Modelling Thermal Interference and Impacts for Ground Source Heating and Cooling Systems

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ABSTRACT

Planning regulations introduced in the London boroughs around 2003 required all new buildings over 10,000 m^2 to source 10% of their energy demand from renewable resources ('renewables'). Ground source heating and cooling (GSHC) systems fall within the definition of renewables, and provide an effective means of meeting these regulations.

This paper provides an overview of numerical and analytical modelling techniques that have been used to evaluate the potential for thermal interference between open loop Ground Source Heating and Cooling (GSHC) system's injection - abstraction well couplets. Thermal interference between individual well couplets is a key risk for sites where small development footprints limit the spacing between injection and abstraction wells. Assessment of the potential for thermal impacts on other groundwater users is also discussed.

A model validation study has been undertaken to evaluate the accuracy with which thermal interference can be predicted for a GSHC system in a fractured aquifer system, using a relatively limited dataset and simple fracture model. Results indicate that an acceptable level of accuracy is achievable.

1. INTRODUCTION

1.1 Planning context

London Plan policy 4A.91 states: 'The Mayor will and boroughs should require major developments to show how the development would generate a proportion of the site's electricity or heat needs from renewables, wherever feasible'. The London Mayor's Energy Strategy proposal 132 notes that: 'To contribute to meeting London's targets for the generation of renewable energy, the Mayor will expect applications referable to him to generate at least ten per cent of the site's energy needs (power and heat) from renewable energy on the site where feasible. Boroughs should develop appropriate planning policies to reflect this strategic policy. The aim of policy 4A.9 is specifically to encourage the installation of renewable energy technologies in London through new developments. This policy aims to contribute to London meeting its carbon dioxide and renewable energy targets and to help stimulate the renewable energy industry in London, benefiting the environment and London's economy (Greater London Authority 2004).

The Greater London Authority 2004 report also states that: 'The Mayor will and boroughs should adopt a presumption that developments will achieve a reduction in carbon dioxide emissions of 20% from onsite renewable energy generation (which can include sources of decentralised renewable energy) unless it can be demonstrated that such provision is not feasible. This will support the Mayor's Climate Change Mitigation and Energy Strategy and its objectives of increasing the proportion of energy used generated from renewable sources by:

- requiring the inclusion of renewable energy technology and design, including: biomass fuelled heating, cooling and electricity generating plant, biomass heating, combined heat, power and cooling, communal heating, cooling and power, renewable energy from waste (Policy 4A.21) photovoltaics, solar water heating, wind, hydrogen fuel cells, and ground-coupled heating and cooling in new developments wherever feasible; and
- facilitating and encouraging the use of all forms of renewable energy where appropriate, and giving consideration to the impact of new development on existing renewable energy schemes.'

1.2 GSHC development

A large number of GSHC schemes have been developed in London in response to these planning requirements. Over 30 open loop systems have been installed to date, with a significant number of additional systems in the planning and development stages. The majority of applications to date are for office buildings, which frequently feature a significant load imbalance in favour of cooling. The London Chalk aquifer is therefore being used as a heat sink for thermal energy from commercial buildings. The predominant efflux of water from the aquifer is water abstraction for potable supply to the city and cooling water abstractions. Consideration of potential hydraulic, hydrochemical and thermal impacts of GSHC systems is therefore required.

2. ENVIRONMENTAL SETTING

2.1 Geology

Central London is underlain by a series of Tertiary deposits comprising the London Clay, the Lambeth Beds and the Thanet Sand, with the latter two formations referred to collectively as the Basal Sands. The Tertiary deposits overlay chalk deposits of the Cretaceous period.

2.2 Hydrogeology

The Chalk is classified as a major aquifer. It dips gently south-south-east from the Chilterns under the Lower London Tertiaries to the synclinal axis. To the south of the synclinal axis the Chalk dips to the north and recharge comes from the North Downs.

The Chalk Aquifer is overlain by London Clay which generally becomes thickest near the centre of the London Basin syncline. The London Clay acts as a confining layer directly over a thin sequence of Lower London Tertiary deposits of the Lambeth Group, which in turn overlies the Chalk. A small amount of infiltration can take place via leakage through the London Clay cover.

The proportion of sand in the Lower London Tertiaries increases significantly eastward until it is almost completely sand or pebble beds. The Basal Sands forms a minor aquifer which is in hydraulic continuity with the major Chalk Aquifer below.

Recharge to the Chalk is principally from precipitation on the main outcrops on the limbs of the syncline to the north and south. From these topographical highs in the Chalk, groundwater flows diffusely through the Chalk matrix, but also through a system of fractures and fissures. Generally groundwater flows down dip towards the axis of the syncline and converge towards the central London groundwater depression. These fissures have been enhanced by erosion and dissolution in the uppermost part of the Chalk.

The Chalk Aquifer has high matrix porosity, however due to exceedingly small pore sizes it has a very low permeability. Hence the Chalk is a dual porosity aquifer. Groundwater flow in the Chalk Aquifer is therefore dependant on the presence and productivity of these fissures and fractures. The extent of fracturing will vary depending on lithology, depth and the structural setting.

In the Chalk Aquifer, fractures are enlarged in areas where groundwater flow is concentrated, such as river valleys and the zone of water table fluctuation. The result is a pattern of aquifer parameters where transmissivity increases towards river valleys in the unconfined chalk and particularly in the confined chalk, and hydraulic conductivity decreases with depth.

Groundwater flows into the central London Basin from the areas of recharge in the north west and south west. The natural flow path for groundwater would be to discharge in areas of chalk outcrop such as in the River Thames area from Greenwich to Woolwich, and where chalk groundwater can discharge through Lambeth Group sediments to surface, such as in Hackney and the Lee Valley. As a result of historic and current abstraction, groundwater flow from the west does not flow beyond central London, and groundwater flow from the east is drawn west into central London. Groundwater from south east London interacts with the River Thames from Greenwich to Woolwich as it flows north west to Stratford and then west to central London. (Environment Agency 2010).

3. CONSIDERATIONS FOR GSHC DEVELOPMENTS

The three main hydrogeological considerations for development of a London GSHC system are the available system capacity based on well yields, the aquifer capacity for heat rejection or abstraction, and the risk of thermal impacts on existing water users.

3.1 Well yields

The rate at which thermal energy can be extracted from or discharged to an aquifer is controlled in part by the achievable flow rate for an open loop system. The peak energy load that can be delivered from an open loop system is described by Equation 1 below:

$$L = C.Q.dT \qquad \text{Equation 1.}$$

Where:

L – the peak load (kW)

C = heat capacity of water (J/g·K)

Q = flow rate (L/s)

dT = temperature differential (°C)

Well yields are a function of the aquifer transmissivity and of well efficiency (controlling Q). The drawdown in a well for a given pumping rate is a function of head losses in the aquifer and head losses in the well. Aquifer head losses are a linear function whilst well losses are an exponential function and hence a good well development programme, coupled with step testing to confirm that well losses have been minimised, is essential. This is particularly so where the system is required to service high peak loads.

3.2 Thermal interference risks

Thermal interference occurs when the rate of thermal energy discharge or extraction from the aquifer via an open loop GSHC system exceeds the rate of energy dissipation or replenishment within the area of the aquifer influenced by the abstraction and recharge boreholes. Problematic thermal interference occurs when changes in groundwater temperatures are sufficient to cause operational or regulatory compliance issues. Figure 1 below provides a schematic example of thermal interference between an abstraction-injection well couplet in a confined aquifer.

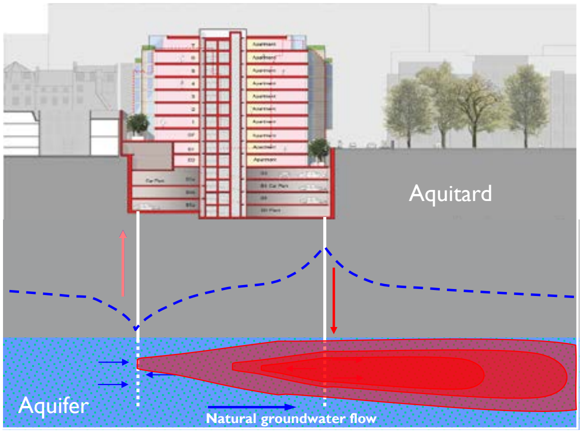

Figure 1: Thermal interference between open loop abstraction-injection well couplet

The occurrence of thermal interference is predominantly controlled by the energy load discharged to/abstracted from the aquifer, the rate of groundwater flow beneath the site, the abstraction-injection well orientation and the thickness of the flow horizon.

3.3 Thermal impacts

Thermal impact, or thermal pollution, is the term used to describe temperature changes in groundwater down gradient of a warm or cold water discharge. In the London Basin the principal receptors for thermal impacts are other GSHC systems and groundwater abstractions. Given that groundwater abstractions are the major water sink in central London, and noting the predominance of cooling load discharges, cumulative thermal impacts on groundwater abstractions are a risk. The development of district heating schemes in some areas (e.g. Pimlico) are exacerbating this situation: planning authorities are requiring developers to utilise the district heating schemes for space and water heating requirements, leaving only the cooling load to be serviced by ground source. This means that heating and cooling loads cannot be balanced over an annual cycle, and also limits the potential for development of highly efficient aquifer thermal energy storage systems.

Evaluation of the potential for thermal impacts on existing water users is a key part of the consenting process for new GSHCs in London.

4. MODELLING TOOLS

Thermal interference and thermal impacts can be evaluated through both analytical and numerical modelling tools.

4.1 Analytical models

Gringarten & Sauty (1975) developed an analytical solution for conductive and advective thermal energy transport in a confined aquifer system. The purpose of the model was to investigate non-steady state temperature behaviour of production wells during the reinjection of heat-depleted water into aquifers with uniform regional flow. Thermal conductivity is neglected in the horizontal direction in the model (i.e. a high Peclet number is assumed), and advective transport is implemented through a piston flow conceptualisation, i.e. no mixing. The Gringarten & Sauty solution can be used to calculate both the spacing between two wells in order not to have any temperature change at the production well during a specified period, and the temperature in the production well after breakthrough.

4.2 Numerical models

A number of numerical models have the capability to simulate thermal energy transport in porous media, including Feflow, SUTRA and HST3D. Feflow has been widely used for GSHC simulations in the London Basin, and modules have been developed within this software to simulate various open loop configurations, couplings with other cooling plant, and also for closed loop systems.

Advantages of numerical modelling include the ability to simulate fracture flow systems, leaky aquifers and the flexibility to model any abstraction-injection well orientation required. These advantages, coupled with the fact that a single generic model mesh can be rapidly adapted to local conditions for any given GSHC site in London, means that numerical modelling has become the tool of choice there.

5. MODEL VALIDATION STUDY

5.1 Research drivers

The Mount Street GSHC system was installed in 2006 to service the cooling requirements for this Mayfair restaurant. The GSHC system comprises an abstraction-injection well couplet installed in the London Chalk aquifer with a 30m separation distance between the wells. Mayfair is located towards the centre of the London Basin, where the piezometric surface is relatively flat and hence groundwater flow rates beneath the site are likely to be low. The small well separation (associated with space limitations at the site) and low groundwater flow rate meant that the potential for thermal interference was significant.

The system was commissioned in 2007, and abstraction water temperatures increased from 13.5 °C to approximately 19.5 °C within six months of operation. Groundwater abstractions from and discharges to the London Chalk are regulated by the Environment Agency (EA). The EA use a maximum discharge water temperature of 25 °C in order to control the risks associated with cooling water discharges to the aquifer. The increasing abstraction water temperature therefore signalled a potential for regulatory compliance issues in forthcoming cooling seasons, as well as a reduction in heat pump efficiency as abstraction water temperatures increased. A consumptive abstraction license was applied for to address this issue, with a license granted for abstraction of up to 200 m^3/d of cooling water for discharge to sewer during the summer months. Although this approach successfully reduced the abstraction water temperatures (see Figure 2 below), significant on-going water disposal costs were incurred for the sewer discharge. Groundwater resource availability is also limited in the London Basin. This is reflected by both the current 200 m^3/d consumptive abstraction limit and an increasing level of Environment Agency of applications for consumptive abstraction licenses for GSHC schemes.

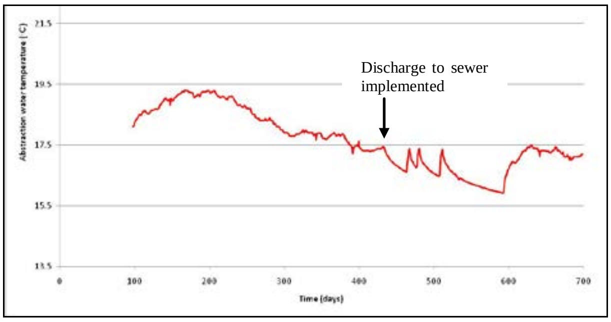

Figure 2: Abstraction water temperatures at Mount Street site

The Mount Street GSHC scheme thermal interference issues summarised above highlight the need to evaluate the capacity of the aquifer to dissipate thermal energy as part of the system design. Such knowledge of thermal energy transport in the aquifer system can facilitate design GSHC systems within the limitations of the environment.

Although a large number of modelling studies have been completed for London Basin GSHC schemes since 2007 for both design and consenting purposes, the predictive accuracy of these models has not been widely tested against data from operational GSHC schemes.

5.2 Mount Street GSHC scheme modelling study

The purpose of the Mount Street modelling study was to investigate the ability of a numerical model developed using the data typically available at the design stage of a GSHC scheme. Model predictions of thermal interference can then be compared to actual data, and the results evaluated to determine whether predictive accuracy is sufficient for design of a sustainable system.

5.2.1 Model inputs

As noted previously, the key inputs for thermal interference modelling are the the energy load discharged to/abstracted from the aquifer, groundwater flow rates beneath the site, the well orientation and the thickness of the flow horizon. These inputs are discussed in turn below.

5.2.1.1 Building loads

Building energy loads are typically evaluated with building design software such as Tas Building Designer, as part of the building design process. Such energy load data were not available for the Mount Street site, however. Operational abstraction and injection well temperature data and flow rate records were therefore processed in order to generate building loads for the model simulation period. Flow and temperature records were not available for the first three months of operation. This data gap was filled using a regression equation developed from the relationship between cooling loads and ambient temperatures over the available data period (prior to implementation of the water discharge to sewer), as shown in Figure 3 below.

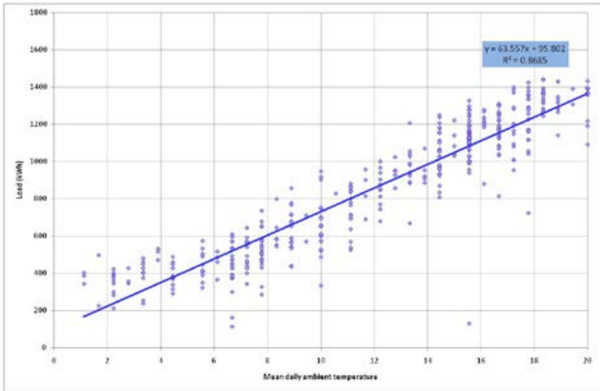

Figure 3: Ambient air temperatures and building cooling loads

5.2.1.2 Groundwater flow rates

Groundwater flow is a function of the aquifer transmissivity and the hydraulic gradient beneath the site.

The transmissivity estimates required for modelling GSHC systems are either sourced from pumping test data from other wells in the vicinity of the site (if the modelling study is undertaken as part of the early design stages, prior to any well drilling on the site), or from pumping test data from the site itself. A series of pumping tests were undertaken on the Mount Street site, and these data were analysed to provide an estimate of the Chalk transmissivity (T) beneath the site. A T value of 2000 m^2/d was used in the model validation study.

Groundwater levels in the London Basin are monitored regularly by the EA as part of the resource management programme, and this water level data is publicly available. Water level monitoring data from four observation wells within the vicinity of the Mount Street site are plotted on Figure 4 below.

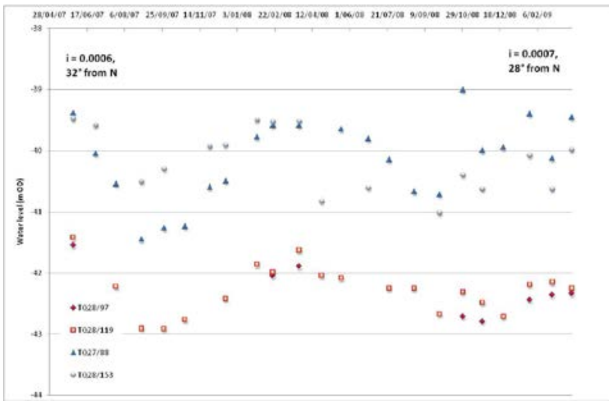

Figure 4: Groundwater level monitoring data

As indicated in Figure 4, the water level monitoring data indicates a north easterly flow direction. The piezometric surface in the site area is controlled by a number of local abstractions and GSHC schemes, however, and the monitoring well network density is not sufficient to characterise the flow direction through the site area with any certainty. A numerical model has therefore been developed for recent GSHC design studies in order to evaluate groundwater flow directions under a range of pumping scenarios (based on consented abstraction and discharge rates) for the nearby abstractions and GSHC schemes. Model results are plotted on Figure 5 below. Model results indicate a south to south easterly flow direction, towards the non-consumptive Green Park Station GSHC scheme and the Buckingham Palace abstraction.

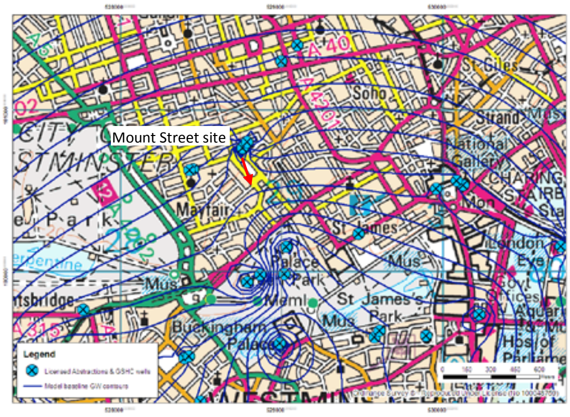

Figure 4: Model groundwater contours with likely flow direction shown

5.2.1.3 Flow horizon

The thickness of the chalk aquifer flow horizon and the distribution of fissuring within the chalk dictate the mass of material through which re-injected water is dispersed. This in turn is a key control on model predictions of thermal interference. Flow horizons between an abstraction-injection well couplet can be investigated through packer testing, geophysical well logging, tracer tests and flow logging; The latter three techniques have been variously used for GSHC investigations in London. Although geophysical logging provides limited data on the distribution of flow within open sections of the well, such surveys are inexpensive and are therefore the most commonly available data source.

Geophysical well logs and a temperature log recorded in the Mount Street injection well during active operation are summarised in Figure 6 below.

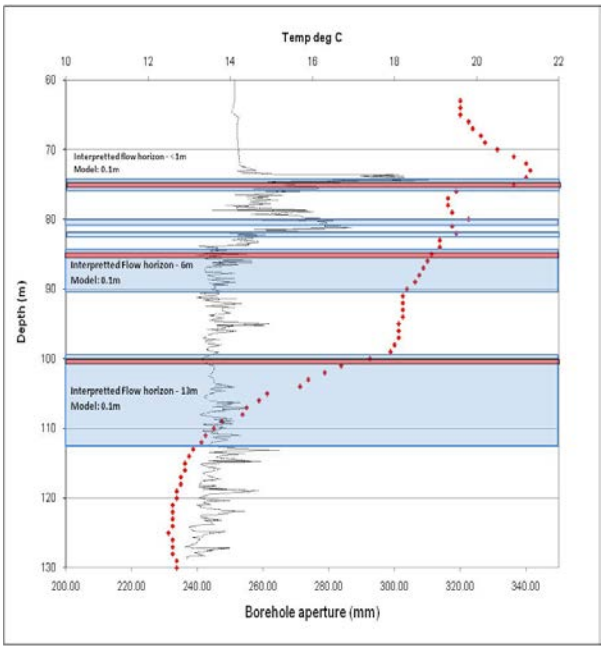

Figure 6 Mount Street well logging data

The Mount Street well log data were interpreted to indicate three main flow horizons with a number of smaller fissures. These were simplified into a model comprising three laterally extensive fissures of 0.1m thickness.

5.2.2 Numerical model of GSHC system

A numerical flow and heat transport model of the Mount Street GSHC scheme was constructed in Feflow using the building load and hydrogeological data discussed above. A north easterly groundwater flow direction was assumed for the study, since the numerical model-based evaluation of flow directions was not available at the time of the validation modelling study. Flow within the Chalk aquifer was implemented using a dual continuum model comprising the three highly transmissive flow fissures described above within a low permeability chalk matrix. Model and observed abstraction water temperatures are summarised in Figure 7 below.

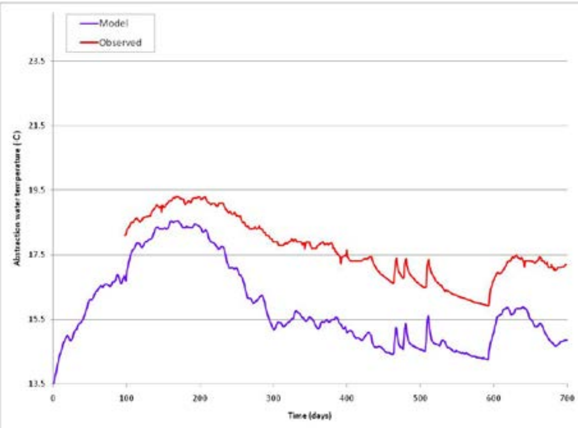

Figure 7 Model and observed abstraction water temperatures

Model results provide a reasonable approximation of the magnitude of thermal interference experienced at this scheme during the first few months of operation. The model predicts a rapid reduction in abstraction well temperatures at the end of the cooling season, however, whilst in reality the recovery towards ambient temperatures is much more gradual. This is likely to relate to the groundwater flow direction assumed for the modelling study; more recent work has indicated that the actual flow direction is likely to differ.

2. CONCLUSION

The London Chalk aquifer has been extensively developed as a thermal energy resource in recent years. The predominance of cooling demands for commercial buildings, coupled with planning department requirements to utilise district heating schemes for building heating loads, means that the aquifer is predominantly utilised as a heat sink. The issues associated with this situation have been communicated to the London planning authority.

Thermal interference between injection-abstraction well couplets is a common risk for London GSHC schemes. Numerical models have been widely used to estimate the risk of thermal interference so that sustainable GSHC schemes can be designed. Published information on the predictive accuracy of these models is currently limited. Model simulations undertaken for this paper indicate that thermal interference can be predicted with sufficient accuracy to inform the design process and assist in the development of sustainable GSHC systems. Further work is required to corroborate the findings of this study, using operational data from other GSHC schemes.

ACKNOWLEDGEMENTS

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