MODELLING OF A THERMAL PLUME IN THE SHERWOOD SANDSTONE: A CASE STUDY IN NORTH YORKSHIRE, UK.

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ABSTRACT

Migration of the groundwater thermal plume from an open-loop, well-doublet industrial cooling system in the Sherwood Sandstone aquifer of Selby, Yorkshire has been assessed using analytical and numerical models. Results suggest that a minor degree of thermal feedback could be occurring between the abstraction and injection boreholes, marginally reducing the cooling efficiency of the system. Down the hydraulic gradient, both analytical and numerical modelling suggest that the warm water plume has not migrated as far as initially estimated - a conclusion supported by empirical field data from observation wells. Indeed, the temperatures in the observation wells are believed to be affected by other heat sources than solely the warm "waste" water from the cooling scheme. In particular, two alternative heat sources were considered important: abstraction-induced upconing of deeper, warm, brackish groundwater and downwards conduction from industrial premises.

1. INTRODUCTION

A factory in North Yorkshire uses groundwater from the Sherwood Sandstone for industrial cooling, via an open-loop well doublet scheme (Banks 2008). Groundwater is abstracted via a 70m deep well up the hydraulic gradient from the factory, absorbs waste heat via heat exchangers in the factory and is then re-injected back into the ground via a 70m deep recharge well. This study proposes to estimate the extent and direction of the warm water plume from the injection well. Numerical and analytical modelling was carried out, the results of which were compared to empirical data collected in the field. The scheme has operated successfully for around 10 years.

The peak cooling capacity is given by the doublet yield (12 L/s) and the maximum temperature differential (20°C - 11°C = 9°C) as 12 L/s x 9 °C x 4.18 KJ/L/°C = 450 kW. The submersible pump used in the cooling system has a rating of 18.5kW and the system is typically used for 15-18.5 hours a day, running between 75-93 hours/week (45 - 55% of full-time). The groundwater-based cooling scheme is believed to result in significant cost savings for the operator and significant reductions in carbon dioxide emissions from electricity usage (Table 1).

In 1998, as part of the feasibility study for the system (Dumpleton et al. 1998), the direction and extent of the warm water plume from the injection well were predicted based on known groundwater levels and pumping rates from surrounding wells. However, recent monitoring data from observation wells do not show the expected increases in down-gradient groundwater temperature. This study re-evaluated the monitoring data and undertook a revised conceptual modelling and more sophisticated analytical and numerical modelling of the area.

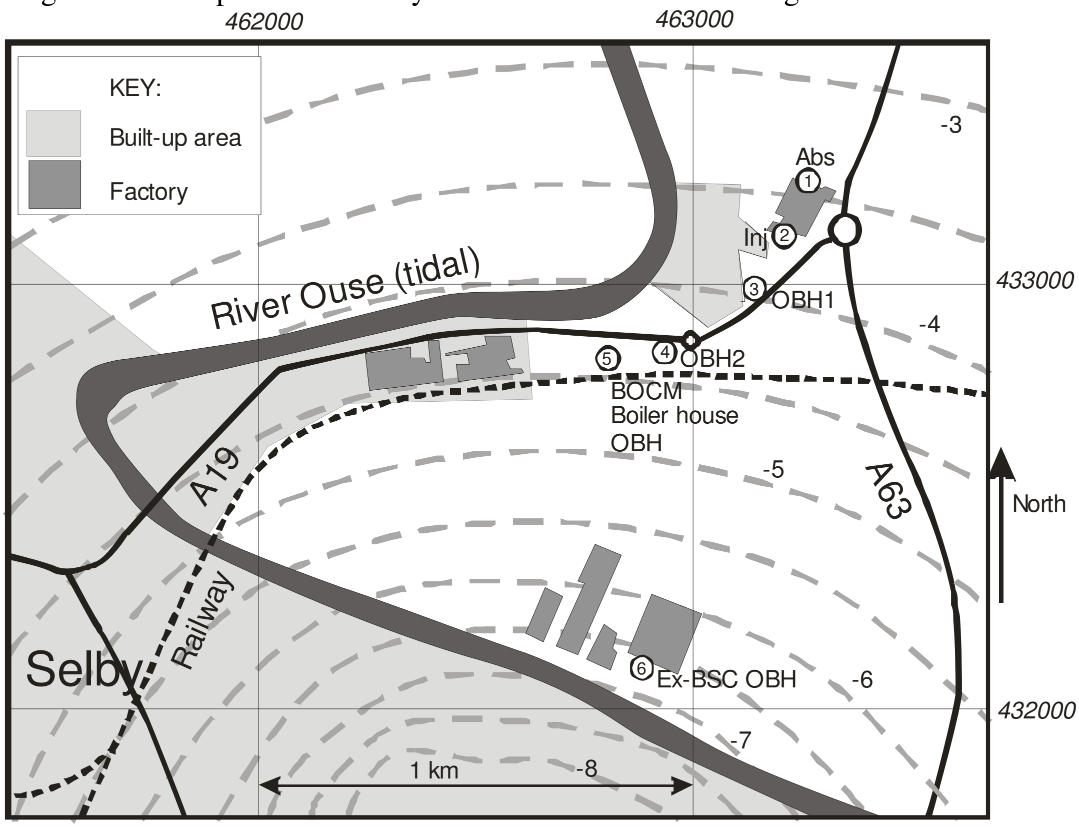

Figure 1. The study area. 1 and 2 = abstraction (Abs) and injection (Inj) boreholes of well doublet, 3 = OBH1, 4 = OBH2, 5 = BOCM observation borehole, 6 = BSC observation borehole. Grey dashed lines show piezometric contours on groundwater in Sherwood Sandstone aquifer (in m above sea level - negative numbers indicate metres below sea level). Note that the contours converge on a cone of depression, caused by industrial abstraction, to the south of the study area.

Table 1: Estimate of the costs of the groundwater cooling system, compared with a conventional 450 kW active chilling system, assuming (i) 3900 to 4840 hours/year usage, (ii) electricity costs 8.5p/kWh and (iii) electricity ultimately results in 0.42kg/kWh of CO_2 emission (Banks 2008).

Item	**Electricity required (kWh/year)**	**Cost per year (£ sterling)**	**CO_2 emission (kg/year)**
Actual well doublet cooling system	72,000-90,000 (submersible pump)	£6100-£7600	30,000-37,500
Conventional industrial chiller (COP_C = 4.5)	390,000-484,000	£33,100-£44,100	164,000-203,000

Study Area

The factory is situated in Selby, North Yorkshire where the geology comprises around 20m of low permeability recent alluvium / glacio-lacustrine deposits (the so-called "Vale of York Drift") overlying and confining the regionally important Sherwood Sandstone aquifer. The Sherwood sandstone is 175m thick at this location and transmits groundwater flow by both fracture and intergranular flow pathways. The head in the Sandstone is only around 3-4 m below ground level. Conventional conceptual models regard the River Ouse as being largely hydraulically separated from the Sandstone by the intervening Drift. The hydrogeological regime of the area is influenced by a number of nearby, large-scale industrial abstractions from the Sandstone. At the present time, regional groundwater modelling indicates that large-scale groundwater abstraction ~4km to the south of the site controls the local hydraulic gradient, which is -0.0022 to -0.0035 (average -0.0028) to the south-south-west (Figure 1).

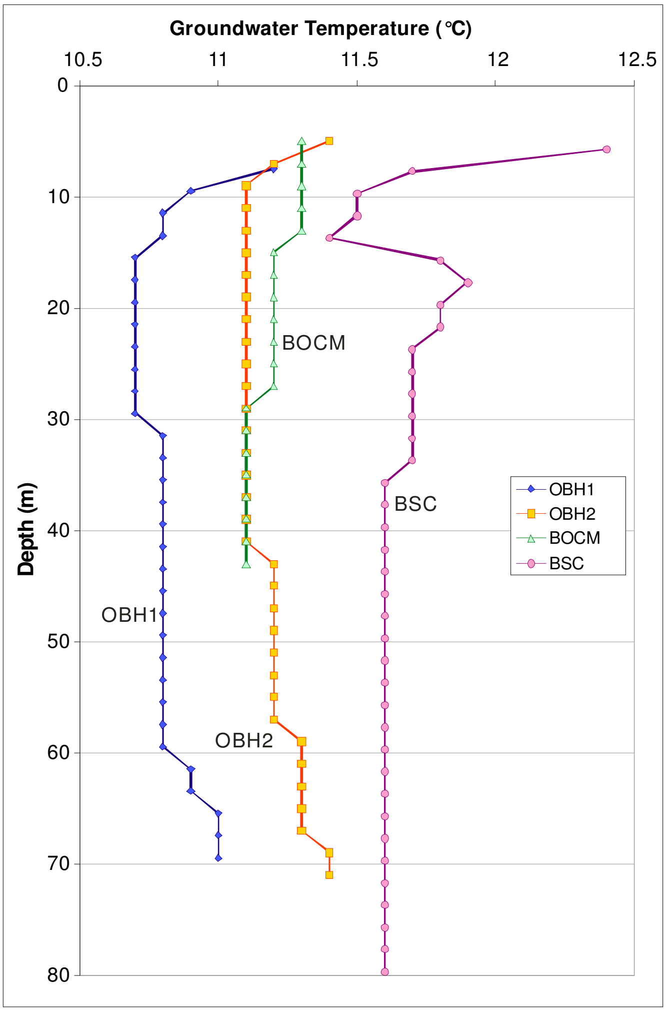

Figure 2. Groundwater fluid temperature profiles, measured in a downhole direction in the four observation boreholes, at 2 m intervals on 29/5/08. In OBH1, OBH2 and BSC the top three readings show elevated temperatures due to an early summer seasonal signal. Below this, OBH1 and OBH2 show a slowly increasing "normal" temperature gradient. BOCM and BSC show a "reversed" gradient down to 30-40 m, which may conceivably reflect downwards migration of an urban/industrial heat signal.

The conditions of the abstraction licence for the site impose temperature limits on several downstream observation boreholes (termed "OBH1", "OBH2", "BOCM" and "BSC"). The injection temperature at the factory is not permitted to exceed 20°C and that in the downstream monitoring wells cannot exceed 12°C (Figure 1). These limits were imposed to protect the aquifer as a resource for downstream users and were based on the plume extent from the feasibility study. OBH1 and OBH2 were specifically constructed as monitoring wells for this system whereas the other two are older wells which were used for industrial abstraction in the past.

2. BACKGROUND TEMPERATURE

The temperature of the abstracted water in the northern well of the doublet was measured at a well-head tap as 12.1°C on 29/5/08. On the same day, a temperature-dipper was used to measure the temperature every 2m below water level in each of the four monitoring wells to produce an accurate temperature depth profile (Figure 2). The groundwater temperature in the observation wells was typically around 11°C but, intriguingly, the lowest temperatures were observed in OBH1 (nearest the well doublet scheme) and the highest temperatures in the BSC borehole (furthest away). It may be relevant to note that the two warmest observation wells were those located at former industrial premises (the BOCM borehole, near to a former boiler-house, and the BSC borehole), while OBH1 and OBH2 were purpose-constructed in undeveloped scrub-land.

The observation wells thus do not provide any evidence of a thermal plume migrating from the well doublet. Indeed, they suggest that there may be other, additional processes or sources that influence the aquifer temperature in the area.

Table 2: Summary of hydro-/thermogeological parameters applied in the mathematical and modelling calculations described in this paper (BGS = British Geological Survey)

Parameter	**Value**	**Unit**	**Source of information**
Doublet pumping rate *(Z)*	850-1000	m^3/d	Estimated average since 2006 (maximum licensed quantity)
Well doublet separation *(L)*	172	m	
Radius of wells (r_w)	0.15	m	Borehole log
Effective aquifer transmissivity *(T)*	200-500	m^2/d	Pumping test
Effective porosity (n_e)	0.1	-	BGS aquifer properties
Effective aquifer thickness at well *(D)*	40	m	Borehole log
Regional hydraulic gradient *(i)*	-0.0022 to -0.0035	-	ESI (2006) model
Volumetric heat capacity of saturated aquifer (S_{vaq})	2.23	$MJ/m^3/K$	BGS data
Volumetric heat capacity of water (S_{vwat})	4.18	$MJ/m^3/K$	
Thermal conductivity of saturated aquifer(λ)	3.03	W/m/K	BGS data
Regional geothermal heat flux*(Q)*	50-70	mW/m^2	BGS maps

3. INTERNAL THERMAL FEEDBACK

The fact that the temperature of the abstracted water (12.1°C) is higher than that in any of the monitoring wells (Figure 2) suggests that there may be some degree of thermal "feedback" of reinjected warm water to the abstraction well. Banks (2008) provides the following equations for the hydraulic (t_{hyd}) and thermal (t_{the}) travel time between injection and abstraction wells in well doublet oriented perpendicular to regional groundwater head contours:

$$t_{hyd} = \pi n_e D \frac{L^2}{3Q} \text{ for i (regional hydraulic gradient) = 0} \qquad \text{(Hoopes \& Harleman 1967)}$$

$$t_{hyd} = \frac{Ln_e}{Ki}\left[1 + \frac{4\alpha}{\sqrt{-1-4\alpha}}\tan^{-1}\left(\frac{1}{\sqrt{-1-4\alpha}}\right)\right] \text{ for } i<0 \text{ where } \alpha = \frac{Z}{2\pi TiL} \qquad \text{(Lippmann \& Tsang 1980)}$$

$$t_{the} = t_{hyd}\frac{S_{VCaq}}{n_e S_{VCwat}} \text{ (retardation of heat front relative to groundwater velocity)}$$

Applying these equations to the Selby scenario, using the parameters specified in Table 2, we can calculate both the hydraulic and thermal breakthrough times (Table 3).

Table 3: Calculated hydraulic and thermal feedback times where T=250m^2/d and D=40m, for i = 0 (flat hydraulic gradient) and i = -0.0028

Method	**Z=1000m^3/d**		**Z=850m^3/d**	
	t_{hyd} (days)	**t_{the} (days)**	**t_{hyd} (days)**	**t_{the} (days)**
Hoopes-Harleman: i = 0	124	660	145	776
Lippmann-Tsang: i = -0.0028	146	779	177	947

The approach predicts that, if the doublet were pumped continuously at an average rate of 850 m^3/d (9.8 L/s), one would expect to see breakthrough of waste heat from the reinjection well after 2.6 years. The exact pattern of abstraction (and hence the actual long term average pumping rate) at the factory is not known, but is does not seem unreasonable to expect some internal feedback of heat within the doublet after 10 years of operation. It is, however, worth considering two alternative sources for the raised temperature in the abstraction well:

(a) heat generated by the pump. A brief assessment of this suggests, however, that the pump cannot account for more than a 0.1°C temperature rise in this situation.
(b) the fact that the well doublet only *partially penetrates* the Sherwood Sandstone and will thus cause "upconing" of deeper (and hence warmer) groundwater to the abstraction well.

4. DOWNGRADIENT THERMAL MIGRATION - ANALYTICAL ESTIMATES

Previous work (Dumpleton et al. 1998, Arup 2007) indicated that a warm water plume from the site would reach the three closest downstream monitoring wells (OBH1, OBH2 and BOCM) within 5 years. The scheme has now been running for 10 years, however, and fieldwork suggests no evidence of the warm water plume reaching these wells (Figure 2). Revised analytical calculations that included the effect of retardation of heat with respect to water (see equations in Section 3) were carried out within this study, with a more accurate groundwater gradient (i).

The groundwater velocity (v_{hyd}) was calculated using Darcy's law and the parameters from Table 2. By applying a thermal retardation factor to this velocity, the rate of migration of a groundwater heat plume was estimated, which in turn was converted into a thermal travel time (Table 4). These results suggest that, since the system began in 1998, the plume of warm water was unlikely to have reached OBH2, BOCM and BSC. The plume may have reached OBH1 under a worst-case parameterisation of the calculation (5 years' travel time), but the lack of an observed plume (Figure 2) is wholly consistent with a best-case parameterisation (20 years).

Table 4: Calculated travel times for thermal plume to monitoring wells a Darcy velocity (specific discharge) of 0.011 – 0.044 m/d (t_{hyd}= *groundwater travel time,* t_{the}= *thermal travel time)* and n_e = 10% (or 0.1), implying a linear velocity (v_{hyd}) of 0.11 to 0.44 m/d)

Monitoring Well	Distance from Injection well	t_{hyd} (years)	t_{the} (years)
OBH1	150	1-4	5-20
OBH2	340	2-9	11-45
BOCM	440	3-11	15-58
BSC	1015	6-25	34-135

5. DOWNGRADIENT THERMAL MIGRATION - NUMERICAL MODEL

The analytical results (Section 4) suggest that the plume is unlikely to have reached the BOCM and BSC observation wells, although the empirical data (Figure 2) indicate that these have the highest temperatures. As a further check, numerical modelling was carried out using SHEMAT (Clauser 2003) - a coupled heat-groundwater flow finite difference modelling code. The Selby well doublet system was simulated using a simple rectangular model domain and the parameters indicated in Table 2. The rectangular model grid was positioned perpendicular to the groundwater contours (taken from Environment Agency's regional groundwater model, ESI 2006, Figure 1). The grid was bounded by constant groundwater flow boundaries to the north and south and no-flow boundaries to the east and west. The finite difference equations were modelled implicitly and heat and flow were coupled via temperature and pressure dependence. The model simulated a 10 year period, although constant pumping/reinjection rates were applied to two 5 year time periods, representing apparent variations in the real pumping rates at the factory.

Various model scenarios were run, reflecting the range of uncertainty in aquifer permeability. The output from one such model run is shown in Figure 3. Along with spatial output, SHEMAT allows one to view the temperature profile for a monitoring well over time. As the modelling process results in dispersion of the thermal plume, the time for the warm water plume "breakthrough" (Table 5) in a monitoring well was defined as a temperature rise of 4.5^{o}C (i.e. 50% breakthrough - half the difference between the injection and initial groundwater temperatures of 20°C and 11°C, respectively). The SHEMAT results suggest that, within 10 years, a distinct rise in temperature would only be recorded in OBH1 due to the thermal plume from the factory. It should be noted, however, that, while SHEMAT simulates thermal dispersion (due to heat conduction), it does not necessarily simulate hydraulic dispersion. Moreover, it was demonstrated (Todd 2008) that some of the apparent dispersion of the plume (Figure 3) was due to numerical dispersion rather than thermal/hydraulic processes. Because of the difficulties in assessing the realism of the simulation of dispersion, it is possible that the model overestimates the extent of thermal migration and there are sound reasons to prefer the analytical assessments (Table 4) to the numerical (Table 5).

Table 5: SHEMAT simulated times for heat to reach monitoring wells based on the time taken for the groundwater temperature to reach 15.5°C (i.e. 50% breakthrough).

Well	**Permeability = 7.7x10^{-12} m^2**		**Permeability = 1.2x10^{-11} m^2**	
	t_{the} (days)	**t_{the} (years)**	**t_{the} (days)**	**t_{the} (years)**
OBH1	1400	3.8	1250	3.5
OBH2*	>3650	>10	>3650	>10
BOCM*	>3650	>10	>3650	>10
BSC*	>3650	>10	>3650	>10

**The temperature in these wells did not reach 15.5°C within the simulation period*

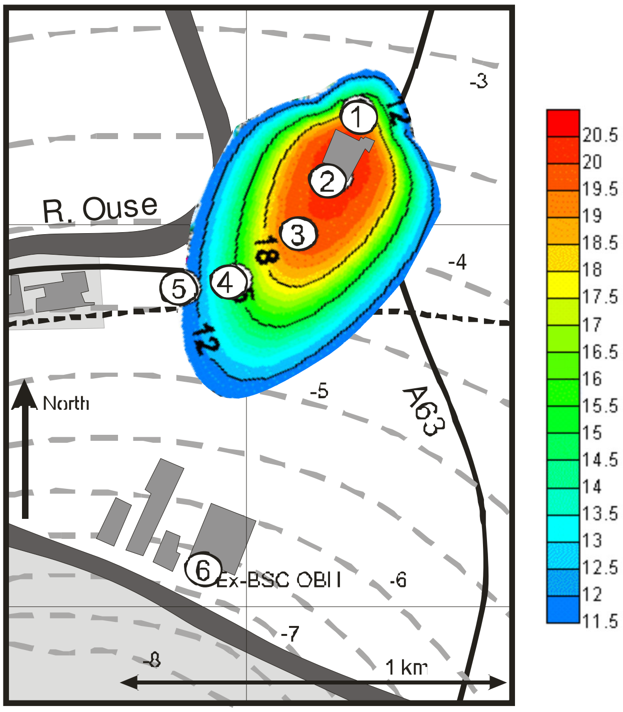

Figure 3. The modelled thermal plume after 10 years for a hydraulic conductivity (*K*) of 11m/d (SHEMAT cell size of 50 x 50m). For key see Figure 1. Colour scale on right shows temperature in °C.

6. ALTERNATIVE HEAT SOURCES FOR THE AQUIFER

The analytical and numerical modelling results suggest that a warm water plume emanating from the factory's cooling system is unlikely to have reached the BOCM and BSC wells. However, the elevated temperatures in Figure 2 suggest that there may be another source of heat to the aquifer in the area to the south of the factory. The most likely candidates for such an additional source of heat are:

(i) The downwards conduction of heat from surface urbanisation and industry, resulting in a reversed temperature gradient in the upper tens of metres of a geothermal profile (Figure 2). This is increasingly well documented from Sweden, Ireland, Canada, Japan and the UK

(Banks et al. 2009). Simple analytical modelling demonstrates that a "step" increase in surface temperature of a few °C can propagate downwards by 50 - 100 m in the course of a century.

(ii) Pumping-induced upwards migration of deeper (hence, warmer) brackish groundwater. Historic pumping has caused a significant cone of depression centred on the Selby area (Figure 1) and it is known that continued abstraction tends to result in increased groundwater salinity (e.g. chloride) in pumped wells. This is ascribed to pumping causing "upconing" of deeper brackish groundwater. In this study (Todd 2008), qualitative comparisons were made between pumping rate, chloride concentration in abstracted groundwater and temperature. These correlations appear to confirm that abstraction results in an increase in chloride content and that elevated chloride content could be tentatively linked to an elevated temperature.

7. CONCLUSIONS

This study demonstrates that analytical and numerical models can be utilised to carry out a risk assessment of the migration of a thermal plume from a groundwater-based cooling well doublet. Lack of consideration of thermal retardation (absorption of heat into the aquifer matrix) can result in significant overestimation of the velocity and extent of the plume. Regulatory authorities should remember that such cooling systems are not the only (or even the most important) factors impacting the temperatures of aquifer systems: (i) pumping-induced upconing of deep, warm groundwater and (ii) downward conduction of head from urban and industrial areas are also likely to be significant.

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