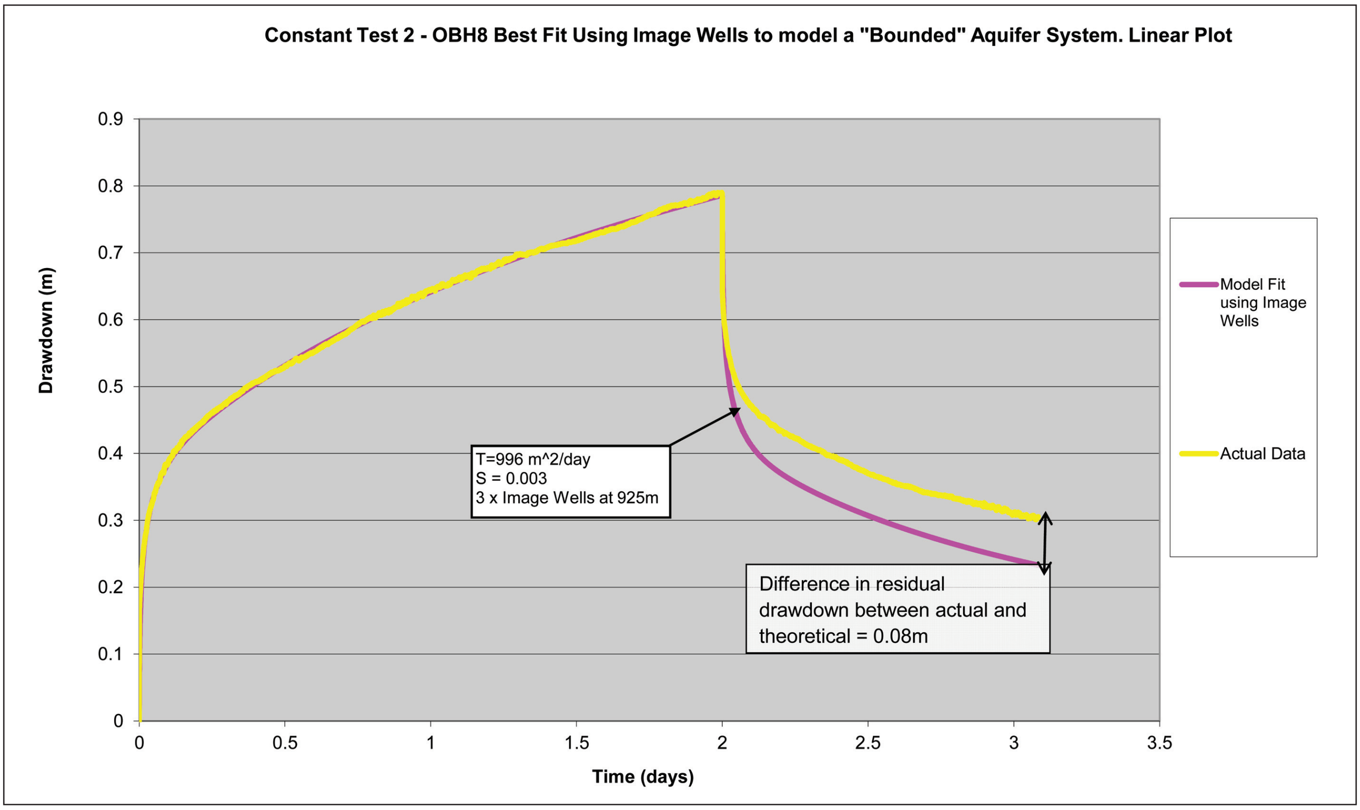


Figure 16. *Constant rate pumping test. Analysis of OBH8 using image wells to fit late time response– linear time plot. Yellow line gives the observed groundwater response data.*

Groundwater levels in the completed monitoring boreholes were monitored on 23 June 2011 (prior to any abstractions as part of the series of pump tests) and again on 26 July 2011, 15 days after pump testing had been completed. The results are presented in Table 5.

Borehole	23/06/11 m bgl	26/07/11 m bgl	Residual Drawdown m
BH1	5.59	5.75	0.26
BH2	7.1	7.35	0.25
BH3	8.41	8.71	0.30
BH4	7.68	7.42	**-0.26**
BH5A	8.04	8.35	0.31
BH6A	7.42	7.74	0.32
ABH7	8.32	8.58	0.26
OBH8	8.38	8.67	0.29
OBH9	7.96	8.26	0.30

Table 5. *Groundwater monitoring results. (mgbl: metres below ground level).*

Table 5 shows that groundwater levels were between 0.25 and 0.32m lower following the pump test in all boreholes except BH4 in which groundwater levels actually increased during (and following) the pump test. This residual drawdown in all of the monitoring boreholes is significantly greater than what would be anticipated and given the rise in groundwater levels in BH4, does not appear to be caused by reduction in recharge or other climatic explanation.

This large and relatively consistent residual drawdown 15 days after completion of the pump test appears to suggest that there is a finite volume of water contained within the sand and gravel aquifer locally, hence the non-linear recovery in groundwater levels.

CONCLUSION

The ground investigation carried out at the site proved the expected, simple geological sequence of overburden (Boulder Clay), overlying Glacial Sand and Gravel mineral deposits overlying London Clay.

However, the hydrogeological conceptual model for the site is relatively complex as shown both by the cross sections produced from the borehole logs and from the results of the pump tests carried out.

Analysis of the pump tests was carried out using both traditional techniques and using the excel spreadsheet function.xls. Both methods of analysis resulted in similar findings for the key hydrogeological parameters, however the key advantages of using function.xls are that:

- Estimates of both storage coefficient and transmissivity can be derived from the step drawdown test.
- Once the model is set up and the measured data entered it is a quick process to undertake a number of calculations for different combinations of parameters and add-ins such as Solver can be used to find the parameters that produce the best fit.
- Using the correct conceptual model and the principles of superposition and time translation, the potential for bounded systems or other physical constraints within the hydrogeological conceptual model can be assessed without the need for detailed numerical modelling.

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