SESKA Groundwater Cooling

Borefield design theory and concepts

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Executive Summary

Groundwater cooling is an appropriate and sustainable heat rejection technology for the Pawsey Supercomputer Centre. It makes use of the local Mullaloo aquifer system which is able to provide cool groundwater at high and reliable flow rates, and is readily able to accept water warmed by excess heat.

This report has considered a range of engineered pumping system designs and has identified a pumping layout that provides maximum longevity and flexibility of thermal performance with minimal capital requirements for borefield construction. The basic design involves production-injection well doublets.

Flow net analysis has shown that shielding wells placed between production and injection wells provide a useful buffer against thermal breakthrough which promotes longevity of heat rejection. Hydrothermal simulations indicate that shielded configurations reduce or delay thermal breakthroughs and hence provide greater energy efficiencies for groundwater cooling systems as compared to unshielded configurations, but at the capital expense of extra injection wells and pipe runs.

Based on the findings above it is recommended that the Pawsey groundwater cooling system be designed using a twin-doublet layout with two extra shielding wells (6 wells in total).
1 Introduction

The SESKA (Sustainable Energy for the Square-Kilometre Array) Geothermal Project has the mission to provide a geothermal cooling solution for the Pawsey Supercomputer Centre which is currently under construction at the Australian Resources Research Centre (ARRC) in Kensington, Western Australia.

Current estimates of the thermal load to be produced by full-scale operation of the computational hardware defined in Phase 1 of the Pawsey Supercomputer Centre business plan are of the order of 2.4 MW$_{th}$ (MegaWatts thermal). One potential means for capturing and rejecting this thermal load is by heat exchange with a cool water stream. The heat exchange process would raise the temperature of the water stream, which could then be disposed of by evaporating the water to the atmosphere (e.g. via a conventional cooling tower solution) or by disposing of the warmed water underground. The latter concept is considered here within the context of the ARRC hydrogeology.

An estimate of the scale of such a groundwater heat exchange system can be gained by considering a nominal 10 °C increase in temperature of the cool water stream through the heat exchange process. In order to absorb heat at a rate of 2.4 MW$_{th}$, this water stream would need to be flowing at approximately 57 L/s (a temperature of 20 °C is assumed).

CSIRO has made a decision to proceed with designing, installing, commissioning and operating a groundwater-based cooling system to support the Pawsey Supercomputer Centre. The cooling system is to be built in 2013 with a minimum operational lifetime of 5 years, and this report presents some of the scientific and engineering concepts employed to design the system and that were subsequently fed into the technical specification of the system for tendering purposes.

1.1 Scope of Report

Previous studies (Rockwater, 2012) commissioned by the SESKA Geothermal Project have concluded that the Mullaloo Aquifer, a shallow aquifer system beneath ARRC, has the capacity to supply the requisite cool water stream and also to accept the rejected warm water stream, simultaneously. Engineering designs have already been developed for a simple instance of such a “groundwater cooling” (GWC) system, but it is the purpose of the present report to consider whether other designs and configurations may be technically feasible, economically viable and robust against unexpected subsurface behaviours. Candidate designs will be compared against the conventional GWC system already proposed.

This report is a brief technical summary report focusing on hydraulic designs and hydrothermal simulations of various borefield and pumping configurations. Only a few candidate designs are listed here out of many that were considered to various levels of detail. The approach is theoretical, involving well-known methods for estimating subsurface hydraulic behaviour and based on hydrogeological parameters previously measured for the Mullaloo Aquifer. Designs are assessed in terms of the number of wells required, pumping load and pumping duty cycle, the thermal breakthrough performance of the system, and the potential for downstream impacts.

In this report, no assessments of environmental impacts arising from the GWC designs are made, for several reasons. First, a preliminary assessment of the consequent biogeochemical disturbances has already been made (Douglas et al., 2012) and has been accepted by the government regulatory agency, Department of Water. Second, a site-specific and much more detailed hydrothermal model of the ARRC GW system will be developed based on the borefield design and configuration recommended in this report, and this model will be used to assist in management and analysis of the actual operation of the GWC system after the construction is complete. Finally, the GWC system will be monitored according to Department of Water license requirements, so that should unexpected behaviours occur in the operating GWC system they will be detected in good time for appropriate interventions to be made.
2 Basic Concepts of Groundwater Cooling

In its simplest form, a groundwater cooling system requires an extraction (production) well that produces cool water from an aquifer, and an injection (disposal) well that disposes of the warmed water into the subsurface. These two wells together form a well doublet which is the basis of subsurface heat exchange systems. Many variations of this basic doublet design are possible, including combinations of the following concepts:

- Balancing status – where net injection and extraction rates are equal (balanced) or unequal (unbalanced)
- Target status – where injection and extraction occur in the same aquifer formation, or at different depths in the same formation, or in different formations altogether
- Chemical status – where recirculated water is modified or treated prior to reinjection
- Multiple wells – where the borefield is extended to include more than a single doublet
- Duty cycle – where pumping may be continuous (steady) or subject to change (transient)

In the present report, attention is confined to balanced GWC schemes in order to preserve the net water resource of the target Mullaloo aquifer. The target is solely the Mullaloo aquifer, although injection and extraction may take place at different depths within the aquifer. It is assumed that chemical status is maintained, that is the above-ground heat exchange system will be kept pressurized and oxygen ingress will be prevented. This will reduce chemical alterations to those produced by thermal variations alone.

It is also noted that measurements of regional (or background) groundwater flux vector are sparse (only two head measurements available) in the vicinity of the Pawsey site. This data gap constitutes a design risk for the GWC design: the background groundwater flux must be included as an unknown quantity in subsequent analysis. It may be anticipated that the groundwater flux may vary about the mean seasonally and at longer timescales, and also at short timescales in response to local pumping activities. Acceptable GWC designs must be robust to potential variations in background groundwater flux.

In scope for the following discussions are the number of wells/doublets to be employed in the GWC design, and also the possibility for using either steady or transient pumping schemes. In order to provide a conservative basis for the discussions, the thermal load to be accommodated by the candidate designs is set at 3.0 MW$_{th}$. This value is above the 2.4 MW$_{th}$ load described earlier – the increase allows a 25% contingency buffer over the thermal load estimate for the Pawsey Centre.

2.1 Potential Fields and Flow Nets

One of the basic tools for assessing groundwater hydraulics is the theory of potential fields. Potential fields are embodied in simple algebraic formulae that represent idealized groundwater flow dynamics. Through mathematical means the potential fields can be displayed either in terms of potential (groundwater head) maps or as conjugate streamline (flow path) maps. Display of heads and flow lines together on the one diagram is termed a flow net diagram. Figure 2-1 shows flow nets for a balanced well doublet with and without the perturbing influence of regional groundwater flow. In the absence of regional flow (plate (a)), groundwater moves through the aquifer from the injection well (right) along the flow lines (white) toward the extraction well (left). The shortest route between the two wells is along the centre line, but a significant amount of the flow takes much longer paths and much longer times to reach the extraction well. When regional flow is added to the model (plate (b)) it is seen that the doublet forms a flow cell embedded in a
larger regional flow system. Depending on the strength of the background flow it is possible for little or no water to move from the injection well to the extraction well (as shown in plate (b)).

There are several key assumptions involved in the potential field approach to understanding flow topology:

- Steady conditions: the flow is assumed to be steady, i.e. independent of time
- Homogeneity: the aquifer properties are assumed to be uniform and isotropic in space
- Linearity: the flow dynamics are assumed to correspond to confined flow conditions

None of these assumptions are strictly true for the Mullaloo aquifer at the ARRC site (see Rockwater, 2012) however there is also no evidence of strong heterogeneity in aquifer properties or of strongly unconfined/phreatic behaviour in the aquifer. Therefore, noting the power of the potential field approach to facilitate rapid development and assessment of hydraulic schemes, this approach is used to perform a survey of pumping designs for later and more detailed assessment. The chief benefits of this approach are clear pictorial summaries of groundwater flow regimes and topologies, rather than detailed quantitative simulations.

![Figure 2-1 Potential field flow net for a well doublet showing dependence on regional groundwater flow. Plate (a) shows a flow net without regional flow, and plate (b) shows regional flow from left to right. Shading indicates groundwater head (dark is low, light is high). Black contours indicate heads and white contours describe flow paths (streamlines).](image)

The analytical formulae (see Bear and Jacobs, 1965) used in generating the plates for the x-y plane in Figure 2-1 are summarized as follows:

**Pumping Well**, of strength $Q$ located at $(x,y) = (x_0,y_0)$

- Potential: $\phi = \frac{Q}{4\pi} \ln\left( (x - x_0)^2 + (y - y_0)^2 \right)$
- Streamfunction: $\psi = \frac{Q}{4\pi} \arctan\left( \frac{y - y_0}{x - x_0} \right)$

**Regional Flow**, gradient $k$

- Potential: $\phi = -k x$
- Streamfunction: $\psi = -k y$
The previous discussion and the algebraic results above pertain only to groundwater flow and no mention is made of heat transport or conduction. Thermal processes will be included in later sections of this report.

2.2 Flow Nets for Candidate GWC Designs

In this section we consider the basic flow nets for several candidate GWC designs. The candidate designs are

1. Two-dipole, balanced, steady design, also referred to as the conventional design.
2. Two-dipole, balanced, switched design.
3. Six-well, balanced, steady design, also referred to as the shielded design.

Figure 2-2 Schematic (left) and flow net for the conventional GWC design. The total thermal load is $2W$, the total pumping rate is $2Q$ and the background groundwater flow is $U$. The arrows indicate direction of flow through the above-ground pipework connecting the GWC dipoles. Blue (red) dots indicate cool (warm) wells.
Figure 2-3 Schematics (left) and flow nets (not to scale) for the switched GWC design. The total thermal load is $2W$, the total pumping rate is $2Q$ and the background groundwater flow is $U$. Only one diagonal pair of wells is active at any time. The arrows indicate direction of flow through the above-ground pipework connecting the GWC dipoles. Blue (red) dots indicate cool (warm) wells.
2.3 Performance Metrics

The aim of this project is to design and optimise alternative pumping strategies for the GWC operation designed to supply a thermal cooling capacity for the Pawsey Supercomputer Centre, and to gauge impact on performance with respect to a conventional pumping design. In terms of performance enhancement, two distinct metrics are considered as a basis for optimisation: (i) the thermal breakthrough time \( t_b \), defined as the time at which the extracted fluid temperature reaches a critical value \( T_{\text{max}} \), at which point heat rejection is no longer viable (e.g. set by the maximum coolant temperature accepted by the Pawsey supercomputer), and (ii) the equilibrium groundwater extraction temperature \( T_{\infty} \), which in the case where thermal breakthrough is avoided altogether gives a measure of the robustness of the GWC operation, as quantified by \( T_{\text{max}}-T_{\infty} \). Ideally thermal breakthrough is to be avoided, meaning that the GWC operation can theoretically operate indefinitely, however for certain physical and operational parameters this situation cannot be avoided due to basic thermodynamics of the GWC system.

The two performance metrics \( t_b \), \( T_{\infty} \) provide a basis for performance enhancement across the two distinct scenarios depending upon whether thermal breakthrough occurs, and are believed to be the most relevant physical performance indicators which correlate to economic performance in terms of e.g. Net Present Value or Internal Rate of Return. Whilst direct calculation of these economic metrics is beyond the scope of this project, in all instances we have strived to minimise the capital and operating costs of the GWC operation by e.g. minimising or avoiding drilling of new wells, minimising pumping requirements, piping infrastructure etc.
2.4 Enhancing Thermal Performance

There exist several distinct approaches to enhancing performance of the GWC operation in terms of the performance metrics above which can be broadly classified as follows:

- Homogenization of the thermal plume within the operational domain
- Confinement of the thermal plume away from the extraction well
- Transport of the thermal plume away from the extraction well via the regional groundwater flow

The first approach essentially strives to mix the fluid within the operational domain (loosely defined as the spatial domain local to and containing all wells) such that the thermal plume is spread throughout this region and so the heat sink represented by the operational domain is utilized to its fullest extent. Ideally, the thermal plume could be spread over as large a volume as possible, in effect maximising the operational domain itself, however the rapid decay of the fluid velocity field away from pumping wells means that there exist bounds on the effective operational domain for a given volumetric flow rate. In general, thermal dispersion throughout the operational domain may be rapidly accelerated via fluid mixing which can be achieved via transient fluid pumping as demonstrated by CSIRO’s patented Subsurface Stirring technology (Metcalfe et al., 2012; Trefry et al., 2012) which has been demonstrated in laboratory scale experiments to be a highly effective means of imparting efficient fluid mixing with little to no additional pumping energy requirements as compared to regular operation.

The second approach is markedly distinct to the first in that as opposed to accelerated dispersion, the goal is to retard thermal transport out of a domain local to the injection wells via fluid confinement. This approach strives to isolate the thermal plume in a closed domain away from the fluid extraction wells so to delay thermal breakthrough for as long a period as possible, and maximizing efficiency of the GWC operation by maintaining the fluid temperature at the initial aquifer temperature for as long as possible. Again, confinement of the thermal plume can be achieved by transient fluid pumping as demonstrated via Subsurface Stirring technology (albeit via different pumping protocols than for fluid mixing), the efficacy of which has been demonstrated in laboratory scale experiments.

The third approach relies upon the presence of a regional groundwater flow which naturally acts to carry the thermal plume downstream and retards thermal breakthrough if the extraction well is situated upstream. By consideration of alternative pumping schemes (including both steady and/or transient pumping) it is possible to promote dispersion of the thermal plume into the background flow, which can further retard thermal breakthrough.

Of the three approaches to performance enhancement, the first two cannot avoid thermal breakthrough altogether as the thermal plume is not removed from the operational domain, and so for a fixed heat load injected into the domain, the plume must reach the extraction well, and eventually the extraction temperature will exceed $T_{max}$. Conversely, the third approach of maximising heat rejection into the background flow can avoid thermal breakthrough altogether if at equilibrium the heat load balances the thermal energy swept downstream. Despite this obvious thermodynamic advantage, this approach is not universally optimal of the three approaches as it is contingent upon the presence of a significant background flow to achieve the desired effect. In general, it is impossible to determine a priori which approach is optimal as each methodology is highly dependent upon the underlying physical and operational parameters of the GWC operation.

As part of this study we performed some preliminary investigations into the relative merits of each approach, and whilst not reported in detail here, it became obvious for the subject GWC operation that the third approach of maximising heat rejection into the background regional flow showed the most promise, chiefly due to the strength of the background Darcy flux $q$, estimated from head measurements and hydraulic conductivities from a pumping test to lie in the range of 1-6 cm/day. Note that this approach is feasible for a particular combination of heat load, temperature difference and pumping rate combined with this range of background Darcy flux, and there exist certain dimensionless groupings which clearly indicate...
the feasibility of such interventions. We shall introduce these groupings as part of the dimensionless GWC model below, but first we shall consider the basic well layout of the conventional GWC system.

A schematic of the conventional GWC system is shown in Figure 2-5 below, depicting the extraction of cold fluid at the extraction wells (blue, left) at volumetric flow rate $Q$, and the injection of hot fluid at the injection wells (red, right) at the same flow rate with the addition of the thermal heat load $W$. The system consists of two well pairs aligned parallel to the background regional flow of magnitude $U = q/\varepsilon_f$ (where $\varepsilon_f$ is the aquifer porosity), and so the total heat load $W_0 = 2W$, with total volumetric flow rate $Q_0 = 2Q$. Thermal breakthrough occurs as the hot re-injected fluid propagates against the background flow $U$ to the extraction well, increasing the extraction well temperature until it reaches $T_{\text{max}}$.

![Figure 2-5: Schematic of conventional GWC operation (see Figure 2-2). $W$ is the thermal power carried by the warmed water flow (measured with respect to ambient water temperature).]

### 2.5 Hydrothermal Processes

To quantify the performance of this system and the impact of enhanced pumping strategies we develop a simple 2D model of thermal transport throughout the aquifer under the simplifying assumption that vertical gradients within the aquifer are negligible and that the depth of the aquifer is approximately constant. The further assumption is made that the timescale of transport between the fluid phase and the porous sandstone is short with respect to the timescale of advection and diffusion, under which case thermal transport may be described by the single-phase advection-dispersion equation

$$\frac{\partial T_m}{\partial t} + \frac{1}{1+r} \mathbf{v}_f \cdot \nabla T_m = \nabla \cdot \left( \left( \frac{1}{1+r} \mathbf{d}_H + D_m \mathbf{I} \right) \cdot \nabla T_m \right) \tag{1}$$

where $T_m$ is the mixture (fluid/sandstone) temperature, $\mathbf{v}_f$ is the fluid pore velocity field, $\mathbf{d}_H$ the hydrodynamic dispersion tensor, $D_m$ the effective thermal diffusivity of the fluid/sandstone matrix and $r$ is the ratio of sandstone to fluid energy density:
\[ r = \frac{\rho_s \varepsilon_s C_{p,s}}{\rho_f \varepsilon_f C_{p,f}}, \]  

where the subscripts \( s, f \) denote the sandstone and fluid phases, respectively, and \( \rho, \varepsilon, C_p \) are the phase density, volume fraction and heat capacity, respectively. As such, the \( 1/(1+r) \) terms in (1) represent retardation of thermal transport due to the fact that the fluid phase is mobile whilst the host sandstone is immobile.

To aid transparency of the model, we reformulate the thermal transport equation (1) in dimensionless terms by introduction of the following scaling:

\[
T_m' = \frac{T_m - T_0}{T_{\text{max}} - T_0}, \quad x' = \frac{x}{L}, \quad \psi = \frac{v_f}{U}, \quad t' = \frac{tU}{L(1+r)},
\]

where \( T_0 \) is the initial aquifer temperature, and \( L \) is the distance between injection and extraction wells. These scalings generate two controlling dimensionless parameters, the Peclét number \( Pe \) which captures the relative timescales of advection and diffusion

\[ Pe = \frac{LU}{D_m(1+r)}, \]

and the ratio \( \beta \) of the pumped to background regional flow

\[ \beta = \frac{V_0}{U}, \]

where \( V_0 \) is the value of the pore velocity field at the mid-point between a well dipole pair. \( V_0 \) is related to the volumetric flow rate \( Q \) as

\[ V_0 = \frac{Q}{L\pi h \varepsilon_f}, \]

where \( h \) is the depth of the aquifer. For a given heat load \( W \) per well pair, the volumetric flow rate \( Q \) may be calculated as

\[ Q = \frac{W}{\rho_f C_{p,f} \Delta T(T_{ex})}, \]

where \( \Delta T(T_{ex}) \) is the temperature difference of the thermal loop as a function of the temperature at the extraction well \( T_{ex} \). An estimate of the Pawsey Centre heat exchanger performance gives this function approximately as

\[ \Delta T(T_{ex}) = 12.5 - 7T_{ex}, \]

And so for a fixed heat load \( W \), the volumetric flow rate \( Q \) must increase with \( T_{ex} \). Therefore, it is desirable to minimise thermal feedback so to keep the associated volumetric flow rate to a minimum.

In the absence of dispersion, \( \beta \) dictates whether thermal breakthrough occurs, where \( \beta_{\text{crit}} = 1 \) represents the bifurcation point at which injected fluid particles are re-extracted (\( \beta > 1 \)) or whether all such fluid particles are advected downstream (\( \beta < 1 \)). Given these scalings and henceforth dropping primes, the dimensionless thermal transport equation is

\[
\frac{\partial T_m}{\partial t} + (u + \beta v) \cdot \nabla T_m = \frac{1}{Pe} \nabla \cdot (\Gamma + I) \cdot \nabla T_m,
\]
where \( \Gamma = \frac{d_0}{D_m(1+r)} \) and \( u, v \) respectively are the dimensionless background and pumped velocity fields. As per (6) and (7), \( Q \) must increase with time if thermal feedback occurs, \( \beta \) must also increase and so a positive feedback loop arises which acts to accelerate thermal breakthrough.

For the subject GWC operation subject to a heat load of 3 MW, \( \beta \) turns out to be 1.30, and so thermal feedback does occur for the midpoint estimate of the regional Darcy flux of 3.5 cm/day. As such, thermal breakthrough occurs for the conventional GWC operation; however enhanced pumping schemes may be able to mitigate thermal breakthrough. The Peclet number under these conditions is \( Pe = 111.2 \), which means thermal transport is dominated by advection, and so analysis of thermal transport in terms of the relative background flow and pumping velocities is valid. We also find that the contribution of hydrodynamic dispersion (as quantified by \( \Gamma \)) is relatively minor except for the region immediate to the injection and extraction wells where the pore fluid velocities are higher.
3 Borefield Designs

A wide range of enhanced pumping methodologies were considered as a means to improve performance of the subject GWC operation, with two methodologies providing the highest impact. Both of these approaches were based on the philosophy of increasing the amount of heat rejected to the background regional flow, and whilst many of the other schemes considered were highly informative with respect to guidance of an optimal pumping technique, they are not reported here.

3.1 Two Doublets, Switched

The first methodology is based upon a transient pumping technique which alters the above ground plumbing of the GWC operation as illustrated in Figure 3-1 below. This methodology of switched pumping involves diagonally opposite wells to be connected as shown, where each diagonal pair is switched on and off, alternating over a time period $\tau$. To achieve the same total thermal load $W_0$, the thermal load for each well is doubled to $2W$, and so the attendant volumetric flow rate $Q$ is also doubled. This method of Subsurface Stirring acts to promote thermal transport into the background flow by increasing downstream flow at the inactive injection well, aided by doubling of the volumetric flow of the active pair. For this methodology, a blob of hot fluid forms at the active injection well, which upon switching tends to be swept downstream due to the increased downstream flow.

![Figure 3-1: Schematic of sequential switched pumping GWC operation](image)

Whilst this methodology does not avoid thermal breakthrough altogether, when $\tau$ is optimised the switched GWC operation does delay thermal breakthrough significantly, extending $t_b$ by 35.8% for the midpoint regional Darcy flux $q = 3.5$ cm/day. Although this improvement is significant for this particular value, over the range of estimated regional fluxes $q = 1$-6 cm/day, the performance fluctuates significantly. For $q = 4$ cm/day, the conventional GWC operation experiences thermal breakthrough whilst the switched case avoids breakthrough. Whilst this result is quite encouraging, for low values of $q \approx 1$-2 cm/day, the improvement given by switching diminishes significantly. As such, given the uncertainty in the magnitude of...
the background flow, it is desirable to consider other performance enhancement methodologies which generate significant enhancement of the GWC operation over the full range of estimated \( q \).

### 3.2 Two Doublets, Shielded

Another approach to enhancing GWC performance is to consider a steady shielding flow, which acts to retard feedback between the injection and extraction wells by an additional injection well as shown in Figure 3-2 below. The two additional shielding wells are plumbed in such a way that no additional heat is added to this loop, and the volumetric flow rate to each shielding well is \( \gamma Q \), where \( \gamma \) is an adjustable parameter which can be used to control the amount of shielding.

![Figure 3-2: Schematic of steady, shielded GWC operation](image)

The impact of shielding is shown in Figure 3-3 below, which depicts the separating streamlines for the shielded GWC flow for different values of \( \gamma \) (note only the upper streamlines are shown for clarity, and symmetry is assumed along the line of wells). As both the shielding well and conventional injection well pump fluid into the aquifer, a stagnation point occurs between these wells, and the fate of the separating streamlines emanating from this stagnation point transverse to the symmetry line determines whether thermal feedback occurs in the system. At \( \gamma = \gamma_{\text{crit}} \) this separating streamline undergoes a topological bifurcation, where for \( \gamma < \gamma_{\text{crit}} \) it terminates at the extraction well, and for \( \gamma > \gamma_{\text{crit}} \) it is swept downstream.
Accordingly, in the absence of thermal diffusion, heat emanating from the conventional injection well either reaches the extraction well or is swept downstream for $\gamma < \gamma_{\text{crit}}$ or $\gamma > \gamma_{\text{crit}}$, respectively. At the bifurcation point itself, all fluid from the shielded well reaches the extraction well and all fluid from the conventional injection well is swept downstream. This represents the most efficient situation where no additional pumping energy is wasted.

The methodology of flow shielding allows thermal feedback to be avoided for cases where $\beta > \beta_{\text{crit}}$, as long as the additional shielding flow satisfies $\gamma > \gamma_{\text{crit}}$. For $\beta > \beta_{\text{crit}}$, we find $\gamma_{\text{crit}}$ to be a monotonic increasing function of $\beta$ which scales close to linearly with $\beta$, and so for large $\beta$, pumping rates required to satisfy $\gamma > \gamma_{\text{crit}}$ are not feasible.

The most important practical limit is given by the volumetric extraction rate $Q(1+\gamma)$ at the extraction well, as there exists some limit $Q_{\text{max}}$ for which the aquifer cannot sustain the pressure drop associated with this flow rate. Early testing of the Mullaloo aquifer has only used extraction rates up to 28 L/s, and so the upper limit $Q_{\text{max}}$ is uncertain. To quantify the impact of this uncertainty we consider two limits of $Q_{\text{max}} = 45 \text{ L/s}$ and $Q_{\text{max}} = 60 \text{ L/s}$ (post-construction testing showed that 45 L/s was achievable). For both of these values across the range of $q = 1$-6 cm/day, the corresponding values of $\gamma$ span values both above and below $\gamma_{\text{crit}}$, and so thermal feedback (and hence thermal breakthrough) is avoided in some cases and not in others.
It must be noted that for $\gamma < \gamma_{crit}$, thermal feedback is still significantly retarded, as the proportion of fluid from the injection well which arrives at the extraction well is small, as per Figure 3-3. Accordingly, the amount of thermal feedback for $\gamma > \gamma_{crit}$ scales as $\gamma_{crit} - \gamma$. The means by which flow shielding is able to increase the pumping flow scale $\beta$ (and hence heat load) whilst avoiding thermal breakthrough is by significantly widening the off-centre separatrices (shown above the wells in Figure 3-3) which in turn widens the separating streamlines which propagate from upstream the background flow. This in turn means much larger amount of the upstream cold fluid is “focused” into the operational domain of the GWC system, and so much higher heat loads can be sustained than would otherwise be possible. A secondary benefit of such separatrix widening is that the downstream separating streamlines are also significantly widened, and so the thermal plume flowing downstream is significantly broader. For a fixed heat load, this corresponds to a significantly lower downstream plume temperature (as shall be shown) which reduces downstream environmental impacts.
4 Computational Results

To ascertain the impact of flow shielding upon the subject GWC operation, we executed a series of computational studies based upon the dimensionless 2D thermal transport model (8). The finite element package COMSOL 4.2a was used to model the GWC operation under both conventional and shielded modes across the range of regional Darcy fluxes $q = 1, 2, 3, 4, 5, 6$ cm/day and for flow shielding subject to the extraction limits $Q_{\text{max}} = 45$ L/s and 60 L/s, corresponding to $\gamma = 0.5$ and 1.0, respectively. The extraction temperature $T_{\text{ex}}$ profile as a function of time was calculated, and from this data the thermal breakthrough time $t_b$ and equilibrium temperature $T_\infty$ were determined.

The results are shown in Figure 4-1 to Figure 4-6, where the green lines depict the extraction temperature profiles for the conventional (unshielded) case, and the blue and red lines depict the profiles for the shielded cases subject to $Q_{\text{max}} = 45$ L/s and 60 L/s, respectively. The black line depicts the maximum extraction temperature $T_{\text{max}}$, and so thermal breakthrough occurs when $T_{\text{ex}}$ crosses this line.

![Figure 4-1: Extraction temperature profiles for $q = 1$ cm/day](image)

![Figure 4-2: Extraction temperature profiles for $q = 2$ cm/day](image)
Figure 4-3: Extraction temperature profiles for $q = 3$ cm/day

Figure 4-4: Extraction temperature profiles for $q = 4$ cm/day

Figure 4-5: Extraction temperature profiles for $q = 5$ cm/day
As shown, the impact of flow shielding is significant across all cases, where shielding acts to delay or avoid thermal breakthrough in all cases, and furthermore acts to reduce the equilibrium temperature throughout (if thermal breakthrough is ignored). As expected, the impact of flow shielding increases with $Q_{\text{max}}$, as more flow is available to promote shielding; however, for both values the impact of shielding is significant.
5 Discussion

The impact of flow shielding upon GWC operation in terms of breakthrough time and equilibrium temperature are summarised in Table 1 and Table 2, where “∞” denotes that thermal breakthrough occurs for the conventional case only, and “–” denotes that thermal breakthrough does not occur for both the conventional and shielded cases. From these results, it is clear that whilst thermal breakthrough cannot be avoided for \( q < 3 \text{ cm/day} \), flow shielding significantly extends the lifespan of the GWC operation, from an increase of 26% at \( q = 1 \text{ cm/day} \) to 642% at \( q = 3 \text{ cm/day} \). Although the range of enhancement is broad, it is anticipated that such extension of the lifespan shall have a significant impact upon the NPV of the GWC operation.

At greater values of \( q \), flow shielding is able to avoid thermal breakthrough altogether, and so the GWC operation can theoretically be run indefinitely. This case is expected to deliver significant economic impact. Although the conventional GWC operation can avoid thermal breakthrough for \( q = 5.6 \text{ cm/day} \), flow shielding has the major benefit of significantly lowering (66-96%) the equilibrium temperature as shown in Table 2. Such a reduction in the equilibrium temperature builds significant robustness against thermal breakthrough in terms of parametric uncertainty, but also reduces the pumping load by reducing \( Q \) as per equations (6) and (7), where an increase in \( T_{ex} \) significantly increases the required flow rate to maintain a fixed heat load. In general, reduction of \( T_{ex} \) corresponds to a more efficient GWC operation.

As such, flow shielding is able to deliver significant benefits to the subject GWC operation across all values of \( q, Q_{\text{max}} \), and it is anticipated that these benefits translate into significant economic outcomes. Although the shielded GWC system involves additional infrastructure through 2 additional wells and associated piping, the increase in pumping energy required to drive the shielding flow is offset by the reduction in the extraction temperature \( T_{ex} \), which in turn reduces the required volumetric flow rate \( Q \). As such, flow shielding results in lower operational costs than conventional GWC systems, and furthermore delivers increased performance in terms of both thermal breakthrough and equilibrium temperature. Another significant benefit of flow shielding (not quantified in this report) is the reduction in temperature of the downstream thermal plume due to broadening of the flow separatrices and associated separating streamlines which is expected to reduce downstream environmental impacts. Whilst it remains to translate these operational impacts into direct economic outcomes, the magnitudes of the enhancements detailed herein provide significant scope for enhanced value of GWC via flow shielding.

<table>
<thead>
<tr>
<th>( Q_{\text{max}}, q )</th>
<th>1 cm/day</th>
<th>2 cm/day</th>
<th>3 cm/day</th>
<th>4 cm/day</th>
<th>5 cm/day</th>
<th>6 cm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 L/s</td>
<td>26.3%</td>
<td>56.8%</td>
<td>102.1%</td>
<td>∞</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>60 L/s</td>
<td>67.3%</td>
<td>147.8%</td>
<td>642.0%</td>
<td>∞</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Change in breakthrough time \( t_b \) for shielded versus conventional GWC operation for various \( Q_{\text{max}}, q \)

<table>
<thead>
<tr>
<th>( Q_{\text{max}}, q )</th>
<th>1 cm/day</th>
<th>2 cm/day</th>
<th>3 cm/day</th>
<th>4 cm/day</th>
<th>5 cm/day</th>
<th>6 cm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 L/s</td>
<td>-0.7%</td>
<td>-4.2%</td>
<td>-13.2%</td>
<td>-30.8%</td>
<td>-66.6%</td>
<td>-84.1%</td>
</tr>
<tr>
<td>60 L/s</td>
<td>-1.3%</td>
<td>-8.6%</td>
<td>-28.3%</td>
<td>-69.4%</td>
<td>-88.7%</td>
<td>-96.2%</td>
</tr>
</tbody>
</table>

Table 2: Change in equilibrium temperature \( T_{\infty} \) for shielded versus conventional GWC operation for various \( Q_{\text{max}}, q \)
6 Conclusions

Groundwater cooling is an appropriate and sustainable heat rejection technology for the Pawsey Supercomputer Centre. It makes use of the local Mullaloo aquifer system which is able to provide cool groundwater at high and reliable flow rates, and is readily able to accept water warmed by excess heat.

Design of a groundwater cooling system requires conceptual analysis of hydraulic and hydrothermal processes. The design phase considers the impacts of pumping activities and likely migration and fate of emplaced thermal distributions. This report has considered a range of engineered pumping system designs and has identified a pumping layout that provides maximum longevity and flexibility of thermal performance with minimal capital requirements for borefield construction.

Properties of the Pawsey site (Mullaloo hydrogeology and spatial scale) reduce the viability of subsurface stirring or other transient schemes for thermal efficiency management. Flow net analysis has shown that shielding wells provide a useful buffer against thermal breakthrough which promotes longevity of heat rejection. Background groundwater flows tend to counteract thermal breakthrough, with the net result that thermal performance of a groundwater cooling system can expressed in terms of shielding and groundwater flux quantities. As noted in Chapter 2, the background groundwater flux is not well constrained by experimental data at the Pawsey, so the flux term is essentially an unknown for the system design process.

Hydrothermal simulations indicate that shielded configurations reduce or delay thermal breakthroughs and hence provide greater energy efficiencies for groundwater cooling systems as compared to unshielded configurations, but at the capital expense of extra injection wells and pipe runs.

Based on the findings above it is recommended that the Pawsey groundwater cooling system be designed using a twin-doublet layout with two extra shielding wells (6 wells in total). This will provide flexibility in managing the thermal breakthrough performance of the system, and will also provide scope for research assessments of the Mullaloo Formation hydrogeology and system geothermics.
References


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