Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

The CSIRO Groundwater Cooling Project – Cooling Australia's Latest Supercomputer with Groundwater

Thomas Poulet[1], Peter Schaubs[1], Praveen Kumar Rachakonda[1], Grant Douglas[2], Daniel Lester[3], Guy Metcalfe[4], Heather A. Sheldon[1], Rebecca Tung[1,5], Lynn B. Reid[6,7], Klaus Regenauer-Lieb[1, 8], Mike Trefry[2,8]

[1]CSIRO Earth Science and Resource Engineering, Australia; [2]CSIRO Land and Water, Australia; [3]CSIRO Mathematics, Informatics and Statistics, Australia; [4]CSIRO Materials Science and Engineering, Australia; [5]School of Science, Curtin University, Australia; [6]School of Environmental System Engineering, the University of Western Australia; [7]CDM Smith, Perth, Australia; [8]School of Earth and Environment, the University of Western Australia

Thomas.poulet@csiro.au

Keywords: Heat sink, groundwater cooling

ABSTRACT

The CSIRO has designed and implemented a geothermal solution using ambient temperature groundwater to cool the recently built Pawsey Supercomputer Centre in Kensington, Western Australia. The corresponding groundwater cooling (GWC) project has developed the system which runs by pumping cool water (~21°C) from the Mullaloo aquifer located approximately 35 to 120 m depth, through an above-ground heat exchanger to cool the supercomputer. The warmed water (up to a maximum of ~31°C) is then reinjected back into the same aquifer, slightly downstream, resulting in no net consumption of water. Two warm water injection boreholes are separated from two cold extraction wells by approximately 340 m. An additional two boreholes are placed in between the injector pair and the extractor pair to potentially serve as a shield by reinjecting cold water to delay thermal breakthrough. The requirements and optimal usage of this shielding functionality is one of the research questions the GWC project will be investigating in the coming years. Nine monitoring wells located in close proximity to the site have been equipped with sondes to collect temperature, pH and other water quality data. These data are in part used to calibrate numerical simulations to help quantify uncertainty, calibrated with various measurements, including real time data as well as regular manual sample analyses. The repository for these data is maintained by CSIRO and partly available to the research community through web portals.

Numerical simulations are performed using various codes, including Feflow (Diersch, 2014; Trefry and Muffels, 2007) and MOOSE (Gaston et al., 2009), to model the performance of the GWC system. The GWC system generates a thermal plume in the aquifer which diffuses away from the injection wells and moves westwards with the groundwater flow. Simulation results show that the effects of the GWC system on the environment were very low in the configuration used for the first year of operation. Various scenarios were investigated to understand the impact of the system on water temperature and drawdown around the site under different configurations. Results suggest a minimal impact with drawdown levels off-site less than 0.8 m and recovering to less than 0.1 m within a year after the cessation of pumping. For a 2.5 MWth system, the time to thermal breakthrough ranges from 3.7 to 4.7 years for a 0.1°C temperature increase at the production wells, and from 6.1 to 8.0 years for a 1°C temperature increase at the production wells. The shielding strategy using the cold reinjection wells was found to be effective at delaying thermal breakthrough.

1. INTRODUCTION

Perth, in Western Australia, is a fast growing city with 1.9 million inhabitants and over 3% annual growth rate in population. At the same time, the natural fresh water resources have declined by a factor of three over the last 30 years. Traditional cooling technologies used in the dry climate employ cooling towers, which use significant amounts of fresh water via evaporation and rejection of waste water. Another important aspect is that cooling towers do not operate effectively at a critical wet bulb temperature of 22°C or higher, which is reached more frequently in recent years due to tropical incursions. Therefore, cooling towers can be ineffective in Perth for several hours on at least 30 days during summer.

The CSIRO Groundwater Cooling (GWC) project has been designed to address these critical problems to cool the Pawsey Centre, Australia's latest supercomputer, with ambient temperature groundwater. The Pawsey Centre is located near the Australian Resources Research Centre (ARRC) in Kensington, Western Australia, above a shallow aquifer, the Mullaloo Aquifer. The requirement of 21°C water therefore makes this an ideal application for groundwater cooling. The GWC system was originally designed based on an estimate of 2.4 MWth (MegaWatts thermal) maximum load produced by the full-scale operation of the Pawsey Centre and was assumed to operate for 5-10 years. The concept consists of pumping cool water (~21°C) from an aquifer located approximately 35 to 120 m depth, through an above-ground heat exchanger to cool the supercomputer. The heated water (up to a maximum of ~31°C) is then reinjected back into the same aquifer, slightly downstream, resulting in no net consumption of water.

The injection and extraction wells for the GWC scheme are screened in the Mullaloo Aquifer, which comprises the Mullaloo Sandstone Member of the Kings Park Formation (Early Tertiary). The ARRC site is situated on an area of land bounded by the Swan River to the north, the Canning River to the south, and the Swan/Canning Rivers to the west (Figure 1). The Superficial Aquifer discharges into the river system, and is recharged from rainfall. The Mullaloo Aquifer is recharged from the Superficial Aquifer to the east and northeast, and is believed to discharge westward offshore into the Superficial Aquifer (Davidson, 1995).

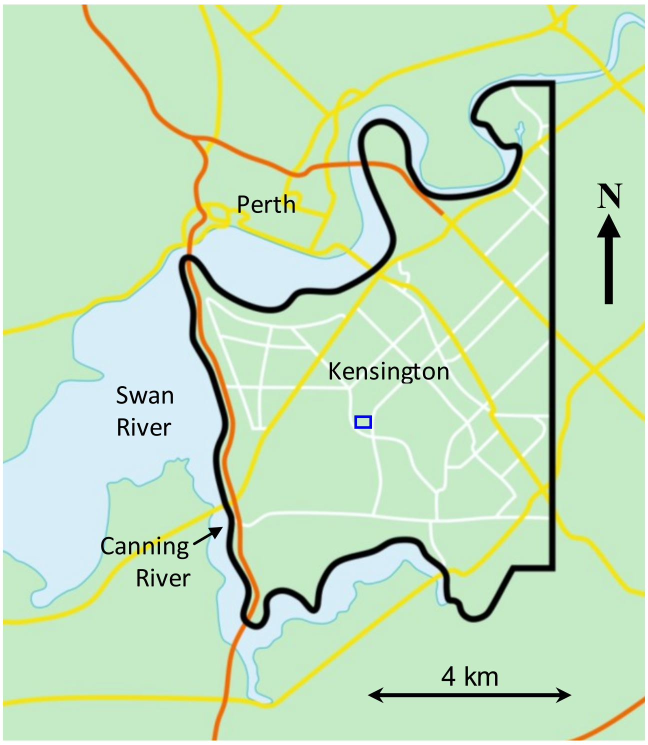

Figure 1: Location of the ARRC/Pawsey Supercomputer Centre, south of Perth, Western Australia. Blue box indicates location of the GWC system. Black outline indicates boundary of hydrothermal simulations.

2. SYSTEM MONITORING

Figure 2 shows the layout of pumping wells and monitoring wells for the GWC scheme. The system comprises two production wells on the east side (~21°C), two injection wells on the west side (up to ~31°C) and two "shielding" wells in the centre (~21°C). The purpose of the shielding wells is to reinject some cool water from the production wells, with the aim of delaying thermal breakthrough using hydrological and thermal shielding effects.

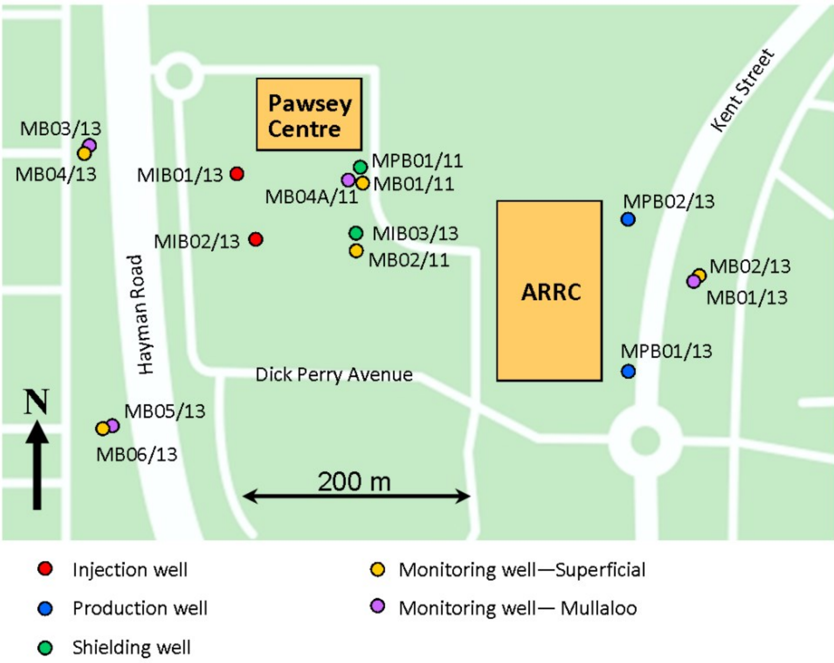

Figure 2: Site map showing locations of GWC and monitoring wells. See blue box in Figure 1 for location of the site.

Those six wells, along with nine surrounding monitoring wells also shown in Figure 2, have been equipped with monitoring devices to log in real time the temperature, turbidity, pH, electrical conductivity, oxidation-reduction (redox) potential and dissolved oxygen concentration. A building management system (BMS) was created to centralise all information at the Pawsey Centre, including this water quality data but also all engineering information like the system's flow rates, pressures etc. All data from the BMS is stored in a repository which will be progressively made available to the research community through web services. An official website (www.groundwatercooling.csiro.au) was launched in October 2013 and displays some live information about the GWC system. A "CSIRO Groundwater Cooling" mobile phone application also exists for iPhone and Android devices.

3. HYDROTHERMAL MODELING

An original feasibility study of the GWC system was based on a simplified representation of the geological structure at the ARRC site. This first study had a slightly different configuration than the one finally implemented as it was including three production wells. The results of that study have been reported by Trefry et al. (2014) and Sheldon et al. (2014). More numerical simulations have since been conducted in order to understand the system in its final configuration and assess the GWC efficiency and ecological impact based on all geological and geophysical information available. Those numerical models will be continually refined and calibrated using all data logged by the monitoring system as it becomes available.

3.1 Geological model

The geological area (Figure 3) modelled encompasses the Superficial Aquifer, Mullaloo Sandstone Member (comprising the Mullaloo Aquitard and Mullaloo Aquifer), Kings Park Formation and Osborne Formation. The bottom of the model represents the top of the Leederville Formation. The stratigraphic and hydrogeological units are listed in Table 1. The top of the model represents the topographic surface defined by a Digital Elevation Model (DEM).

Table 1: Hydrogeological units in the model.

Hydrogeological unit	Stratigraphic units	Hydrogeologic type
Superficial Aquifer	Bassendan Sand, Tamala Limestone	Aquifer
Mullaloo Aquitard	Shales of the Mullaloo Sandstone Member	Aquitard
Mullaloo Aquifer	Mullaloo Sandstone Member	Aquifer
Kings Park Formation	Kings Park Formation	Aquitard
Osborne Formation	Kardinya Shale, Henley Sandstone	Aquifer

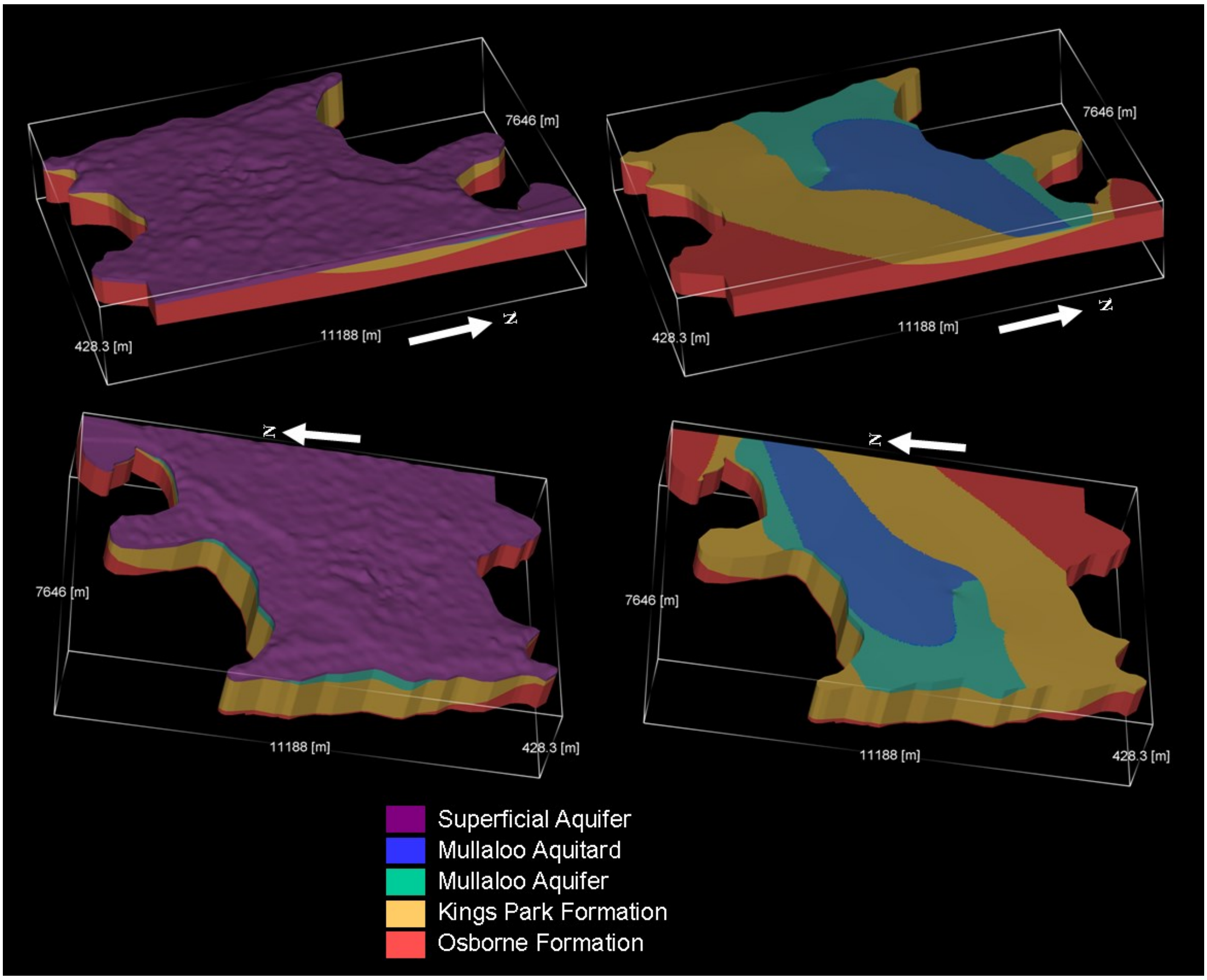

Figure 3: Different views of the 3D structure of the model. Left: complete model. Right: Model with Superficial Aquifer removed. Top: view from the East. Bottom: view from the West.

3.2 Model construction, discretization and calibration

All geological surfaces were created in Paradigm's SKUA package and exported from SKUA to an ASCII format to be imported in the FEFLOW modelling package (Diersch, 2014; Trefry and Muffels, 2007). In the FEFLOW model, the top surface was created from a DEM and the remaining surfaces/layers were created from the surfaces exported from SKUA. The FEFLOW model comprises 20 layers with a total of 771,300 triangular prismatic elements with mesh refinement around the injection/production well locations at the ARRC site.

3.2.1 Boundary conditions

The following boundary conditions were applied at the sides of the model in the Superficial and Mullaloo Aquifers:

- A phreatic boundary condition was applied at the top of the model, allowing the water table to move within the Superficial Aquifer.
- A fixed head boundary condition of 0.5 m in the top two slices of the Superficial Aquifer, at nodes intersecting the Swan and Canning Rivers.
- A fixed head boundary condition of 13 m where the Mullaloo Aquifer intersects the eastern edge of the model domain. This water level was determined by extrapolating the measured hydraulic gradient to the east.
- A fluid-transfer ("third type") boundary condition where the Mullaloo Aquifer intersects the western edge of the model domain. A reference head of 0 m was assumed to exist at a distance of 1 km west of the model boundary. The in/out-transfer conductance was assigned by dividing the horizontal hydraulic conductivity of the aquifer by 1000 m.
- A fluid-transfer ("third type") boundary condition along the eastern boundary of the Superficial Aquifer. The reference heads were interpolated from 2003 groundwater elevation contours published by the Western Australian Department of Water in the Perth Groundwater Atlas along a line located 1 km east of the model boundary.
- The top of the model was assigned a fixed temperature and the bottom was assigned a fixed heat flux. The values of the fixed temperature and fixed heat flux were determined during thermal calibration

3.2.2 Recharge

Rainfall recharge was applied to the top of the model with values determined from vertical flux modeling that was carried out for the Perth Regional Aquifer Modeling System (PRAMS) (Xu et al., 2009). Using this PRAMS data as a guide, the recharge rate was allowed to vary based on soil type and geomorphology, with three areas being defined and the recharge rates for these areas determined during hydrogeological calibration

3.2.3 Hydraulic and thermal properties

All model units were assigned constant property values. Hydraulic conductivities were assumed to be isotropic in the horizontal plane and have a ratio of 10:1 (horizontal:vertical). Initial property values were determined from a variety of sources and were adjusted through a 2-stage calibration process, involving hydrogeological and thermal calibrations. The final property values are listed in Tables 2 and 3. Specific storage and specific yield values were obtained from the H3 hydrogeological assessment conducted by Rockwater Pty (2012), who conducted a transient calibration of their SEAWAT model of the GWC system using seasonally varying rainfall and recharge patterns for the period 1995 to 2011.

Table 2: Final property values after calibration

	Horizontal hydraulic	**Specific storage**	**Specific yield**	**Porosity (%)**	**Thermal conductivity of**	**Specific heat capacity of solid (10^6 J/m^3/K)**
Superficial Tamala	15	0.001	0.2	25	3.75	2.1
Superficial Bassendean	18	0.001	0.2	25	3.75	2.1
Mullaloo Aquitard	0.29	10^{-5}	N/A	5	2.9	2.3
Mullaloo Aquifer	11	0.0005	N/A	25	4	2.05
Kings Park Formation	0.1	0.0001	N/A	5	2.25	2.3
Osborne Formation	2	0.0001	N/A	20	3.2	2.05

Table 3: Thermal properties of pore fluid

Property	**Value**
Longitudinal thermal dispersivity	1 m
Transverse thermal dispersivity	0.1 m
Specific heat capacity of fluid	4.185 x 10^6 J/m^3/K
Thermal conductivity of fluid	0.6 W/m/K
Thermal expansion coefficient of fluid	0.00021 /K

3.2.4 Calibration

Table 4 lists the wells that were used for hydrogeological calibration, whose locations are shown on Figure 5, along with the error of the calibrated model relative to the end-of-winter 2011 water levels in these wells. End-of-summer water levels are also shown (where available) to give an indication of the annual range in these wells. Well names starting with "M" are on the Pawsey Centre site. The modeled water levels were compared on the slice in the FEFLOW model that was closest to the mid screen depth of each well.

The largest error occurs in well SCC23/08 (error = -1.82 m), however this is also the furthest well from the GWC site (see Fig. 5). Errors are small in wells located at or close to the Pawsey Centre site (well names starting with M in Table 4; see Fig. 5). It should be noted that very little is known about the groundwater flow regime in the Mullaloo Aquifer due to the very small number of wells in the model area with water level measurements in this aquifer. The accuracy of the hydrogeological calibration is therefore limited by this lack of data.

Table 4: Wells used for hydrogeological calibration. Water levels are shown at end-of-winter (EOW) 2011. AHD = Australian Height Datum. DoW = Department of Water. Error indicates difference between modeled and measured head.

Name	Aquifer	2011 EOW (mAHD)	Error (m)
149	Superficial	10.62	-1.20
2025A	Superficial	4.22	-0.01
2729	Superficial	8.37	-0.20
AM40B	Mullaloo	5.21	-0.85
SCC 23/08	Superficial	7.98	-1.82
MB01	Superficial	4.31	0.22
MB02	Superficial	4.30	0.20
MB03	Superficial	4.27	0.15
MB04A	Mullaloo	4.19	0.21
MPB01	Mullaloo	4.15	0.24

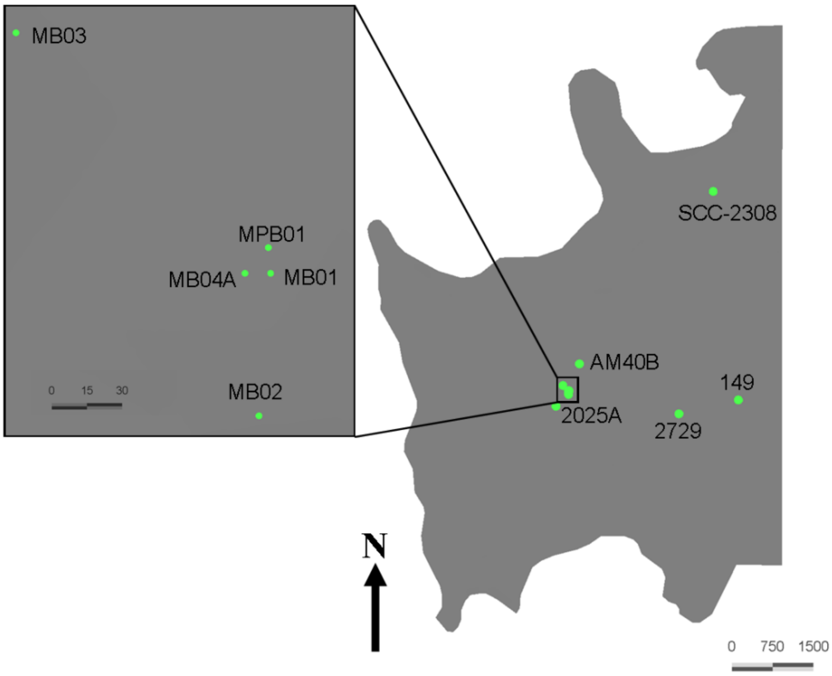

Figure 4: Location of wells used for hydrogeological calibration (see Table 4). Scale in m.

3.3 Simulation strategy

Starting from the steady-state conditions obtained during model calibration, pumping in the GWC scheme wells was simulated for a period of 10 years. Temperature and hydraulic head were monitored at the following well locations:

- 3 groundwater extraction wells in the Mullaloo Aquifer
- 176 groundwater extraction wells in the Superficial Aquifer
- 9 monitoring well locations around the ARRC site (5 in the Superficial Aquifer and 4 in the Mullaloo Aquifer)

The following parameters were varied to investigate their impact on the GWC scheme:

- Lithology of the ARRC site (e.g. presence or absence of the Mullaloo Aquitard),
- System capacity (0.5 or 2.5 MW, spanning the range of expected operating conditions),
- Pumping rates (from 6 to 45 L/s per production well, from 0 to 15 L/s per shielding well and from 6 to 30 L/s per injection well),
- Use of shielding wells.

Injection of warm water creates a thermal plume in the Mullaloo Aquifer. Figure 6 shows the shape of the thermal plume near the base of the Mullaloo Aquifer. The thermal effect of the reinjected heat is limited to a small area covering a few hundred meters in diameter, confirming the preliminary results from the feasibility study and reinforcing the prediction that the GWC system can safely be operated for the planned operating timeframe of 5-10 years without impacting the marine wildlife in the river or the Kensington bushland, an area of native vegetation located approximately 500 m northeast of the ARRC site.

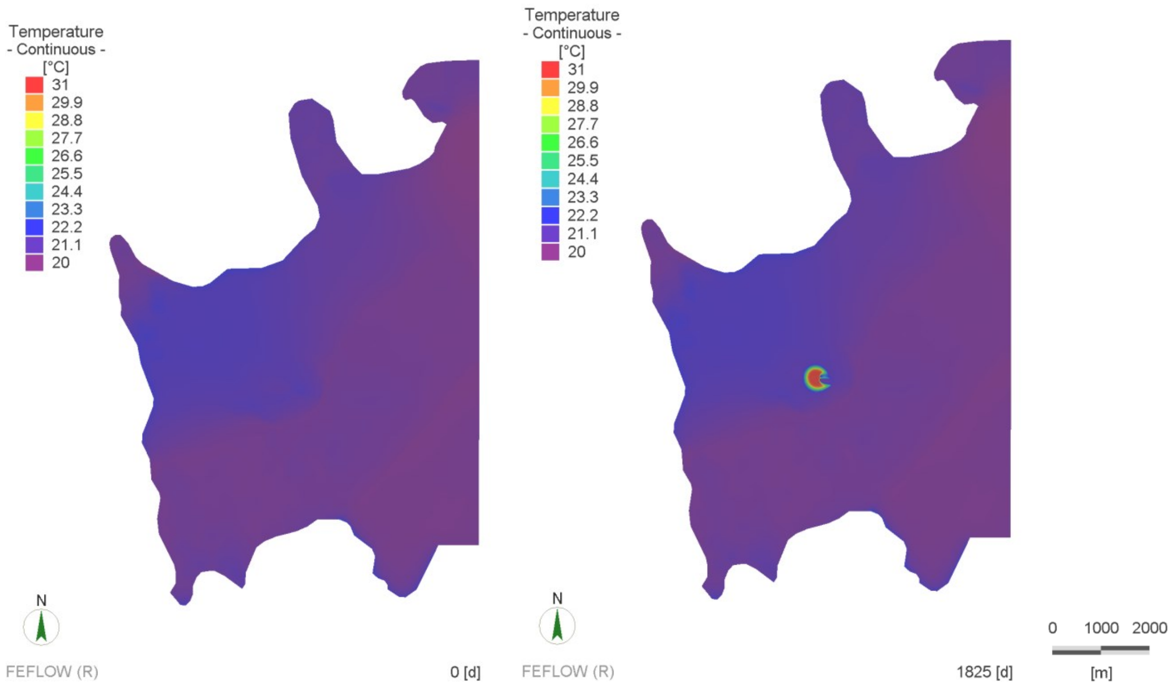

Figure 5: Temperature in the Mullaloo Aquifer before implementation of the GWC system (left) and after 5 years using the GWC system with a thermal load of 2.5 MWth (right).

The water pressure results indicate no major impact on aquifer water levels for neighboring residents, with a drawdown around the extraction wells and elevation of the water table on the injection side (Figure 6), as expected from a system running in a balanced (i.e. no net water loss) loop. Water levels in existing groundwater wells dropped by less than 0.8 m and recovered to within 0.1 m of their initial values within a year after cessation of pumping.

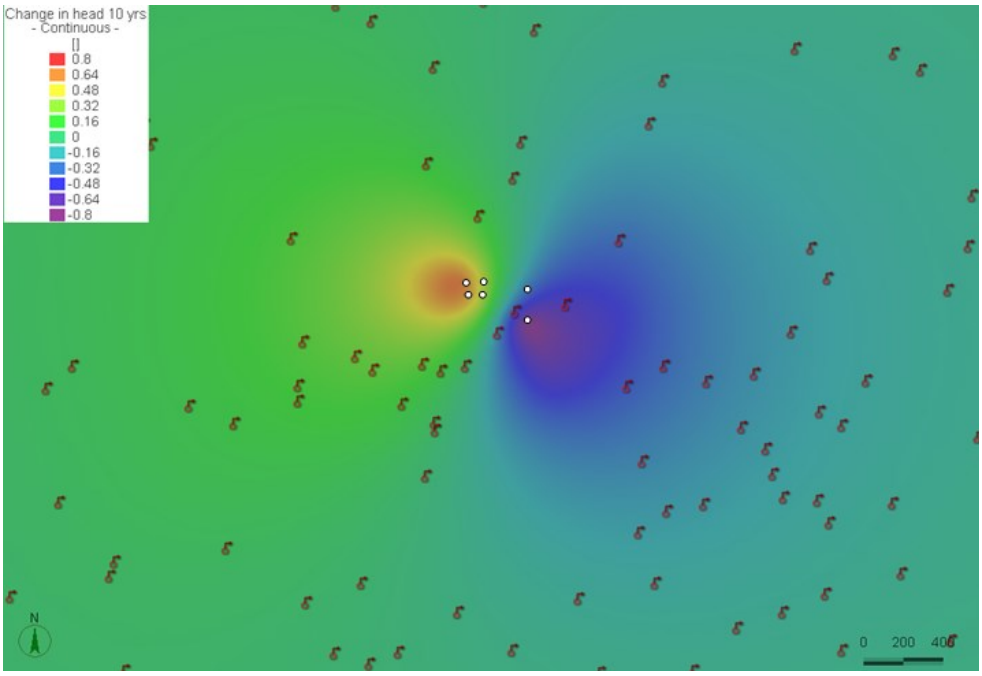

Figure 6: Change in hydraulic head (m) in the Superficial Aquifer after 10 years of pumping. Markers indicate existing groundwater extraction wells, white dots indicate GWC wells. Scale in m.

3.4 Uncertainty analysis

Due to the lack of deep wells away from the immediate project area there is some geologic uncertainty regarding the extent of the Mullaloo Aquitard below the Superficial Aquifer and the dimensions of the Mullaloo Aquifer itself. Geologic logging carried out during the construction of production, injection and monitoring wells for the project uncovered a number of clay lenses. The effect of these low permeability regions has not been incorporated into the models as yet and their effect on flow patterns and the time to thermal breakthrough at the production wells is not understood. An uncertainty analysis is underway which will assess these geologic variables as the hydraulic and thermal properties of Mullaloo Aquitard, Mullaloo Aquifer, Kings Park Formation and Osborne Formation.

CONCLUSIONS

The operation of the GWC system started in 2013 and real time data is now being collected at the production, injection and shielding wells and nine monitoring wells to better understand the behavior of the system. An official website was launched in October 2013 to present the project and make some of the live data available. Web services are now being built to distribute to researchers and the public all data from the repository.

As the system is now in production mode, a research program based on numerical modeling is investigating the behavior of the system, refining the underlying hydrogeological model based on geophysical results and the real time tracking of all parameters from the monitoring system. This work has only just begun and the wealth of data being collected promises some exciting research possibilities in low-temperature geothermics and facilities integration. Preliminary results indicate that the GWC system has had no detrimental effect on the surrounding environment. It also has minimum consequences on the groundwater levels as the system functions in a closed loop. This is a major advantage of the system over traditional technology using cooling towers, which evaporate large amounts of fresh water. The technology concept, if deployed more widely, has the potential to replace cooling towers in commercial and residential buildings in the Perth Basin.

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