Development of a groundwater heating and cooling scheme in a Permo-Triassic sandstone aquifer in South-West England and approach to managing risks

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There are approximately 100 licensed groundwater heating and cooling applications in the UK, of which approximately 25% are installed in Permo-Triassic sandstone. The Permo-Triassic sandstones are extensively developed in the north of England, the midlands and to a smaller extent in the southwest, and are second only to the Chalk aquifer in terms of numbers of this type of application. In contrast to the Chalk, matrix flow is a more important component of the overall groundwater flow regime and, consequently, it is possible to predict groundwater behaviour with more confidence than for the Chalk and other aquifers with fracture-dominated flow. This equates to less uncertainty and is a significant consideration in regard to managing the overall risk-investment profile for this type of development. Development of an open-loop groundwater system to provide an estimated 871,000 kWh heating and 1,003,250 kWh cooling per annum, respectively for a proposed custody centre at Devon and Cornwall Police HQ in Exeter highlights the potential deployment of the technology in a relatively small fault bounded block of Permo-Triassic sandstone in South-West England. Development started in 2010 with an initial hydrogeological assessment and through 2012 an exploration well was constructed and subsequently tested for both abstraction and injection. Notwithstanding that the scheme is not yet fully developed, it is now licensed and the project serves as a good example of how the risk investment profile for similar projects might be managed. In addition, it highlights some specific properties of Permo-Triassic sandstones considered by the authors to be more favourable than other aquifers, including the Chalk.

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Introduction

The UK building stock is required to reduce its environmental impact and designers and engineers are obliged to consider ways of achieving this. Groundwater sourced heating and cooling is one of a number of low carbon technologies that has attracted an increasing level of interest in response to legislative and economic drivers (Clarkson *et al.* 2009; Younger, 2008).

Open-loop groundwater heating and cooling systems operate on the premise of extracting groundwater and pumping it through a heat pump or heat exchanger. Heat is transferred to or from the pumped groundwater providing heating and or cooling. Until recently the effluent water from these types of operations was typically disposed to surface watercourses. In the last 10 years, however, as the number of this type of application has increased significantly there has been an increasing requirement to return the effluent water to the originating aquifers.

Groundwater has proven to be a highly efficient means of heating and cooling, with coefficients of performance (COP) of 3-4 for heating and 4 to >10 for cooling commonly reported (e.g. Banks, 2012). Furthermore, unlike other low carbon heating and cooling options (i.e. solar, biomass), most of the infrastructure is located below ground such that the building aesthetic and valuable occupancy space is maintained. Demands on occupancy space are reduced further by the increasing use of plate heat exchangers in some of the larger applications of this technology (e.g. this development at Exeter, the Tate Modern, the Royal Festival Hall, Green Park Underground Station) where the requirement for large water storage vessels is negated. For these and other reasons groundwater is an attractive option for architects and the building services designer.

In the last 10 years the use of shallow groundwater for space heating and cooling utilising heat pumps has increased. However, in spite of this interest, development and commercial deployment of this technology has been limited. For example, the Environment Agency database (December 2014) had records of just over 100 licensed systems in England; the majority of these for commercial buildings including offices, retail space and public buildings. The Environment Agency database does not specify heating/cooling capacities but it is reasonable to conclude heating and cooling capacities of several hundred thousand kWh per annum or more in these types of buildings. The number of licensed applications of a scale approaching that proposed at the development site in Exeter is very small indeed, probably no more than 10 or 20 such applications in total. Furthermore, there is very little in the published literature pertaining to actual case studies documenting the development of groundwater heating and cooling projects in the UK and even less pertaining to operational performance after construction. Most published case studies relate to development projects in London, for example the 2 MW groundwater cooling system in the confined Chalk aquifer at the Royal Festival Hall described in Clarkson *et al.* (2009) and the 1.5 MW groundwater cooling system in the shallow Thames Valley Gravels at the Tate Modern Art Gallery described in Birks *et al.* (2013, 2015).

For the proposed development at the Devon and Cornwall Constabulary Headquarters, Middlemoor, Exeter, use of groundwater for space heating and cooling was selected as the best practicable, low carbon energy option.

Risk as a barrier to technology deployment

Oldmeadow *et al.* (2011) reported that limited precedent and uncertainties with regard performance and resilience has constrained uptake of open-loop ground source heating and cooling technology. This continues to be the case. Of critical importance to the success of any geothermal development project is an understanding of the challenges and risks associated with the coupling of a geologic system (with all its inherent uncertainties) to a building services network with defined levels of efficiency and performance. Key to success is the effective integration of two distinct and very different disciplines: Building Services Engineering and Geoscience.

From a geoscience perspective, development of groundwater for heating and cooling purposes requires significant upfront investment in investigation drilling and pump testing merely to establish the viability of the concept with no guarantee of a successful outcome. This applies to any groundwater development proposal and, whilst generally accepted in the water industry, is often not well understood in other industries, including building services. This risk investment profile is illustrated in Figure 1.

Whilst the development programme (engineering and geoscience) can be designed such that the risk investment profile is managed, there is no escaping the fact that the performance of the technology is influenced, to a very considerable extent, by site specific factors. Most, if not all, developments of this kind are effectively bespoke and considerable uncertainties in regard to performance persist well beyond the development programme and into the first few years of operation.

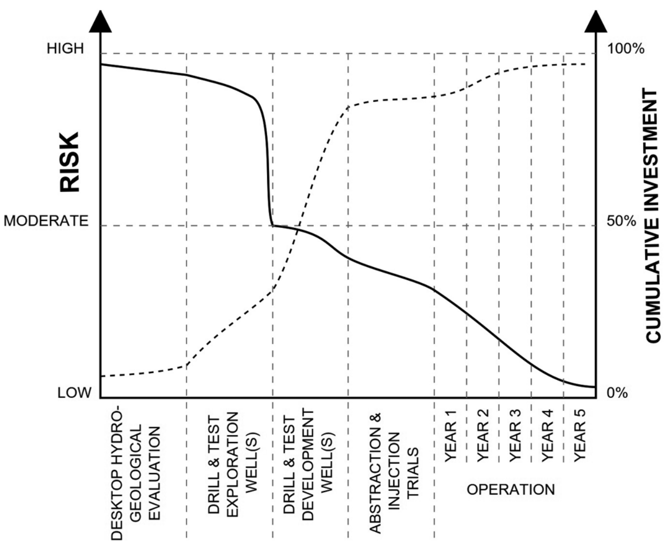

Figure 1. *Risk-investment profile for groundwater heating and cooling projects (modified after Gehringer and Loksha, 2012).*

Project details

This paper considers an approach to dealing with these uncertainties in the context of a development project within a Permo-Triassic Sandstone aquifer at the Headquarters of Devon and Cornwall Constabulary in Exeter. Such sandstones are second only to the Chalk as a major public water supply aquifer in the UK, albeit the Exeter occurrence is in an isolated block that is not hydraulically connected on a regional scale. Elsewhere, Permo-Triassic sandstones occur in a series of deep sedimentary basins, in western England and on the eastern and western flanks of the Pennines, following a roughly north-south ancient linear rift system, the Clyde Belt (Benton *et al.*, 2002). The sediments infilling these basins largely comprise thick sequences of red sandstones (red beds), a product of the erosion of the uplands and subsequent deposition during the hot and arid climatic conditions persistent through the Permian and Triassic. Given their widespread occurrence in many regions of the UK, this case study is important, as it is the first published investigation documenting the development of a medium to large scale, shallow groundwater heating and cooling system in a major Permo-Triassic sandstone aquifer. Although widely used for water supply, and thus not always available for further pumping, in several parts of the UK (e.g. Teesside, and in many places down-dip from outcrop zones) this aquifer is relatively under-used for various reasons, but often due to elevated sulphate concentrations (Younger, 2004). Heating and cooling uses would be particularly feasible in such areas.

The Exeter project comprises two new buildings, a custody suite with a 40 cell capacity and office and welfare accommodation for various police departments. The estimated heating and cooling loads are 871,000 kWh and 1,003,250 kWh, respectively. Use of groundwater for heating and cooling was selected as the best practicable low carbon energy option. The site is located within a relatively small fault bounded block of Permo -Triassic Sandstone as shown in Figure 2. The proposed development comprises a relatively large scheme providing *c.* 1,000,000 kWh heating and cooling per annum. Proposed heating and cooling demands are relatively closely balanced.

Development programme and approach to dealing with risk

An estimate of the rate of water supply to and from the plant room was provided by the mechanical and electrical designer. This was nominally set at a minimum rate of 6 ls^{-1} to meet the peak heating and cooling demands, and allowed an initial high level assessment of the borehole infrastructure requirement, an initial business case evaluation and comparison with other techniologies to be made. For this project a nominal 3 ls^{-1} per abstraction and injection well was adopted as a realistic and conservative design basis and as the basis of allocating a provisional capital cost estimate for the borehole infrastructure to the project cost plan.

Whilst each development project is different and site specific factors will vary considerably, there are a number of generic geoscience risks common to all open-loop development projects of this kind. These are represented in Figure 3 and comprise:

1) Abstraction. The aquifer may not be capable of supporting the requisite flow rates to satisfy the heating and cooling requirement, denoted R1.
2) Injection. There may be problems with recharging effluent

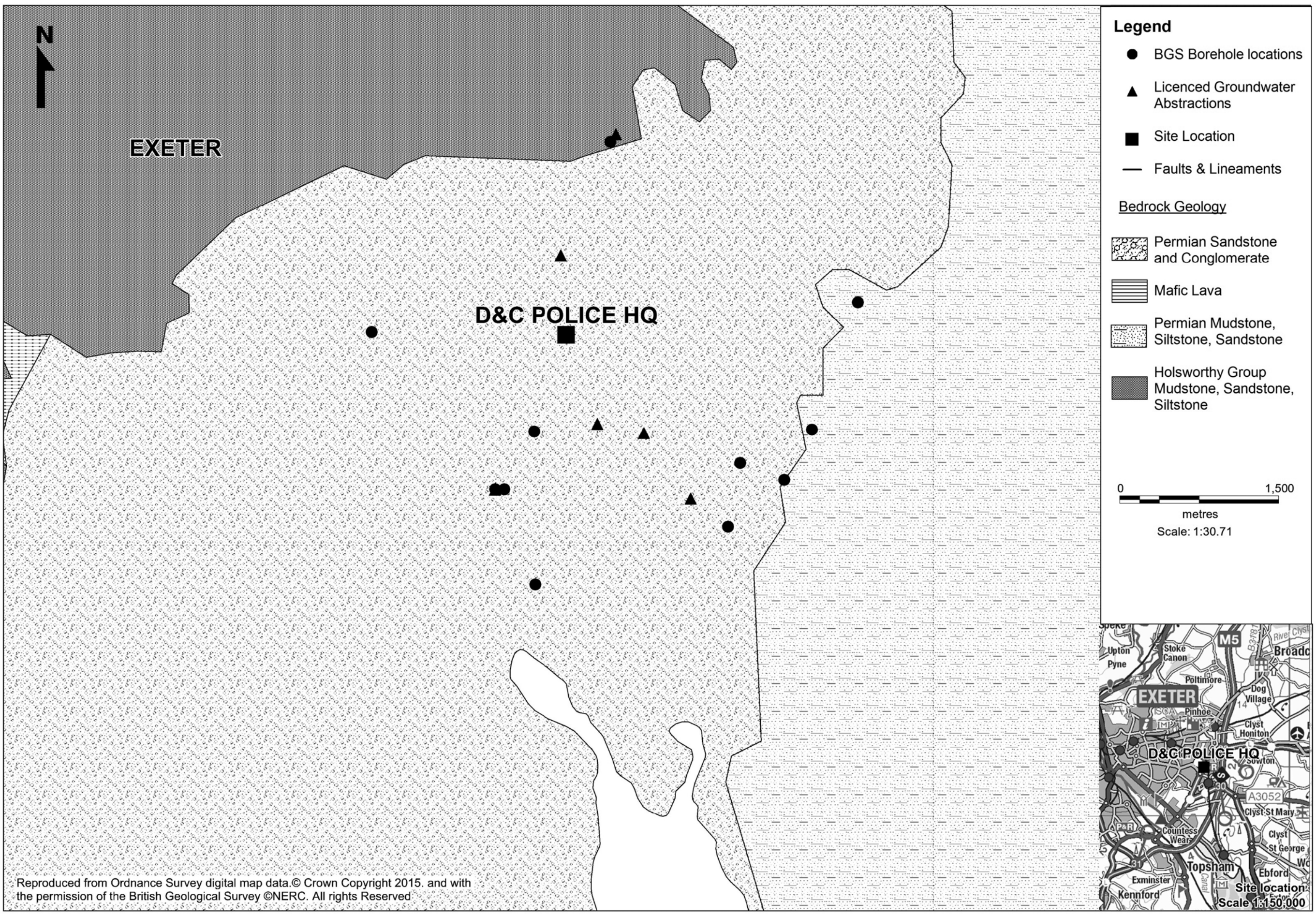

Figure 2. *Geological map showing project location, licenced groundwater abstractions and BGS borehole records.*

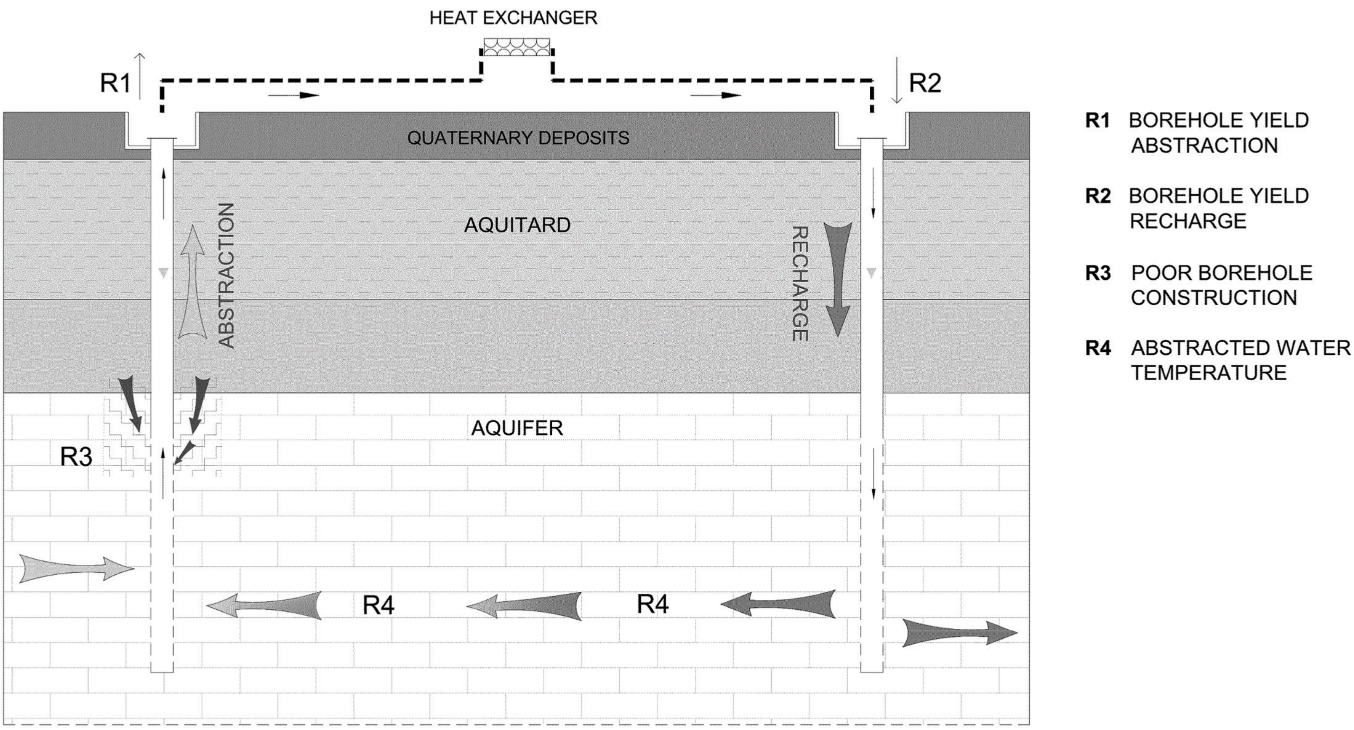

Figure 3. *Schematic showing generic geoscience risks associated with open-loop groundwater heating and cooling.*

water back into the aquifer, denoted R2. The risks associated with exceeding the capacity of the injection boreholes and clogging need to be considered.

3) Filtration and water chemistry. Poorly designed and constructed wells can result in poor water quality, denoted R3. In poorly constructed wells problems associated with sediment content and water chemistry can manifest.

4) Thermal degradation. The volume of rock in which the abstraction and injection boreholes interact has a finite capacity to yield and absorb heat, denoted R4.

The approach taken to dealing with the above geoscience risks is reflected in the development programme, summarised in Table 1 and described in more detail below.

Abstraction

Initial technical and business case evaluation had determined that abstraction and injection boreholes should be capable of at least 3 ls^{-1}, such that no more than two of each would be required. The first step in understanding the abstraction risk (R1), specifically the likelihood that the minimum flow requirement of 3 ls^{-1} per well might not be satisfied, was an initial high level hydrogeological evaluation in which the following lines of enquiry were investigated:

1) A review of published literature including published geological maps, geological memoirs, borehole records from the British Geological Survey and commercial ground investigation reports.

2) Consultation with the regional office of the Environment Agency to collate local knowledge and to establish possible constraints on the proposed development.

3) Details of existing groundwater abstractions were obtained from the Environment Agency.

On completion of initial hydrogeological evaluation the abstraction risk (R1) and to a lesser extent all other geoscience risks were partially de-risked. It was concluded that the development site was a good prospect for groundwater heating and cooling insomuch that it was judged that the minimum flow requirement was likely to be met or exceeded.

The second step in understanding the abstraction risk was to drill and test an exploration well. This represented the first significant expenditure in the risk investment profile amounting to *c.* £50,000 to design the investigation, procure the drilling contractor, to execute the works and report. The exploration well was sunk in January 2011 by Apex Drilling Ltd, under subcontract to Parsons Brinckerhoff using a Frastle XL MAX rotary drilling rig and tricone rotary bit. A trial pit was excavated by hand to a depth of 1.2 m below ground level. The borehole was then advanced to a depth of 10 m below ground level (bgl) at 450 mm diameter and a steel liner installed and cemented in place. Below 10 m the borehole was advanced at 300 mm diameter to its completion depth at 71.5 m bgl. The top of the Dawlish Sandstone was encountered at 4.2 m bgl and the base was unproven at 71.5 m bgl. Slow water ingress was observed below 24 m bgl and rapid inflows between 30 m and 42 m bgl. The well was lined with Boode (225 mm / 203mm) screen and liner, with the screened section installed between 71.5 m bgl to 21 m bgl within a gravel pack. Plain casing was installed between 21 m bgl and ground surface and grouted in place.

On completion of the drilling and test pumping the geological sequence was confirmed (Figure 4) and the output of the well under testing was also confirmed (Figure 5). Testing confirmed a sustainable pumping rate of at least 10 ls^{-1}, which exceeded the target (3 ls^{-1}) by a considerable margin. Indeed testing confirmed that only one abstraction well was needed to satisfy the full flow requirement of 6 ls^{-1}. At this stage the abstraction risk was considered fully de-risked.

Injection

Of the four principal geoscience risks listed above it is the view of the authors that injection (R2) is the most problematic. Indeed, the practicalities of groundwater injection and the challenges associated with it are well documented (e.g. Driscoll, 1986; Harris *et al*., 2005; Martin, 2013). Further, depending on whether the system is providing heating or cooling the temperature of the injected water has a significant effect on how easily the water is injected (e.g. Kestlin *et al*., 1978; Heilwell and Watt, 2011; Martin, 2013). Subject to programme and financial considerations, the Client was keen to investigate the risks associated with injection as rigorously as possible before committing fully to the design concept. The approach to dealing with the injection risk is summarised below.

An initial feasibility study allowed a very preliminary assessment of the injection risk, the key points being:

1) The underlying sandstone aquifer was considered to be unconfined with an estimated rest groundwater level of 15m bgl. This was judged to be a reasonable condition to allow injection under gravity, maintaining a water level below ground surface.

2) The development site is large enough to allow the injection wells to be located an adequate distance from features which might be adversely affected by the localised effects of injection (e.g. infiltration of groundwater into basement structures, risk of groundwater and surface water flooding). At the project there are a number of extensive areas of open space allowing injection boreholes to be positioned at least 50 m from infrastructure which might be vulnerable to the effects of injection (e.g. buildings with subterranean basements, railway lines, busy roads etc.).

On completion of initial hydrogeological evaluation it was judged that the injection risk (R2) was sufficiently well understood to conclude that the risks associated with it could be managed without undue difficulty. At this stage injection (R2) was considered partially de-risked. On completion of drilling and (abstraction) test pumping the exploration well it was considered that understanding of the injection risk (R2) was improved sufficiently to conclude that the design concept was viable and practicable. The favourable performance of the borehole under abstraction testing was considered a reasonable proxy for injection performance. However, at this stage in the design the Client required a more definitive assessment of injection performance without going to the expense of drilling another (injection) borehole. In order to meet this design requirement the decision was taken to carry out an injection test on the first (abstraction) test borehole.

An injection test on the first test borehole was subsequently carried out in February 2012. In the absence of another borehole to supply the water for the test and insufficient capacity in the mains water supply, the decision was taken to conduct a number of 30-60 minute injection step tests using storage and associated pumping and metering equipment brought to site specifically for this purpose. The equipment used for the injection tests comprised a clean water storage tank of 20 m^3 capacity, two electric submersible pumps, flow meters, manifold and hoses. The storage capacity of 20 m^3 limited the duration of the injection tests, particularly at higher flow rates (approximately 30 minutes of testing at an injection flow rate of 10 ls^{-1}). The results of the injection testing are presented in Figure 6. Flow rates were 0.3 ls^{-1}, 2.3 ls^{-1}, 5.3 ls^{-1} and 9.7 ls^{-1}. The main findings were as follows:

1) As expected there was a barely discernible rise in the water level in response to injection at 0.3 ls^{-1}.

Date	Task	Outcome
June-August 2010	Initial consultations with Environment Agency	An understanding of possible development constraints was established
August 2010	Initial Hydrogeological and Thermal Feasibility Study	Concluded that: 1) The development site was a good prospect for groundwater heating and cooling 2) That individual bore duplets should be capable of at least 3 ls^{-1} 3) Recommended a financial provision of £120k for the initial cost plan based on two borehole duplets
August 2010-January 2011	Further consultation with Environment Agency	Established broad agreement on the findings and assessment of Initial Hydrogeological Feasibility Study; license to drill and test a water-well was obtained
October 2010	Tender package for drilling and testing an exploration well	A specification for water-well drilling and testing was prepared and a drilling contractor procured through competitive tender
January-February 2011	Drilling and test pumping	A water-well was sunk to a depth of 71 m below ground level; beneath a thin covering of topsoil and clay the strata comprised Dawlish Sandstone Formation; the rest water level was approximately 14 m below ground level; a stabilised drawdown of 7 m was observed after a 14-hour constant rate test at 10 ls^{-1}
August- November 2011	A scope of work for a recharge test on the existing water-well was developed	Before committing to further design development the client wished to investigate recharge performance
February 2012	Recharge testing	Recharge step testing was undertaken over a period of 3 days; testing was constrained by the capacity of storage mobilised for the testing, 20,000 l; the duration of the 10 ls^{-1} recharge step was 32 minutes
June 2012	Permit obtained from Environment Agency	A permit with stipulated conditions was granted; the conditions reflected the fact that the system configuration was not complete and that recharge testing was constrained by storage capacity

Table 1. *Main stages of development and approach to mitigating geoscience risk.*

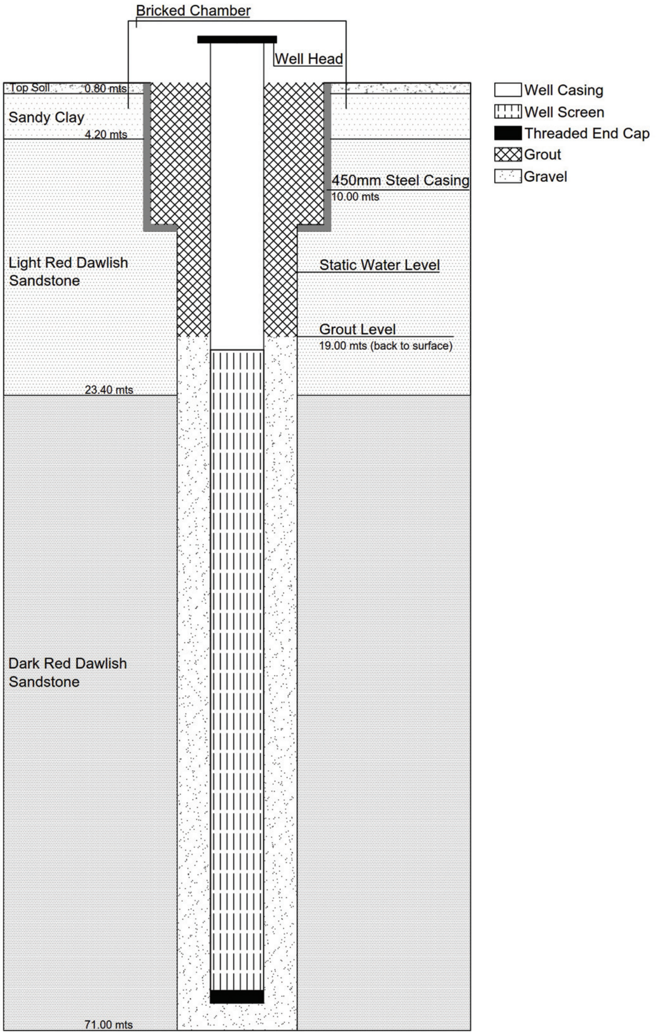

Figure 4. *Borehole schematic showing geological sequence.*

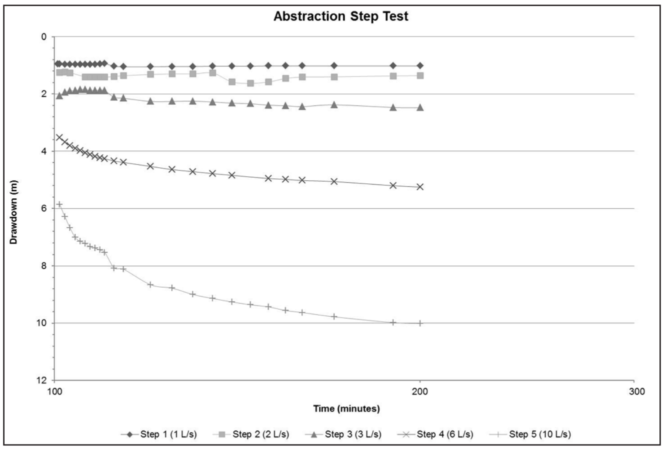

Figure 5. *Results of abstraction step testing.*

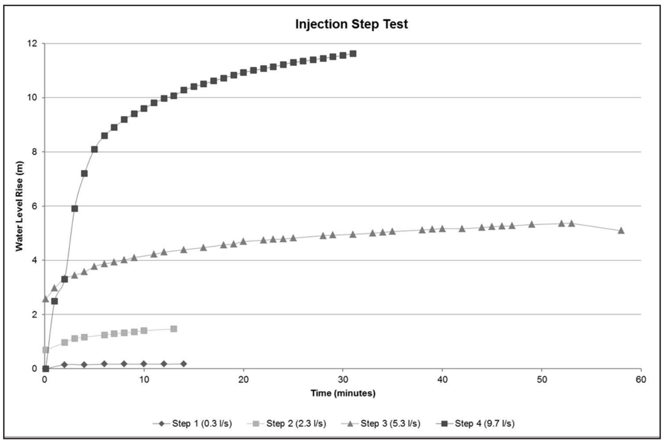

Figure 6. *Results of injection step test.*

2) There was a small rise in water level in response to injection at 2.3 ls^{-1} of approximately 1.3m, which stabilised after approximately 15 minutes.

3) The water level rise in response to injection at 5.3 ls^{-1} was approximately 5 m, which stabilised after approximately 50 minutes.

4) At an injection rate of 9.7 ls^{-1} the water level rise was approximately 12 m and the water level was still rising at the end of the test (test stopped when storage exhausted). Had testing continued for longer it is likely that the water level rise would have approached or exceeded 15 m, i.e. the water level would have approached or exceeded the ground surface.

Based on the observed response under injection testing it was concluded that at an injection rate of 5-6 ls^{-1} it should be possible to maintain the water level in the recharge borehole a few metres below ground surface. Whilst acknowledging the relatively short duration of the recharge tests in the context of sustained injection over many years, it was concluded that injection performance was reasonable. Furthermore, whilst accepting that that some degradation in injection performance might be expected over the longer term it was concluded that the injection risk was substantially de-risked at this point and that a nominal injection rate of 5-6 ls^{-1} should be adopted as the maximum design injection rate for the injection borehole(s).

Filtration and water chemistry

Filtration of groundwater prior to use for heating and cooling, or indeed any other purpose, should be considered to protect the heat exchange equipment and prevent clogging of the injection wells (denoted R3, Figure 1). The effects of progressive clogging and the importance of filtration are discussed in Moltz *et al.* (1978, 1983). Examples of typical filtration systems are described in Clarkson *et al.* (2009) and Birks *et al.* (2015).

Whilst properly designed and constructed water wells will generally yield water of a very good quality with low sediment content this is not always the case. Further, even if water quality is deemed suitable for use without filtration after initial well development, it may be prudent to make provision for filtration anyway. For example, short-lived episodes of impaired water quality can sometimes occur in response to specific circumstances such as high intensity rainfall events and disturbance due to ground engineering activities.

The starting point in assessing the need for and the type of filtration is usually taken as the water quality (chemistry and suspended solid content) on completion of well development. This is typically established through laboratory analysis of groundwater samples collected during the well development. A single groundwater sample was obtained towards the end of the 14 hour constant rate test after removal of approximately 500 m^3. Water quality was good with no evidence of anthropogenic pollutants and slightly elevated suspended solids content. Key water quality indicators are summarised in Table 2 alongside Drinking Water guidelines for context.

Determinant	Measured Concentration	Drinking Water Guideline
pH	7.36	6.5-9.5
Total Dissolved Solids (mgl^{-1})	292	n.a.
Total Suspended Solids (mgl^{-1})	45	n.a.
Alkalinity as $CaCO_3$ (mgl^{-1})	95	n.a.
Hardness as $CaCO_3$ (mgl^{-1})	161	n.a.
Total Organic Carbon (mgl^{-1})	<3	No abnormal change
Conductivity ($mScm^{-1}$)	0.435	2,500 μScm^{-1} at 20°C
Sulphate (mgl^{-1})	44.3	250 mgl^{-1}
Chloride (mgl^{-1})	41.7	250 mgl^{-1}
Nitrate (mgl^{-1})	49.2	50 mgl^{-1}
Iron (mgl^{-1})	0.264	0.2 mgl^{-1}
Manganese (mgl^{-1})	0.0288	0.05 mgl^{-1}
Petroleum Hydrocarbons (mgl^{-1})	<0.046	0.1 μgl^{-1}
Volatile Organic Compounds (mgl^{-1})	<0.001	0.01-100 μgl^{-1} (depending on the compound)

Table 2. *Key water quality indicators.*

Thermal degradation

As heat is injected into an aquifer or withdrawn from it the aquifer will either warm up or cool down as a result (e.g. Doughty *et al.*, 1982; Guven *et al.*, 1983). Depending on how much heat is injected or withdrawn and the degree to which heat inputs and outputs are balanced (either by mode of operation or through naturally occurring replenishment), the temperature of the abstracted water will either rise or fall. The resultant changes in water temperature can, particularly over the longer term, lead to significant reductions in efficiency. Various authors have considered the impact of thermal degradation in terms of long term impact on sustainability (e.g. Younger, 2008, 2014), the rate at which changes in abstracted water temperature may be expected to occur (e.g. Banks, 2009, 2011) and the magnitude of various naturally occurring heat replenishment mechanisms (e.g. Guven *et al.*, 1983; Birks *et al.*, 2013).

Of the four principal geoscience risks, thermal degradation is the one where options to investigate through physical testing are most limited. Consequently, assessment of the thermal degradation risk is almost wholly reliant on predictive analysis and modelling, with little or no benchmarking against empirical data. Furthermore, the effects of thermal degradation tend to manifest very slowly due to the size of the heat sink and the mode of heat extraction or injection common to this type of application. As a result, the thermal degradation risk (R4) is often given less attention than it deserves.

An approach to assessing thermal degradation was developed using the assessment of Younger (2008) regarding separation between abstraction and injection locations, the assessment of Banks (2009, 2011) in predicting how long before the abstracted water temperature starts to change (commonly referred to as thermal breakthrough) and the thermal volume concept introduced by Guven *et al.* (1983) and developed further by Birks *et al.* (2013, 2015) in quantifying the likely changes in abstracted groundwater temperature over the longer term. Accepting that this is a very simplified approach, with a number of inherent assumptions, it is, nonetheless, considered by the authors a very useful preliminary modelling tool. It is underpinned by relatively straightforward heat physics and can be readily understood by a non-technical audience, an important consideration when communicating risk.

An important consideration in our approach to assessing thermal degradation is the proposed mode of operation, specifically the amount of heat extracted from and rejected to the notional thermal volume in a typical year and how closely heat inputs balance heat outputs. For the proposed development it was assumed that heat inputs and heat outputs in a typical year are closely balanced at about *c.* 1,000,000 kWh heating and cooling per annum. The thermal degradation analysis therefore considers the impact of *c.* 1,000,000 kWh heat input or output on the theoretical thermal volume in terms of induced temperature changes within that thermal volume. Any imbalance between heat inputs and outputs in a typical year are considered to be small relative to processes through which heat is dissipated through natural processes (Guven *et al.*, 1983; Birks *et al.*, 2013, 2015). Our analysis is based on a number of assumptions and simplifications as follows:

1) A thermal volume is derived as the product of the distance between abstraction and discharge locations, a nominal width based on an assumed dispersion and a thickness based on the saturated portion of the aquifer penetrated by the abstraction and injection wells as shown in Figure 7.
2) For given heat inputs and outputs it is assumed that the thermal volume warms or cools in a uniform, homogenous way. It is accepted that this may represent a significant over-simplification but one that is considered reasonable in the context of the timescales.
3) An assumed specific heat capacity value is assigned to the entire thermal volume, in this case using literature values for quartz sand and assumed water saturation.

The estimated change in temperature within the theoretical thermal volume is derived using the equation:

$$dT = 3600\ Q / (M \times SHC) \qquad (1)$$

where dT is the induced change in temperature within the thermal volume (°C); Q is heat input or output (kWh); M is mass within thermal volume, derived from the combined rock and pore water volume of based on a well doublet spacing (200 m), a saturated aquifer thickness (55 m), a nominal width based

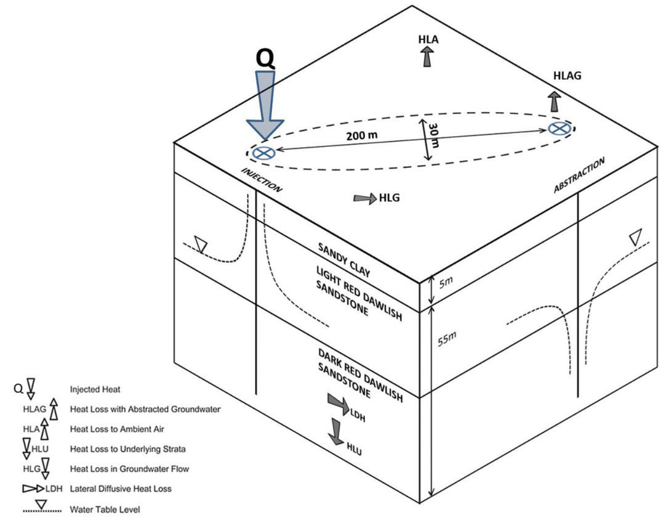

Figure 7. *Block model showing heat dissipation within an assumed thermal volume (modified after Birks* et al.*, 2013).*

on an assumed hydrodynamic dispersion of 30m and assumed bulk density of 2.1 (kg); SHC is specific heat capacity (kJ/kg°C) a porosity weighted average of quartz sand (0.83 kJ/kg°C) and water (4.19 kJ/kg°C). For the purposes of this analysis, we have assumed Q is 1,000,000 kWh, M is 866,250,000 kg and SHC is 2.5 kJ/kg°C. Substituting these values into equation (1), and accepting the simplifications and assumptions which underpin this simplified analysis, the derived temperature change resulting from 1,000,000 kWh heat rejection or consumption amounts to approximately 2.08°C. Thus a large imbalance in heat rejection and consumption maintained over a number of years will likely result in changes in abstracted water temperature that will progressively degrade the efficiency of the system.

Assuming a balanced mode of operation but with heating prevalent in the winter and cooling dominant in the summer it is important to understand how quickly the temperature of abstracted groundwater will be affected. For this analysis a two dimensional analytical model proposed by Banks (2009, 2011) was applied to the Exeter doublet, parameterised as follows: well doublet spacing 200 m, aquifer thickness 55 m, hydraulic conductivity 5 md^{-1}, pumping rate 10 ls^{-1} and effective kinematic porosity 20%. Hydraulic conductivity and porosity values were derived from Allen *et al.* (1997). A nominal flow rate of 10 ls^{-1} is used to be conservative and also to account for the fact that the building heating and cooling regime will likely utilise the maximum output of the borehole to achieve maximum efficiency.

The analysis predicts a hydraulic breakthrough time of approximately 662 days between the injection and abstraction well. In contrast, hydraulic breakthrough in the fracture dominated Chalk aquifer over a distance of 144 m was observed in just 14 hours (Clarkson *et al.*, 2009). This is due to the effective porosity of the Chalk (*c.* 1%), which is significantly lower than the sandstone aquifer at the site, resulting in much faster groundwater travel times.

Banks (2012) observed that the movement of heat through an aquifer is slower than the groundwater flow and attributes this to the fact that heat transport is governed by three mechanisms:

1) Conduction through mineral grains and water filled pores.
2) Advection with bulk groundwater flow.
3) Exchange between moving groundwater and the matrix of the aquifer (mineral grains and water filled pore spaces).

Through these mechanisms adsorption of heat by the aquifer matrix is retarded relative to the groundwater flow. Thus a retardation factor (R) can be defined allowing us to estimate thermal breakthrough time by simply multiplying the hydraulic breakthrough time by a retardation factor (R). Banks (2012) proposes the following equation to derive a thermal retardation factor (R):

$$R = xhyd/xthe = SVCaq/neSVCwat \qquad (2)$$

where R is thermal retardation factor (dimensionless); Xhyd is hydraulic breakthrough time (days); Xwthe is thermal breakthrough time (days); SVCaq is volumetric heat capacity of the aquifer; Ne is effective porosity; SVCwat is volumetric heat capacity of water.

In estimating a thermal breakthrough time for the project site, a volumetric heat capacity of 2.2 MJ m^{-3} K^{-1} is assumed for the saturated sandstone aquifer, a thermal retardation factor of 2.12 is calculated, resulting in a thermal breakthrough time of approximately 1,403 days. As Banks (2011) points out, this is likely to prove a significant underestimate, as in a real three-dimensional situation heat would be attenuated by conduction into over- and underlying strata and to the atmosphere via the ground surface (Guven *et al.*, 1983; Doughty *et al.*,1982).

Given that heating and cooling will be closely balanced in a typical operating year, with cooling prevalent in the summer and heating prevalent in the winter, the estimated thermal breakthrough time is considered significant. The fact that the estimated thermal breakthrough time is considerably larger than the heating or cooling dominated intervals in a typical operating year (1,403 days compared to 180-200), supports the view that changes in abstracted groundwater temperature in a typical operating year will be small. The efficiency and reliability of groundwater heating and cooling applications are influenced to a significant degree by variations in abstracted groundwater temperature. The more stable the abstracted groundwater temperature the more efficient and reliable the system operation.

CONCLUSIONS AND WIDER APPLICATION

This case study highlights a number of important differences between Permo-Triassic sandstone aquifers and fracture-dominated aquifers including the UK's most important aquifer, the Chalk. These differences are considered significant in terms of the overall risk profile for this type of development and highlight some significant advantages for the development of this type of system in the Permo-Triassic sandstone aquifers. Specifically:

1) Groundwater yields (Risk R1) can be predicted with much greater confidence in aquifers where matrix flow is more prevalent following a competent desk study reconnaissance in which the saturated aquifer thickness is determined reliably. Groundwater yields in fracture-dominated aquifers are notoriously difficult to predict.

2) Similarly, injection performance (Risk R2) can also be predicted with much greater confidence in aquifers where matrix flow is dominant.

3) Matrix flow is more prevalent in the Permo-Triassic sandstone aquifers and, consequently, groundwater travel times between abstraction and injection locations are significantly longer than in fracture flow-dominated aquifers such as the Chalk. This case study demonstrates a groundwater travel time between abstraction and injection locations of approximately 662 days and a thermal breakthrough time of approximately 1,403 days. Both hydraulic and thermal breakthrough times are significantly larger than similar systems in fracture dominated aquifers such as the Chalk, where groundwater travel times are typically less than 1 day.

Permo-Triassic sandstones are one of the UK's principal aquifers and the second most important aquifer after the Chalk. Represented to a relatively small degree in South-West England they are, however, extensively developed throughout the midlands and the north of England. The deposits are present at outcrop beneath some of the largest urban centres in the north of England including Manchester, Birmingham, and urban conurbations east of the Pennines. Throughout Cheshire, Shropshire and South-West England the deposits are well developed beneath both rural and urban centres. Based on geographical representation and the advantages of development in this type of aquifer discussed above, the Permo-Triassic sandstones of England have considerable potential as a source of heating and cooling for a wide range of applications including large buildings, housing, industry and horticulture.

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