Groundwater reinjection and heat dissipation: lessons from the operation of a large groundwater cooling system in Central London

David Birks[1,2], Paul L. Younger[2], Leila Tavendale[3], Catherine Coutts[4], Geoff Parkin[5], Paul Button[6] and Steven Whittall[7]

[1]Parsons Brinckerhoff, Queen Victoria House, Redland Hill, Redland, Bristol BS6 US, UK

[2]School of Engineering, James Watt Building (South), University of Glasgow, Glasgow G12 8QQ, UK

[3]Parsons Brinckerhoff, Amber Court, William Armstrong Drive, Newcastle upon Tyne NE4 7YQ, UK

[4]Parsons Brinckerhoff, 6 Devonshire Square, London, EC2M 4YE, UK

[5]School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne NE1 7RU, UK

[6]Max Fordham LLP, 42-43 Gloucester Crescent, London NW1 7PE, UK

[7]Worley Parsons, Parkview, Great West Road, Brentford, Middlesex TW8 9AZ

Birksd@pbworld.com

INTRODUCTION

The practicalities of groundwater reinjection have long been investigated for water resources purposes, as part of aquifer storage and recovery projects (Driscoll, 1986, Harris, 2005, Martin 2013). More recently, analysis of the fate of surplus heat introduced to aquifers with water from cooling systems has become a pressing issue, as the number of systems using the subsurface as a low-carbon heat sink increase (e.g. Younger 2007; 2014). This paper examines two years of operational data from the first large system of this type exploiting the Quaternary valley-train sand-and-gravel aquifer associated with the River Thames. Given that similar aquifers are widespread, not only in the UK but worldwide, the findings of this investigation offer valuable insights for designers and managers of such systems elsewhere, particularly in other large cities.

SITE DESCRIPTION

The site is housed within the former Bankside Power Station, built in two stages between 1947 and 1963. A former oil-fired power station, Bankside closed its doors in 1981, although the EDF Energy owned substation at the back of the building continued to operate. In 2006, half of the sub-station building was released back to the art gallery that now occupies the former power station, and the newly available space makes up part of the footprint of an expansion. The other half of the site continues to be used as the major electrical substation serving much of South London and waste heat from water cooled transformers provides 65-96% of the overall heat demand within the new development at the site. Whilst waste heat is utilized to provide most of the heating requirement approximately 11% of the buildings entire energy demand comes from cooling, even after a number of passive cooling systems were developed.

Groundwater in the shallow alluvial aquifer underlying the site provides the sole source of cooling for the new development at the site and was developed between 2008 and 2010. Starting in 2012 the performance of this large open loop groundwater cooling system has been monitored closely over its first two years of operation. This has allowed closer examination of two operational aspects which are of critical importance to the efficient running and longevity of the installed system, namely the stability of the recharge and induced changes in the temperature of the groundwater in response to sustained heat rejection.

In an initial nine month trial period, approximately 131,300 m^3 of groundwater was abstracted and recharged and approximately 1.3 GWh of heat was rejected to the subsurface, which verges on a proposed typical year of operation. Monitoring described in this paper has enabled closer examination of the resilience of the installed system in terms of recharge and heat rejection.

A detailed description of the development of the cooling system at the site, including an assessment of the geological and hydrogeological setting, the installed borehole infrastructure, and the results of early commissioning tests and analysis, is given in Birks et al. (2013). Briefly, the groundwater cooling system utilises a shallow sand and gravel aquifer referred to as the Thames River Terrace Gravels.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The site is located on the south bank of the River Thames in Central London as shown in Figure 1. At the site the River Thames is tidal with up to 9.32 m difference in levels based on Port of London Authority Records for the period 2011 – 2014 (Elliott 2014). Freshwater flow is typically 7 m^3/s in summer, increasing to over 600 m^3/s under flood events. Water temperature in the River Thames varies between 5°C and 22.5°C. Native groundwater temperature in the River Terrace Gravels aquifer beneath the site ranged between 13.5°C and 15.9°C when measured in 2010.

The River Terrace Gravels occur as a sequence of sediment bodies that are differentiated broadly on the basis of elevation relative to the present flood plain. The deposits at the site comprise the lowest terrace above the flood plain of the present River Thames, referred to as the Kempton Park Gravels, which are approximately 5 m thick in the vicinity of the site. The Kempton Park Gravels comprise fine to coarse sand and flint gravel. Analysis of samples at the site confirms a particle size distribution of approximately 60% gravel and 40% sand (Bucherer et al., 2006). The sand fraction is predominantly within the medium to coarse grain size range (0.2 – 0.7 mm) with the fine sand fraction accounting for a relatively small proportion overall (<5%). Analysis indicates the proportion of silt and clay particles (<0.06 mm) to be very small at <<1%. These observations are consistent with the findings of Naylor (1974) and Gibbard (1994).

The aquifer is covered by approximately 6m combined thickness of made ground and alluvium and underlain by >30m London Clay. The underlying London Clay is an effective aquitard that completely isolates the River Terrace Gravels from the underlying Chalk and Basal Tertiary Sands. In contrast the overlying alluvium is considered by the authors to behave as a leaky aquitard. Groundwater levels in the River Terrace Gravels are subject to diurnal variation of up to 1.5m in response to tidally induced changes in water levels in the River Thames.

Figure 1: Location map showing the site boundary, borehole locations and line of section for Figure 2 (adapted from Birks et al., 2013).

INFRASTRUCTRE

Borehole Infrastructure and Construction

Borehole infrastructure at the site comprises three abstraction boreholes, two injection boreholes and seven observation boreholes, five of which derived from earlier site investigations. For the operations herein described, only one abstraction (ABS1) and one injection borehole (INJ2) have been utilised. The nomenclature of three observation boreholes, referred to herein as OBH1, OBH2 and OBH3, have been changed for greater clarity.

The recharge borehole (INJ2) is 13 m deep and lined with a 1.22 m diameter mild steel casing with a slotted section between 6 m and 11.5 m below ground level (mbgl). The slotted section comprises 300 slots of 10 mm by 300 mm aligned vertically with 24 slots per circumference giving an open area of approximately 8%. Below the slotted section is a steel lined sump, 1.5 m in length. The River Terrace Gravel deposit was allowed to fall in around the slotted section forming its own natural gravel pack. Above the gravel pack the bore annulus was sealed with a bentonite cement grout, the volume of sealant material amounting to approximately 3.5 m^3. The borehole construction and a stylised geological cross section are given in Figure 2.

Figure 2: Borehole construction & stylised geological cross section. Section line is shown in Figure 1 (adapted from Birks et al., 2013).

Filtration

Groundwater is filtered in a plant room before it passes through the heat exchangers and is subsequently injected back into the aquifer. Primary filtration comprises an Auto – Klean type 060-793 strainer with a 250 micron reversed wedgewire screen. Secondary filtration comprises an automatic self-clean disc filter of 50 micron filtration grade and hydraulically actuated backflush facility coupled to a groundwater backwash acceptance buffer tank. During routine operations a backflush cycle is typically actuated three times a day (pers comm. Paul Button). On visual inspection of the backwash tank on 24 March 2014 the water in the tank was clear with no evident discolouration, sediment or biological growth. The recharge borehole (INJ2) has been sounded on two occasions with a small diameter shelling tool fabricated by G Stow plc for evidence of sediment accumulation. The first sounding was obtained in November 2010 (after the first period of recharge testing) and most recently on 9 December 2013. On both occasions the sounded depth was the same at 11.73m below flange plate level (approximately 12.73m below ground level) indicating negligible sediment accumulation between the two sampling intervals. The base of the borehole was firm and recovered material comprised fine sand. There was no evidence of sludge or slime on the shelling tool or cable.

Injection History & Monitoring

Injection of groundwater at the site has been undertaken over three separate injection intervals between October 2010 and October 2013 as shown in Figures 3 and 4.

- October 2010 – an eight day continuous period of injection where the rate of injection was reduced progressively from 16 L/s to 8 L/s in order to maintain a water level in the injection well at 0.5 m below ground surface (ground elevation 5.509 mAOD). The final flow step (8 L/s) was sustained for 34 hours after which testing stopped. The total volume of water injected is 9,307 m^3;
- June 2012 to May 2013 – a period of continuous injection at variable rates between 2 and 12 L/s during which the total cumulative injected water volume was approximately 131,295 m^3. Gaps in the flow record necessitated an estimation of flows for some periods, which were derived from observed responses in observation wells where a continuous record was maintained; and
- July – October 2013 – a period of cyclic and subsequently continuous injection at variable rates. Between 26 July and 12 August 2013 injection was continuous at 5 L/s, followed by approximately 1 month of cyclic injection at 7 L/s for two hours per day, followed by cyclic injection at up to 18 L/s for 8 hours per day, followed by a period of continuous injection between 2nd and 17th October 2013 at up to 21 L/s.

An injection rate of 8 L/s sustained for the last 34 hours of the 2010 abstraction – recharge test is used as the principal basis for assessment of injection capacity. As shown in Figure 3a, on conclusion of testing at a rate of injection of 8L/s in 2010 the pressure head in INJ2 was approximately 5.17 mAOD and corresponding pressure heads for the same rate of injection in November 2012 and October 2013 were 4.73 mAOD (Figure 3b) and 5.44 mAOD (Figure 3c) respectively.

Figure 3: Comparison of injection rate and water level (head) in the injection borehole (INJ2) 2010 – 2013. Baseline injection at 8 L/s is indicated with a dashed line.

Figure 4: Groundwater level in observation boreholes (OBH1 and OBH2) between May and November 2013. Flow rate (into injection borehole INJ2) shown for comparison.

INJECTIVITY ASSESSMENT

Injection capacity is usually quantified in terms of specific injectivity, which is the injection rate divided by the pressure increase (Maliva, 2013) and is a fundamental aspect of optimizing and maintaining injection bore systems. Table 1 and Figure 5present a representation of injection capacities for the main periods of injection between 2010 and2013The benchmark for comparison is the injection rate of 8 L/s sustained for the final 34 hours of testing in 2010 from which injectivity of 1.8 L/s/m is estimated. The derived injectivity for the most recent phase of testing was 1.65 L/s/m on 6 October 2013 and, when background variation in aquifer water levels due to tidal variation (equivalent c 0.5L/s/m) is taken in consideration, indicates little change. The apparent increase in injectivity in November 2012 is attributed to increased injection water temperatures (see Figure 6) and corresponding reduction in the viscosity of the recharge and receiving groundwater. Various authors (e.g. Martin, 2013 and Heilweil, 2010) observed that infiltration rates varied inversely with viscosity. In areas with large seasonal temperature variation, infiltration rates in winter were found to be as low as half those in the summer. In the period July – November 2012 temperature of the recharge water was consistently 5°C to 10°C higher than the native groundwater and through August and September the temperature of the recharge was routinely in the range 30 – 40°C. The apparent decrease in injectivity on 9 October 2013 is attributed to the capacity of the injection bore being exceeded at this rate of injection (12 L/s), analogous to the rapid dewatering of a well when it is pumped beyond its capacity. The derived injectivity of 2.3 L/m/s for the same rate in October 2012 is attributed to elevated water temperatures in the preceding period and corresponding decrease in viscosity.

Table 1: INJ2 Injectivity

Figure 5: Injectivity of INJ2 compared to the baseline established in 2010 (solid line). Potential variation in injectivity due to background tidal variation of 1.5m is shown by the error bars. Injectivity during testing on 25 - 26th of October and 10th of November 2012 are impacted by the viscosity of the injected fluid.

Clogging

The stability of the recharge is of critical importance to the efficient running of the groundwater cooling system at the site, indeed for all kinds of managed aquifer recharge applications. Various authors (e.g. Martin 2013) have observed that clogging of the borehole commonly causes impaired injectivity, restricting the volume of water that can be injected into an aquifer. Under a constant injection rate this can lead to excessive pressure heads that result in failure of the aquifer or overlying confining layer (Moltz, 1978, 1983) or, more commonly, a reduction in injection rate where the pressure is held constant. Martin (2013) observes that understanding the types of clogging that are likely to occur in a particular hydrogeological setting/managed aquifer recharge application is important and advances four principal reasons for clogging– physical, mechanical, chemical and biological. None of these clogging processes appear to have manifested significantly at the site and the principal reasons for this are given below.

A predominant cause of physical clogging is blinding of the well screen, gravel pack and formation matrix with suspended solids. Martin (2013) observes that clogging by suspended particles is characterised by a slow but steady increase in hydraulic head for a given rate of recharge. Over the first year of operation there has been no such evidence of physical clogging and this is attributed to filtration of the water prior to recharge, the physical properties of the well bore and formation. In the context of bore slot size and matrix properties (particle size distribution) it is envisaged that any residual sediment load passing through the filters also passes readily through the bore screen and formation matrix. Measured concentrations of suspended solids in the pumped groundwater during testing undertaken between 19 and 28 October 2009 were consistently in the range 6.5 – 14.5 mgL^{-1} (Birks et al., 2013), equivalent to approximately 85 kg total accumulation of suspended solid, based on the volume of groundwater pumped (8435 m^3) and an assumed average suspended solid concentration of 10 mgL^{-1}. If the suspended solid content had remained at the same or a similar level for all subsequent pumping (c. 160,000 m^3) the accumulated suspended solid would have been in the region of 1.5t. However, based on visual inspection of the filtration plant in March 2014 and depth sounding obtained in the recharge borehole in 2010 and 2013 there is no evidence of sediment accumulation of this magnitude. It is therefore concluded by the authors that the suspended solid content in abstracted groundwater has either reduced significantly as a result of continued borehole development and/or that any residual suspended solid passing through the filters is pumped back into the aquifer via the injection borehole rather than accumulating within the basal sump. It is acknowledged that further monitoring of this parameter will be required to establish this definitively.

An additional cause of physical clogging is viscosity, where injectivity varies inversely with water temperature. Kestlin (1978) derived viscosity ratios for liquid water benchmarked against the viscosity of liquid water at 20°C which, for water temperatures of 15°C and 40°C, were 1.1351 and 0.6510 respectively. In the absence of other plausible explanation, observed increases in injectivity in November 2012 are considered by the authors most likely attributable to elevated injection water temperatures of up to 40°C in the preceding months and a proportional reduction in the viscosity of the groundwater local to the injection bore (Figure 6). This assessment is consistent with the observations of Martin (2013) and Heilweil (2010), where infiltration rates were found to vary inversely with viscosity (and hence temperature).

A predominant cause of mechanical clogging is air entrapment within the aquifer and this effect is typically experienced within hours of commencement of recharge. Various authors (e.g. Martin, 2013 and Pyne, 2005) observed that where downward velocity exceeds 0.3 $msec^{-1}$ then the entrapped air can enter the formation where it lodges in the pore space. This increases the resistance to flow, resulting in higher water levels. It is considered possible that air entrapment may have contributed to the reduction in injectivity experienced during the initial commissioning trial although it remains the view of the authors that the observed reduction was primarily related to the filling of storage in the alluvium overlying the aquifer (Birks et al., 2013).

Biological clogging processes are influenced by levels of nutrients and bacteria in the injected water and receiving aquifer (Martin, 2013) and the nature of the substrate needed to foster biological growth (Pyne, 2005). Measured concentrations of total organic carbon (TOC) in pumped groundwater samples at the site have been found to be consistently in the range 5.5 – 6.5 mgL^{-1} and compare closely with groundwater samples obtained from the River Thames on conclusion of testing in 2010 of 5.2 – 6.12 mgL^{-1}. Measured concentrations of TOC in groundwater at the site compare quite closely with the mean value reported by Gooddy et al. (2008) for groundwater in the UK Chalk and Sandstone aquifers of 3.02 mgL^{-1} (range 0.49 mgL^{-1} to 19.2 mgL^{-1}). Thus the availability of carbon for creating biomass is considered to be relatively low especially in the context of polluted groundwater or landfill leachates where TOC concentrations of 1000 mgL^{-1} to 10,000 mgL^{-1} have been observed (Lee et al., 1993). Various authors (Wood, 2013) have observed that biological clogging is more prevalent in finer grained materials. Following nine months continuous injection and subsequent intermittent injection over a period of three months no evidence of biological clogging has been observed and the primary reasons for this are considered to be i) the properties of the aquifer, namely a clean flint gravel with minimal fines content and ii) that the entire borehole and filtration system is sealed from atmosphere.

Evidence of mineral precipitation, the principal cause of chemical clogging, was observed on the air dried surfaces of testing equipment during testing in 2010 (Birks et al., 2013). Monitoring of the groundwater through 2012 and 2013 confirmed dissolved iron concentrations of typically <1 mgL^{-1} and dissolved manganese typically <0.1 mgL^{-1}. Measured concentrations of dissolved iron in 2010 were slightly higher, being in the range 0.2 – 3 mgL^{-1}. Measured concentrations of dissolved manganese in 2010 were consistently in the range 0.12 – 0.16 mgL^{-1}, again slightly elevated compared to measured concentrations in 2012 to 2013 The relatively low concentrations of iron and manganese dissolved in the groundwater and the fact that the entire system is effectively sealed from atmosphere are considered to be the primary reasons why chemical clogging has not yet manifested as a significant problem

It is accepted, however, that recharge has only been sustained for a relatively short period and in such a high permeability aquifer it would be unwise to conclude that mineral or biological precipitation may not manifest as a problem at some point during the full working life of the system. In the event clogging does manifest as a problem in the future it will be necessary to establish the reason why and more detailed investigations (such as digital camera surveys, further groundwater sampling etc.) may be required.

HEAT REJECTION

The main phase of heat rejection occurred between June 2012 and the end of April 2013, the amount of heat rejected being approximately 1.3 GWh. Heat rejection was stopped on 30th April 2013 and for the duration of the subsequent monitoring period (to March 2014) no further heat rejection occurred. Monitoring of water temperatures during testing in 2010 provided a baseline of temperature data against which induced changes in groundwater temperature resulting from the heat rejection have been compared. Continuous monitoring of water temperatures in the period May 2013 to March 2014 shows how groundwater temperature in the aquifer has recovered following the main phase of heat rejection allowing earlier estimates of heat losses and heat loss mechanisms to be evaluated (Birks et al., 2013). Development of the heat plume in the groundwater in response to heat rejection in terms of thermal breakthrough times and the timing and magnitude of temperature increases provides a useful validation of analytical solutions proposed by various authors including Dougherty (1982), Guven (1983) and Banks (2009 and 2011). Observed temperature changes approximate quite closely to the projections made on the basis of these analytical solutions.

Figure 6 below presents a plot of abstracted and recharged water temperatures and flow rate for the period July 2012 to April 2013, which was used as the basis for estimating heat rejection. Gaps in the data series are due to data being lost by the building management system (BMS) and where this has occurred heat rejection has been estimated on the basis of responses in observation wells. Based on a total abstraction – recharge volume of approximately 131,295 m^3 and the average temperature differential, estimated heat rejection is approximately 1,370,000 kWh. Heat rejection in any given month ranged from 62,000 kWh to 208,700 kWh as shown in Figure 7.

In the context of UK water resources regulation the Environment Agency specify as a guideline that the recharge water temperature should not exceed 10°C above the baseline in the aquifer. Averaged over the full term of the 2012 – 2013 injection period, the heat rejection equated to an average temperature differential of 9°C, which is within this general guideline. However, a time averaged temperature differential does not reflect the day to day variation where temperatures of up to 40°C (some 25°C above the baseline) were observed. In practice it is very difficult to maintain instantaneous recharge temperatures within 10°C of the baseline water temperature as indicated by the work of Clarkson et al (2009) where peaks in recharge temperature of 30 – 35°C were observed routinely. It is important that these practical considerations are factored into the Environment Agency License agreement as they have been at the site by stipulating a time averaged temperature differential. Notwithstanding, it does raise the question of whether the recharge temperature differential is the most appropriate regulatory control on thermal pollution and whether total net heat rejection expressed as a kWh value is a more appropriate measure.

Figure 6: Comparison of the abstracted water temperature with temperature of the River Thames. Abstraction rate is shown for comparison.

Figure 7: Monthly Heat Rejection

Figure 8 below presents an almost continuous record of groundwater temperature in three observation boreholes (OBH1, OBH2 & OBH3 between August 2012 and March 2014. The loggers were installed on 23 August 2012, approximately 2 months after commencement of heat rejection, and a break in the monitoring of approximately 2 months occurred between 10 October and 9 December 2013 due to the logger memory capacity being exceeded in this period. Notwithstanding these gaps in the data series, a number of conclusions can be made.

Thermal breakthrough, as defined by a rise in water temperature, occurred at different times in the three observation boreholes.

Breakthrough in OBH2, located approximately 25 m SSE (Figure 1), and subsequent changes in temperature as a result of variation in the rate and temperature of recharge were relatively fast and are indicative of rapid groundwater flow between the injection location and OBH2. This is attributed to remnant structures in the made ground and boundary effects associated with the basement structure, which penetrates the full thickness of the aquifer. The highest recorded water temperature in OBH2 was 23°C on 26 September 2012 and appears to correspond to short-lived peaks in the temperature of the recharge of 45 – 50°C in late August and early September, followed by a sustained increase in recharge water temperature from 30°C to 40°C in mid-September 2012. Between 26 September and 30 October water temperature in OBH2 decreased rapidly to around 17.2°C and this corresponds closely with a reduction in the temperature of the recharge around the same time (see Figure 6). A second peak in the temperature of water in OBH2 of 21.1°C occurred on 7 May 2013, seven days after the reported cessation of heat rejection. A third peak in water temperature is evident on 5 September 2013 and this coincides with the commencement of the recharge testing, which started on 26 July 2013. Observed responses are all indicative of groundwater and heat travel times between OBH2 and INJ2 of around seven days.

Breakthrough in OBH3, located approximately 130m east of the injection location (Figure 1), occurred around mid-October 2012, approximately 3.5 months after commencement of heat rejection. This is broadly consistent with the breakthrough estimate given in Birks et al. (2013), where the breakthrough time at the abstraction location was estimated at approximately 117 days. Water temperature in OBH3 peaked on 25 December 2012 at approximately 15.9°C, a rise of approximately 2.4°C above the baseline. The observed peak in OBH3 occurred approximately 3 months after the first peak in OBH2 and corresponding period of maximum recharge temperatures.

The temperature record for OBH1 appears to show thermal breakthrough commencing approximately 1 week after logger installation. For about 1 week after logger installation the groundwater temperature is approximately 13.5°C, after which (from 1st September 2012) groundwater temperature starts to rise and continues to rise until late November 2012 where it reaches approximately 18.6°C, an increase of 5°C above the baseline. After the late November peak the temperature of groundwater appears to stabilise at approximately 18.3°C before starting to rise again in mid-March 2013 where a maximum water temperature of 19.3°C is attained on 7th May 2013, seven days after heat rejection stopped.

Figure 6 presents a near continuous plot of abstracted groundwater temperature for the main period of heat rejection. Between mid-July and mid – late September 2012 the abstracted water temperature was relatively constant at 15.2 – 15.4°C and is consistent with the baseline temperatures observed in 2010. Notwithstanding the observed rises in groundwater temperature in the three observation wells (Figure 8), there is no evidence of thermal breakthrough at the abstraction bore itself in this period. Following a gap in the abstraction temperature record of about one month there is a progressive decrease in abstracted water temperature from late October 2012 to late April 2013. A minimum recorded temperature of 6.59°C was recorded in late January 2013 and the abstracted water temperature at the end of the monitoring period (20 April 2013) was 11.9°C, some 3.5°C lower than the baseline established in October 2010. Monitoring through the most recent phase of testing in July – October 2013 confirmed an abstracted groundwater temperature of 14.9°C.

On comparing the abstracted groundwater temperature with temperature data for the River Thames provided by the Environment Agency (see Figure 9), the reason for the observed decrease in abstracted water temperature becomes clear. The data shows that the effects of the river aquifer interchange on the overall heat mass balance observed in Birks et al. (2013) are much greater than originally anticipated and appears to have a much greater impact on the abstraction water temperature than heat rejection from the scheme itself.

Birks et al. (2013) estimated heat losses via surface heat exchange to be in the region of 500,000 kWh pa. Monitoring of temperatures in OBH1, OBH2 and OBH3 during the heat rejection period and for 11 months afterwards is summarised in Table 2 below and allows this assessment to be evaluated.

As an overall average the proportional decline in temperatures observed in the three boreholes equates to approximately 1 GWh reduction as a result of a combination of heat dissipation processes including heat loss to ambient air, losses to overlying and underlying strata and lateral diffusive heat losses. In this context heat losses via surface heat exchange estimated in Birks et al. 2013 seem reasonable.

Table 2: Groundwater temperature

Figure 8: Groundwater temperature in observation boreholes OBH1, OBH2 & OBH3. OBH1 is closest to the injection borehole, and OBH3 is the furthest. The temperature response seen in OBH2 is attributed to remnant structures in the made ground and boundary effects associated with the basement structure, which penetrates the full thickness of the aquifer.

Figure 9: Temperature of abstracted groundwater compared to the temperature of the River Thames.

CONCLUSIONS

The groundwater cooling system has a design life of 25 years. In this context, continuous injection over a period of nine months in 2012-2013 at c. 50% of the full annual abstraction - recharge total allows a reasonable assessment of the stability of the borehole system in terms of its hydraulic and thermal performance to be made. Further, it is now possible to predict the nature and frequency of borehole maintenance over the full working life of the scheme more robustly.

Injectivity

With regard to hydraulic stability, there appears to have been little change in injectivity between the commissioning tests undertaken in 2010 and the most recent phase of testing in July – October 2013. To date there is no tangible evidence of clogging of the injection bore. Given that clogging is considered relatively common (Martin, 2013), the lack in this case merits explanation.

The following are considered the primary reasons why injection appears to work relatively well here:

- Grain size distribution and mineralogy of the aquifer matrix, which comprises a clean flint gravel with interstitial sand and minimal fines content;
- Relatively low concentrations of dissolved iron and manganese in the groundwater;
- Relatively small pressure changes in the abstracted and recharged groundwater owing to the shallow nature of the aquifer;
- The aquifer is fully saturated;
- Filtration of the groundwater; and
- The entire borehole system is effectively sealed from atmosphere.

Whilst the evidence to date indicates that injectivity at the site has not been impaired by clogging it is acknowledged that to presume this will remain the case over the full working life of the system would be unwise. The building management system at the site provides a continuous record of injected water pressure and flow rate and it is imperative that the relationship between injection pressure and flow rate be monitored closely over the full working life of the scheme. Presently this facility is accommodated within the license agreement and requirement to provide annual license returns.

Thermal Response

The amount of heat rejected during the 9 month period of continuous injection approximates closely to the projected net heat rejection in a typical year. Monitoring of groundwater temperatures in response to that heat rejection and subsequent decrease in groundwater temperatures, analogous to thermal recovery, in the months following allows closer examination of some of the assumptions and predictions relating to thermal performance (Birks et al., 2013).

Most significantly, the interaction between the aquifer and the River Thames is much greater than originally anticipated and is a more significant influence on abstracted water temperature than heat rejection from the development. Through the months of October to March abstracted groundwater temperature fell by more than 9°C with a corresponding decrease in river water temperatures of 16°C. If freshwater flow of 20 m^3/s is taken as an average in this period, the cooling effect of one day of freshwater flux is equivalent to ten years of heat rejection at the development. Under a flood event the cooling effect is equivalent to more than one hundred years of heat rejection. When viewed in this context the impact of the river on abstracted groundwater temperature is perhaps less surprising.

Wider Implications

Despite an extensive literature review, which preceded this and the earlier publication in Birks et al. 2013, very little information pertaining to managed recharge in a comparable setting could be found. Indeed the closest analogue in terms of aquifer type, recharge rates, heat rejection and longevity of operations was that reported by Moltz et al. (1978 and 1983), highlighting the paucity of this type of operation in the published literature. Notwithstanding, the authors are aware of a number of unpublished accounts of recharge of groundwater in similar deposits by a small number of UK dewatering contractors and extensive use of soak-aways in this type of deposit used for surface water drainage.

Given the evident influence of the River Thames on abstracted groundwater temperature it is reasonable to question what distinguishes the system installed at the site with a direct river off-take and discharge arrangement.

Firstly, abstraction of groundwater inland from the Thames embankment means any infiltration from the river is drawn from the river bed, filtered and buffered through approximately 80 m of sand and gravel. As a result the abstracted groundwater is of a higher and more consistent quality and the variation in temperature less than the River Thames. Importantly, groundwater temperatures are some 7°C lower than the observed summer time peaks in the River Thames.

Secondly, discharge back into the River Thames is of a more diffuse nature than a pipe point source, effectively a seepage face aligned with the Thames embankment where groundwater levels are raised in response to recharge. Again the body of aquifer between the recharge location and the river acts as a buffer attenuating hydraulic heads and heat transfer back into the river.

The above distinctions are considered important for both economic and environmental considerations. The cost of constructing and maintaining abstraction and discharge points within the River Thames might reasonably be expected to be considerably higher than the equivalent borehole configuration. Further, higher summertime temperatures in the River Thames would significantly reduce the efficiency of the cooling system and more variable water quality and sediment loads would affect filtration. With regard environmental considerations and assuming diffuse infiltration back into the River Thames the environmental impact in terms of flow derogation and thermal pollution are negligible. In this regard a large number of similar sized schemes would be needed to induce any measurable effect in river water temperature at all.

To put this in context, and assuming an annual flow through the lower reaches of the River Thames of c 2 $x10^9$ m^3 p.a., then the amount of heat energy deriving from just a 1°C change in temperature would be of the order of 2,000 GWh. Further, under effective regulation and by balancing heat extraction and heat rejection from multiple schemes in a responsible way, such that net changes in river water temperature are kept within acceptable limits, the potential for this mode of low carbon heating and cooling is considerable. In the context of some of the world's major continental river systems flows and background heat fluxes through the River Thames are very small and, arguably, the potential for this mode of heating and cooling on world cities located on the lower reaches of the major continental river systems much greater.

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Table 1: INJ2 Injectivity

Date	Flow Rate (L/s)	INJ2 Head Rise (mH2O)	Injectivity (L/s/m)
25 - 26 October 2010	8	4.45	1.8
25 - 26 October 2012	12	5.11	2.35
10 November 2012	10	4.68	2.14
23 – 27 November 2012	8	4.16	1.92
2 – 5 October 2013	6	3.95	1.52
6 October 2013	8	4.84	1.65
7 October 2013	10	5.67	1.76
9 October 2013	12	9.28	1.29

Table 2: Groundwater temperature

Monitoring Period	OBH2 (°C)	OBH1 (°C)	OBH3 (°C)
October 2010	14.6	13.3	14
Peak	23	19	16
March 2014	16	15.5	14.5
Max Rise	8.4	5.7	2
Residual March 2014	1.4	2.2	0.5
% Recovery	83%	61%	75%

Figure Titles

Figure 1: Location map showing the site boundary, borehole locations and line of section for Figure 2 (adapted from Birks et al., 2013).

Figure 2: Borehole construction & stylised geological cross section. Section line is shown in Figure 1 (adapted from Birks et al., 2013).

Figure 3: Comparison of injection rate and water level (head) in the injection borehole (INJ2) 2010 – 2013. Baseline injection at 8 L/s is indicated with a dashed line.

Figure 4: Groundwater level in observation boreholes (OBH1 and OBH2) between May and November 2013. Flow rate (into injection borehole INJ2) shown for comparison.

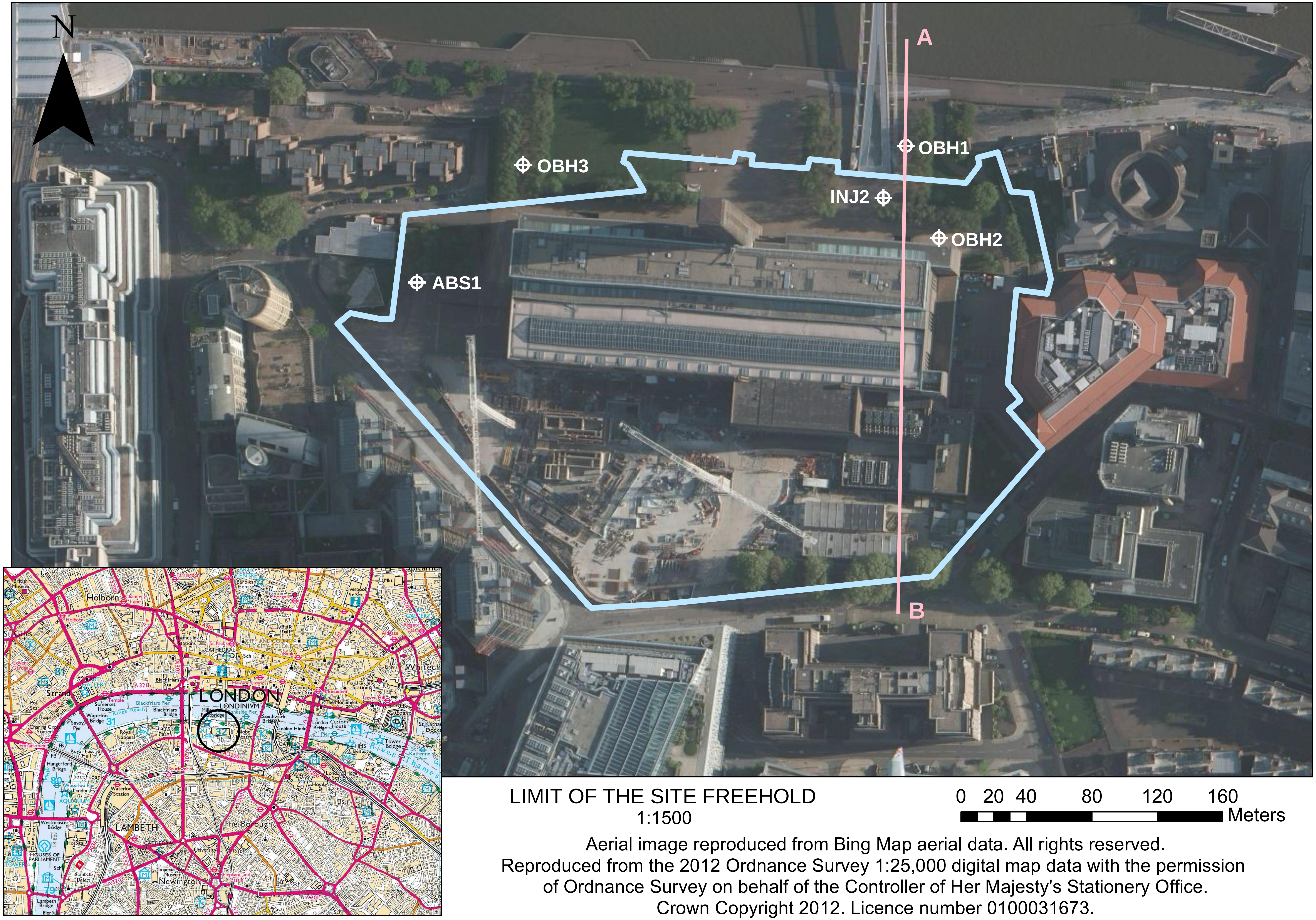
Figure 5: Injectivity of INJ2 compared to the baseline established in 2010 (solid line). Potential variation in injectivity due to background tidal variation of 1.5m is shown by the error bars. Injectivity during testing on 25 - 26th of October and 10th of November 2012 are impacted by the viscosity of the injected fluid.

Figure 6: Comparison of the abstracted water temperature with temperature of the River Thames. Abstraction rate is shown for comparison.

Figure 7: Monthly Heat Rejection

Figure 8: Groundwater temperature in observation boreholes OBH1, OBH2 & OBH3. OBH1 is closest to the injection borehole, and OBH3 is the furthest. The temperature response seen in OBH2 is attributed to remnant structures in the made ground and boundary effects associated with the basement structure, which penetrates the full thickness of the aquifer.

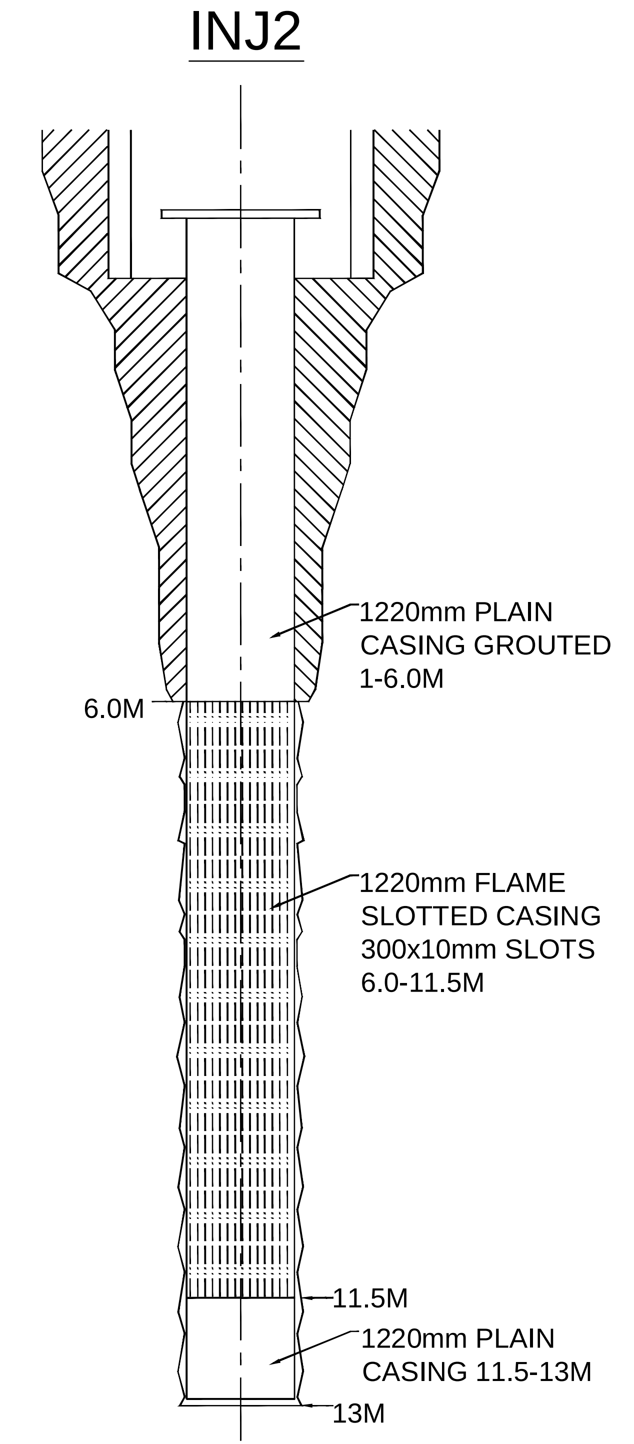
Figure 9: Temperature of abstracted groundwater compared to the temperature of the River Thames.

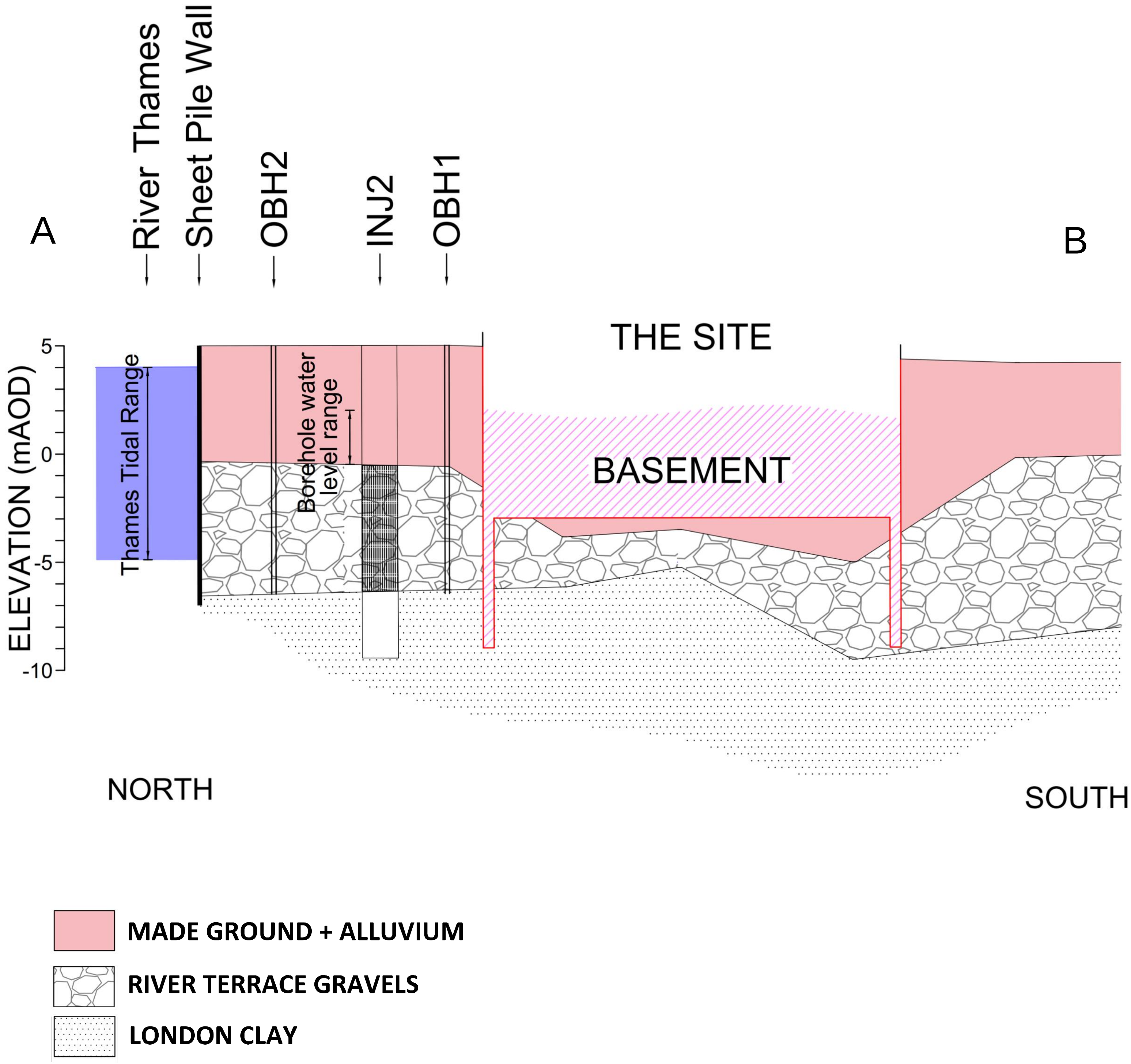


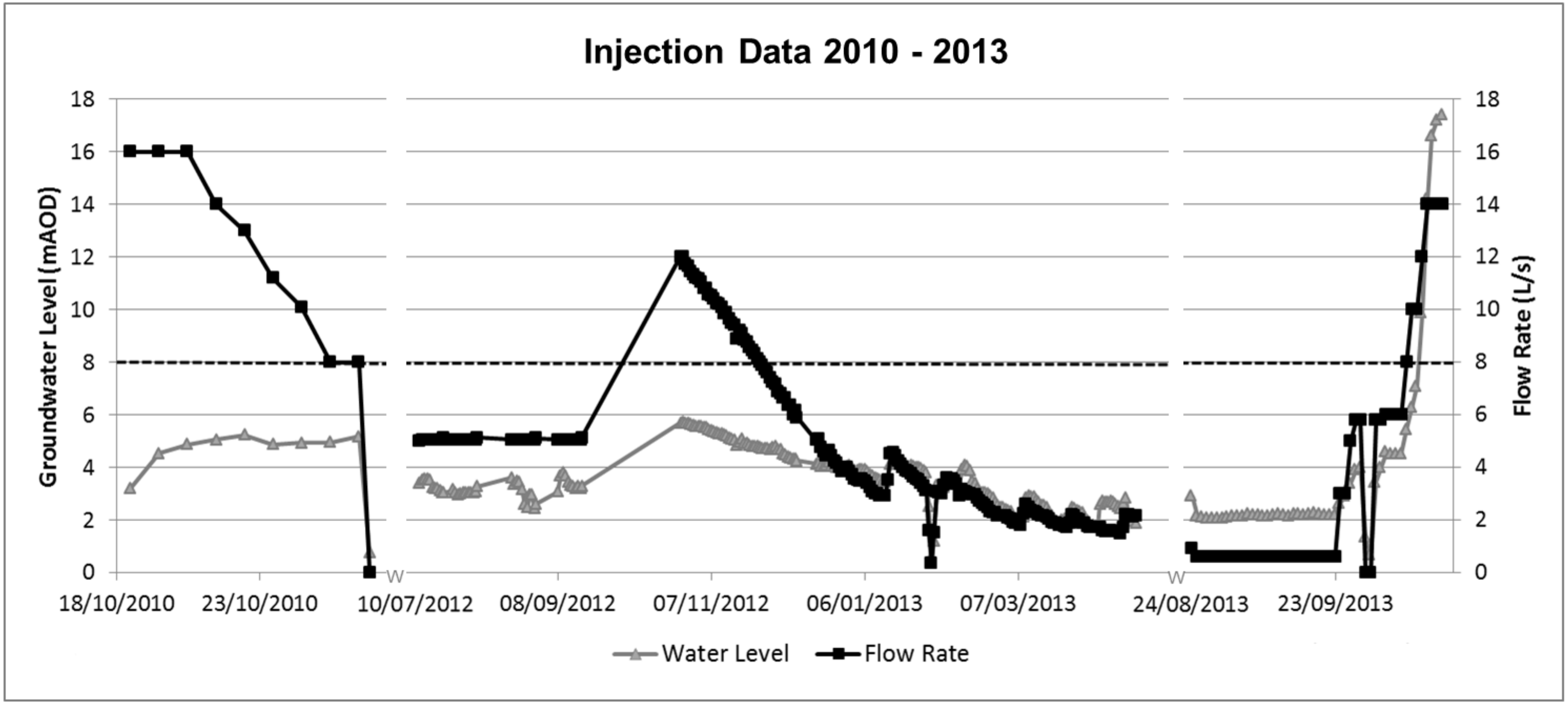
LIMIT OF THE SITE FREEHOLD

1:1500

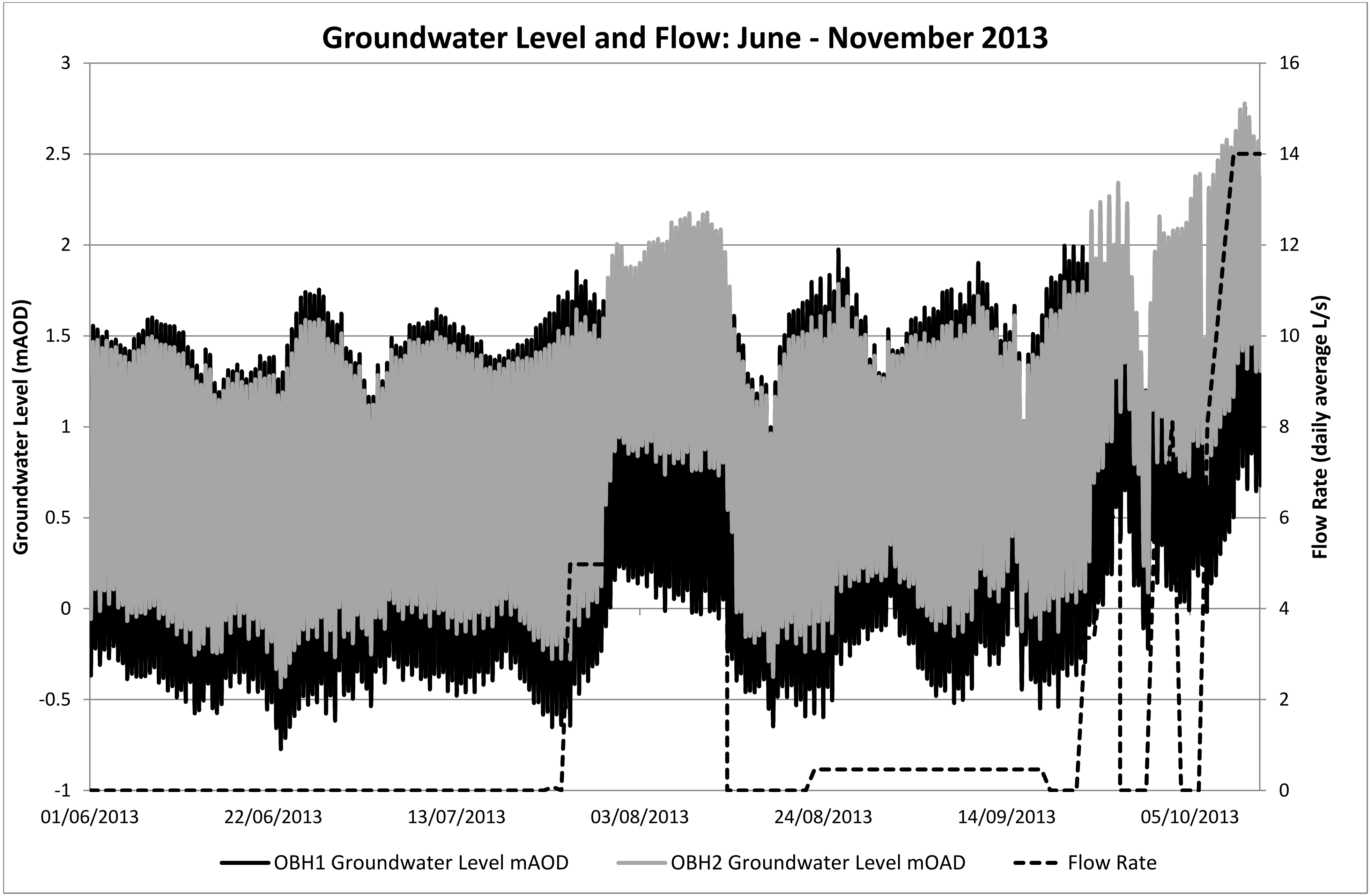
0 20 40 80 120 160 Meters


INJ2
1220mm PLAIN
CASING GROUTED
1-6.0M
6.0M
1220mm FLAME
SLOTTED CASING
300x10mm SLOTS
6.0-11.5M
11.5M
1220mm PLAIN
CASING 11.5-13M
13M

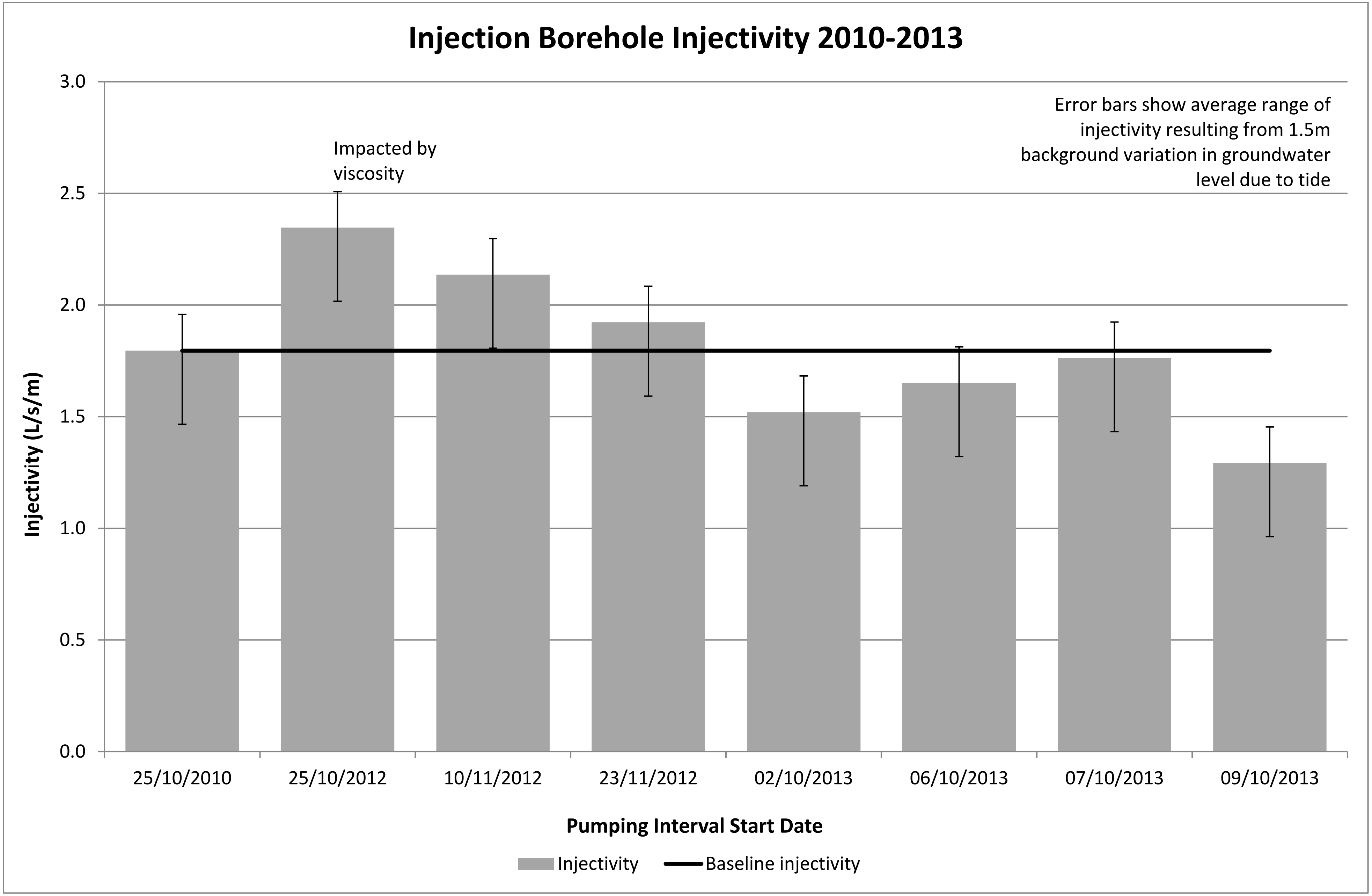

A
B
River Thames
Sheet Pile Wall
OBH2
INJ2
OBH1
THE SITE
BASEMENT
ELEVATION (mAOD)
5
0
-5
-10
Thames Tidal Range
Borehole water level range
NORTH
SOUTH
MADE GROUND + ALLUVIUM
RIVER TERRACE GRAVELS
LONDON CLAY

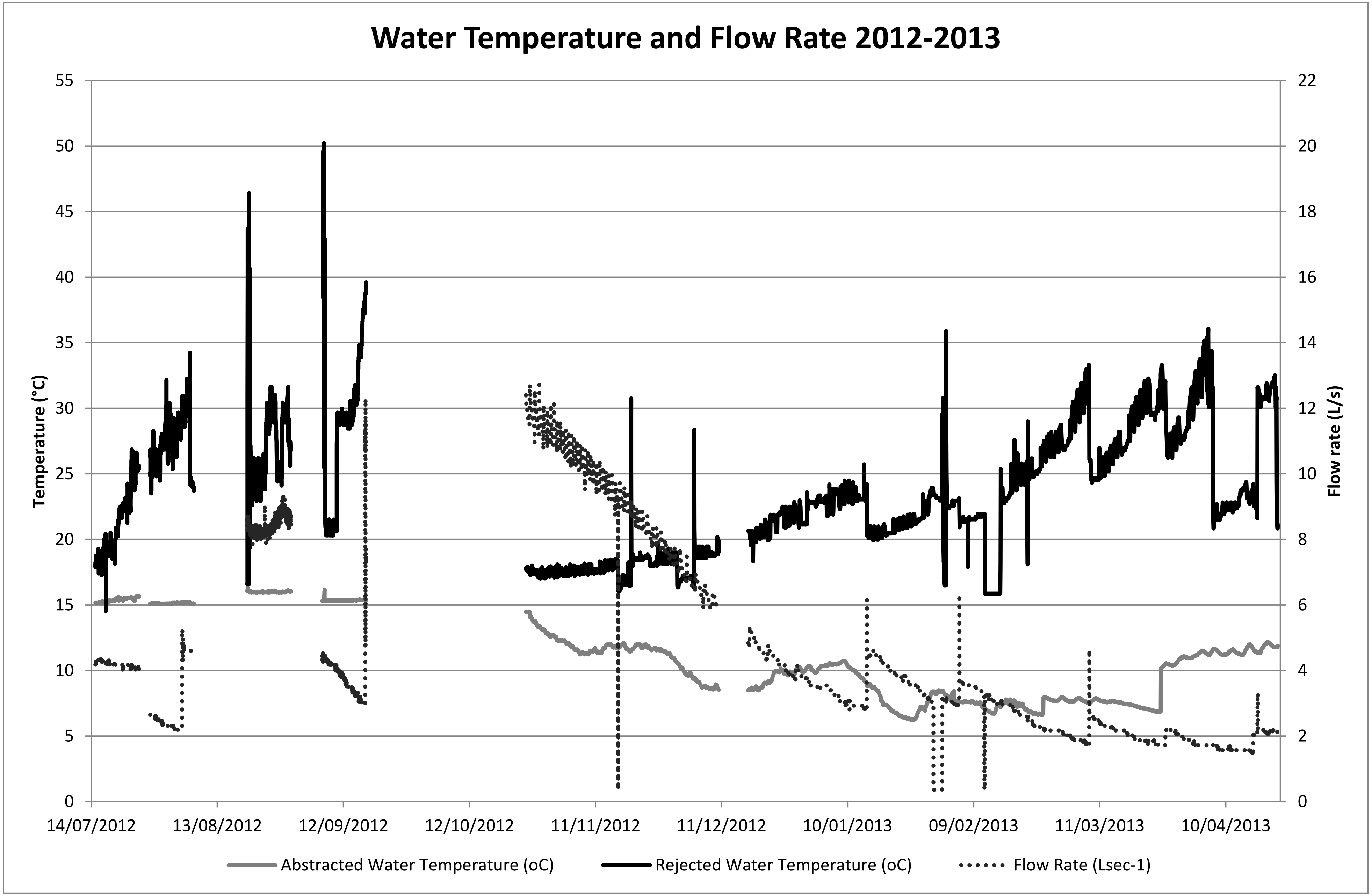


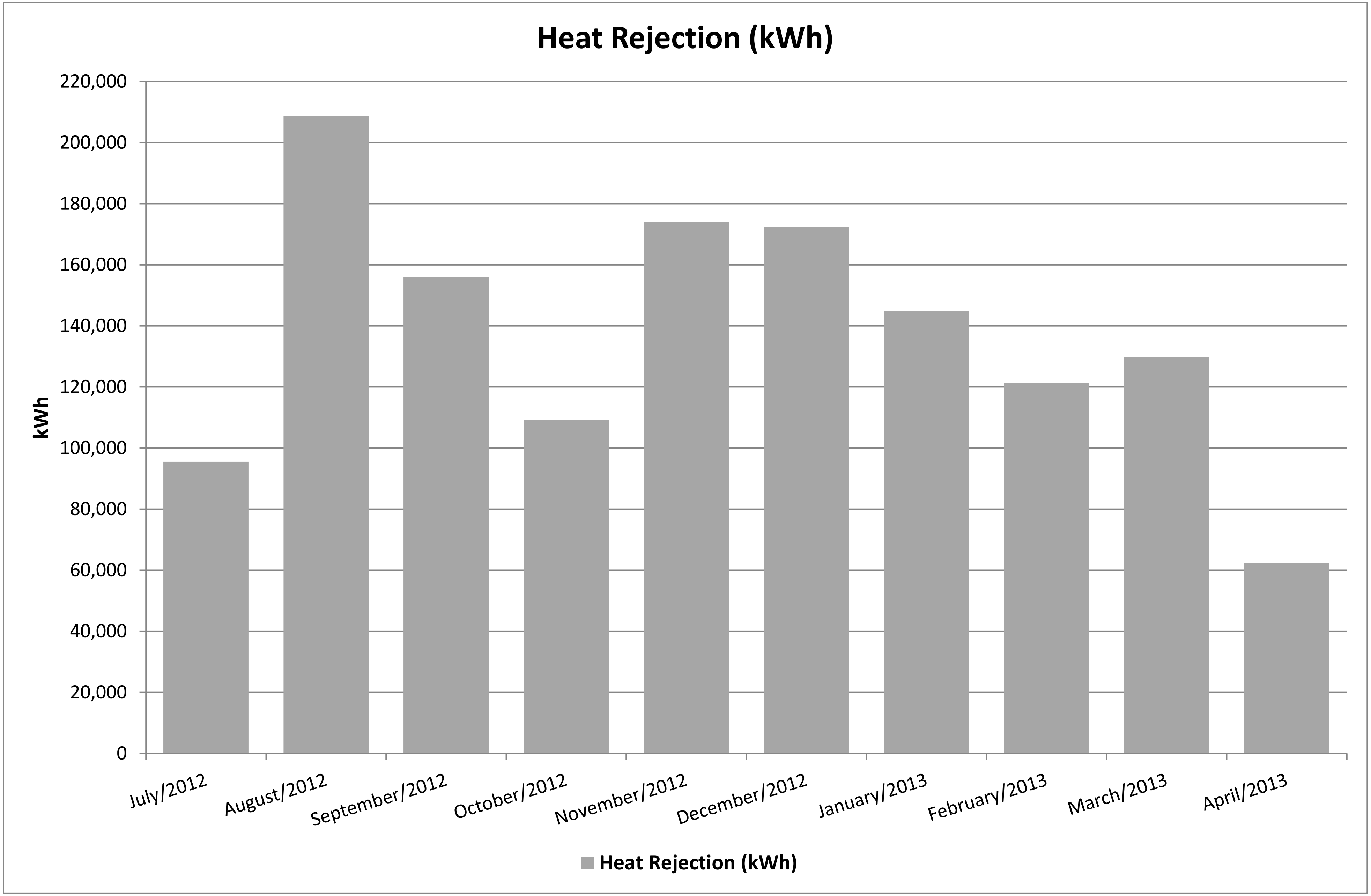
Injection Data 2010 - 2013
Groundwater Level (mAOD)
Flow Rate (L/s)
0
2
4
6
8
10
12
14
16
18
18/10/2010
23/10/2010
10/07/2012
08/09/2012
07/11/2012
06/01/2013
07/03/2013
24/08/2013
23/09/2013
Water Level
Flow Rate

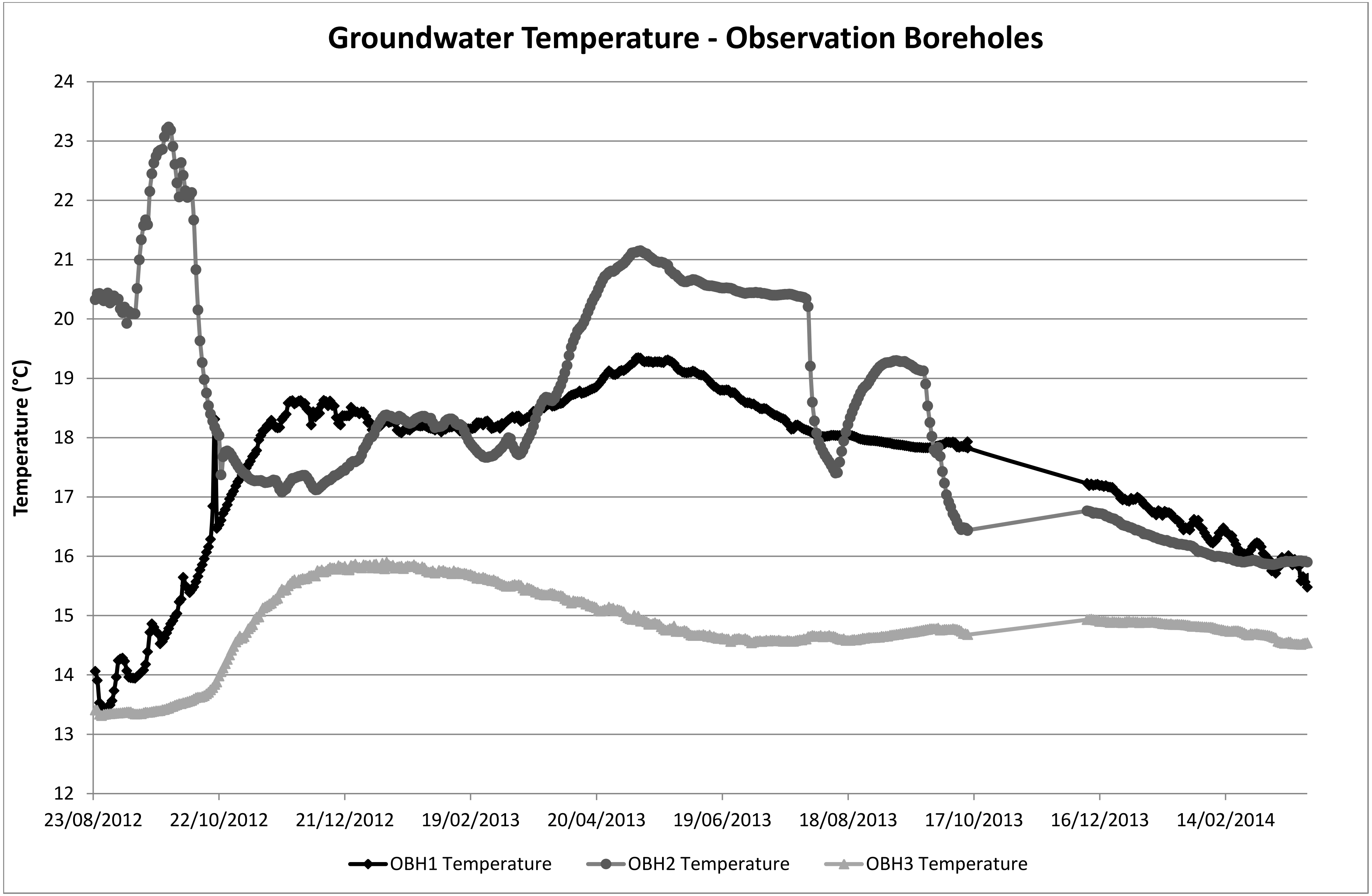


Groundwater Level and Flow: June - November 2013
Groundwater Level (mAOD)
Flow Rate (daily average L/s)
3
2.5
2
1.5
1
0.5
0
-0.5
-1
16
14
12
10
8
6
4
2
0
01/06/2013
22/06/2013
13/07/2013
03/08/2013
24/08/2013
14/09/2013
05/10/2013
OBH1 Groundwater Level mAOD
OBH2 Groundwater Level mOAD
Flow Rate

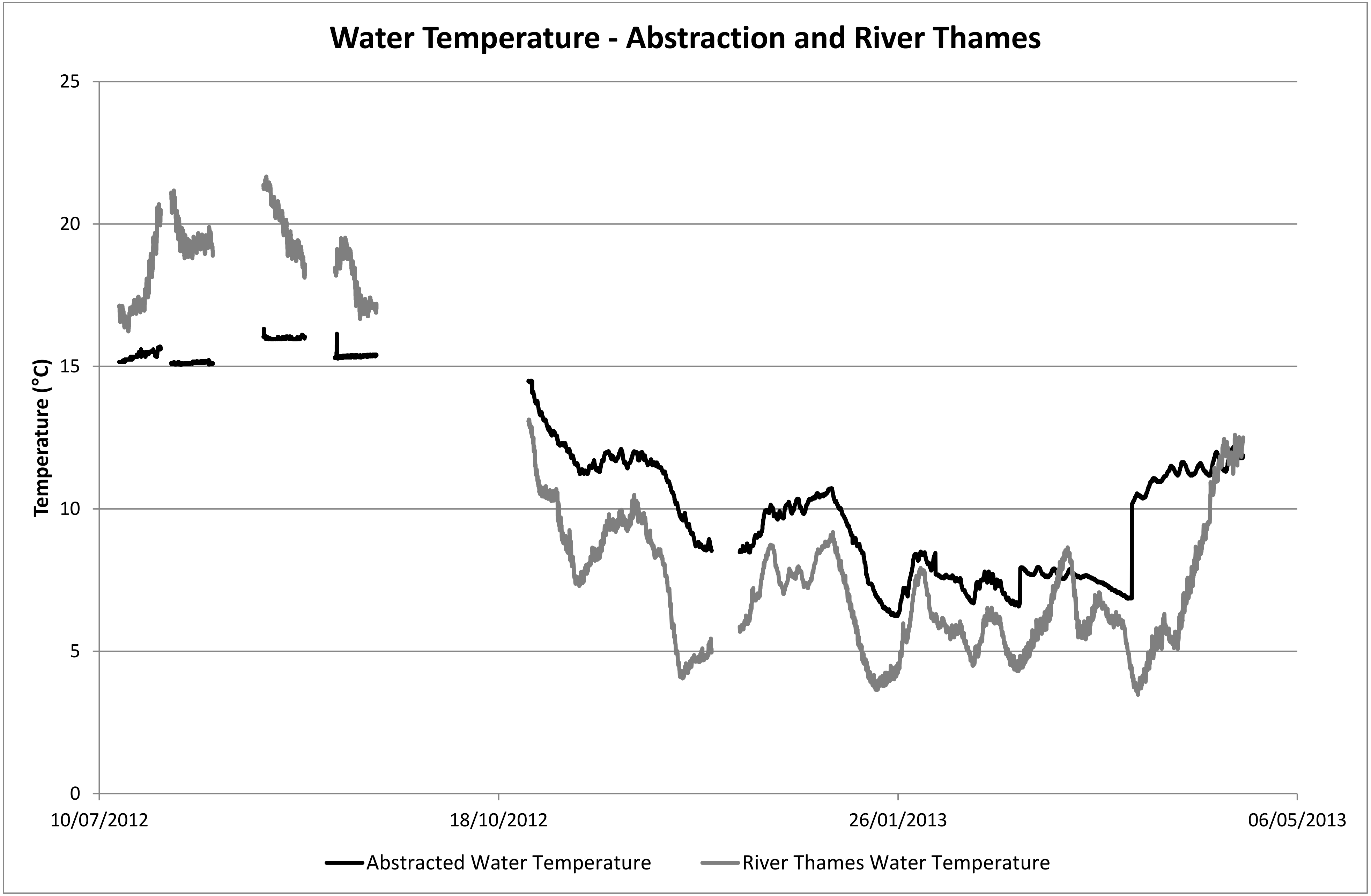

Injection Borehole Injectivity 2010-2013
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Injectivity (L/s/m)
Impacted by viscosity
Error bars show average range of injectivity resulting from 1.5m background variation in groundwater level due to tide
25/10/2010
25/10/2012
10/11/2012
23/11/2012
02/10/2013
06/10/2013
07/10/2013
09/10/2013
Pumping Interval Start Date
Injectivity
Baseline injectivity


Water Temperature and Flow Rate 2012-2013
Temperature (°C)
Flow rate (L/s)
55
50
45
40
35
30
25
20
15
10
5
0
22
20
18
16
14
12
10
8
6
4
2
0
14/07/2012
13/08/2012
12/09/2012
12/10/2012
11/11/2012
11/12/2012
10/01/2013
09/02/2013
11/03/2013
10/04/2013
Abstracted Water Temperature (oC)
Rejected Water Temperature (oC)
Flow Rate (Lsec-1)


Heat Rejection (kWh)
220,000
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
kWh
July/2012
August/2012
September/2012
October/2012
November/2012
December/2012
January/2013
February/2013
March/2013
April/2013
Heat Rejection (kWh)



Groundwater Temperature - Observation Boreholes
Temperature (°C)
24
23
22
21
20
19
18
17
16
15
14
13
12
23/08/2012
22/10/2012
21/12/2012
19/02/2013
20/04/2013
19/06/2013
18/08/2013
17/10/2013
16/12/2013
14/02/2014
OBH1 Temperature
OBH2 Temperature
OBH3 Temperature


Water Temperature - Abstraction and River Thames
Temperature (°C)
25
20
15
10
5
0
10/07/2012
18/10/2012
26/01/2013
06/05/2013
Abstracted Water Temperature
River Thames Water Temperature