Flow and heat modelling of a Hot Sedimentary Aquifer (HSA) for direct-use geothermal heat production in the Perth urban area, Western Australia (WA)

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The deep confined aquifers of the Perth basin have been explored for water supply and heat production since the beginning of the 20th century. The availability of warm water was an additional asset and was very popular with laundries and bathing services. Currently, six geothermal bores use warm water from the Yarragadee confined aquifer for heating swimming pools and buildings and several new bores are proposed to be drilled. The cooled formation groundwater is injected into the same aquifer for environmental reasons.

Following the recent success of the release of geothermal acreage for geothermal exploration in WA, HSA direct-use is getting more recognition and support, and the number of projects is likely to increase because the technology is now more advanced, low-risk, and has relatively low $C0_2$ emissions and at low cost. Typical savings after 20 years of production can be as high as $6,000,000, with payback in about 5 years and $C0_2$ savings of up to 800 tonnes/annum.

A key concern for HSA future development in Perth is sustainability and management. This will be achieved through a more comprehensive assessment of HSA geothermal resources. The latter will also require a good estimation of the longevity of existing and future direct-use HSA systems.

In this paper we discuss how simple numerical modelling of temperature and fluid flow using SEAWAT software and the "equivalent solute" approach allows for more accurate evaluations of geothermal resources and sustainability. This is an interesting management tool for existing and future HSA projects in Perth and is an alternative approach compared to the classical interpolation of measured temperatures between bores. Above all, the scope of this paper is to raise questions and discuss the future management of existing geothermal bores in the Perth area and to assist geothermal explorers to develop shallow HSA direct-use projects in the Perth area.

Keywords: Western Australia, Perth, Hot Sedimentary Aquifer, HSA, geothermal, injection, direct-use, heat transport modelling, SEAWAT.

HSA direct-use in the central Perth basin

Geological setting

The Perth urban area is located on the Swan Coastal Plain and is underlain by the Perth sedimentary Basin. The basin is comprised of a series of sub-basins, troughs, shelves and ridges containing predominantly Early Permian to Late Cretaceous sedimentary sequences that are up to 15 km thick.

The central Perth basin comprises a thick sequence of sedimentary rock, of which the upper 3,000 m of Quaternary to Jurassic age are relevant for geothermal projects targeting low temperature HSA systems.

Existing geothermal bores have been drilled to depths up to 1,000 m in Perth; which have targeted aquifers within the Yarragadee Formation and/or the overlying Gage Formation. The Yarragadee Formation consists of laterally discontinuous interbedded sandstones, siltstones and shales and is inferred to be about 1,350 to 1,500 m thick in the Perth urban area.

Hydrogeology

The interbedded sandstones of the Yarragadee Formation form the Yarragadee confined aquifer and are hydraulically connected with interbedded sandstone aquifers of the Gage Formation.

The hydraulic properties of the Yarragadee aquifer vary with location. In the study area, the discontinuous nature of the sandstone beds has lowered the average horizontal hydraulic conductivity to about 3 m/day. Hydraulic conductivity can locally be higher as indicated by pumping tests.

The average rate of groundwater flow through the Yarragadee aquifer is about 0.9 m/year, confirming the very slow rate of flow indicated by the $_{14}C$ dating of the groundwater (Thorpe and Davidson, 1991). It is likely that most of the groundwater flow occurs in the top part of the aquifer, in about the top 500 m. Beneath this depth, the groundwater flow is likely to be lower as indicated by higher salinities (Davidson and Yu, 2005).

HSA Resource Assessment: Temperature, Heat in Place, Bore Deliverability and Recoverable Heat

Using a typical "stored heat" method as applied by Beardsmore et al (2009), the HSA geothermal resource for a specific direct-use application can be estimated. However, the authors of this paper emphasize that the Stored Heat calculated below is given as an element of comparison and is not to be used for other purposes.

For the purpose of reservoir volume estimations, we assume a minimum cut-off temperature of 40°C for direct-use projects, and an injection temperature of 30°C. The base of the Yarragadee aquifer is inferred to be at about 70.6°C. This yields a reservoir volume of 126 km^3 below the 100km^2 modelled area where most of the geothermal bores operate. The average reservoir temperature is 55.3°C. Using calculated values of heat capacity for the fluid and solid, an average porosity of 0.15, we estimate 7,926 PetaJoules (PJ=10^{15} Joules) of heat in the modelled reservoir. Should other uses be considered, the cut-off temperature, injection temperature and inferred resource may differ.

The deliverable thermal energy for a typical direct-use geothermal bore is a function of source temperature, heat exchanger efficiency, flow-rate and injection temperature. Typical values of 25 L/s and 12°C temperature drop can provide a deliverable thermal power of 1,113 kilowatt (kW_{th}) and recoverable heat energy of 0.04 PJ/annum or 9747 Megawatts hours/annum (MWh_{th}).

Hence, in first estimation, the Yarragadee aquifer appears to be able to sustain a generalised use of HSA for heating buildings and swimming pools among other uses in the Perth urban area for many years. However, this may only be possible if there is no (or very little) thermal contamination between the geothermal and injection bores. This can be predicted using a numerical model of groundwater flow and heat transport. This is the general purpose of this study.

HSA modelling: Initial temperature distribution in the aquifer (Conductive model)

3D structural model of a selected area of the Perth basin

Data from Davidson and Yu (2005), and proprietary data from Rockwater Pty Ltd have been used to create a detailed structural model of an area of about 100 km^2 of the central Perth Basin where most of the geothermal bores operate. The model comprises seven geological formations: superficial sediments (TQ), Tertiary alluvial (Tk), Cretaceous sediments (Kco, Kwl, Kws and Kwg) and Jurassic sediments (Jy).

Geostatistical methods have been used to infer formation top and bottom surfaces. Additionally, formation coverages specifying the extent of each geological formation (derived from contours in Davidson and Yu (2005) and modified in areas where new data had become available) have been used to constrain the model.

Purely conductive heat flow 1D modelling

A common practice in the geothermal industry, when modelling steady state temperature conditions of HSA geothermal reservoirs, is to assume purely conductive heat transfer and constant heat conductivity within each of the geological layers. This is referred as conductive heat flow 1D modelling and is considered more accurate than the classical approach of average gradient as it accounts for thermal resistance variations within the lithological column. This has been demonstrated in several studies including Cooper and Beardsmore (1998).

The conductive heat flow 1D assumption fails when heat convection occurs such as in areas of high groundwater velocity such as faults, bores or when significant heterogeneity occurs. However, purely conductive models have proven to satisfactorily represent temperature conditions in the Perth Basin and will be used to provide initial temperatures for a more comprehensive conductive and convective numerical model.

In a conductive heat regime the temperature (T) at the bottom of a geological layer, is equal to the temperature at the top of the layer (T_0) plus the product of Heat Flow (Q) and thermal resistance of the geological layer (R) (where the thermal resistance equals the thickness of the layer divided by the average thermal conductivity).

Consequently, the occurrence of prospective geothermally warmed groundwater in sedimentary aquifers results from sufficiently low conductivity (high thermal resistance) of the sedimentary cover combined with high flow of heat from the centre of the Earth. Heat Flow (Q) is a function of the heat generated within the crust by the decay of radiogenic minerals plus heat conducted from the mantle. A commonly accepted value, derived from nearby temperature logs for the modelled area is 74 mW/m^2.

Conceptual model

In order to represent the temperature distribution in the basin, several physical properties and boundary conditions have to be estimated and a so called conceptual model must be constructed. For each modelled stratigraphic layer, it is assumed that the lithology and physical properties are the same throughout. Measured thermal conductivities are available for the formations of the Perth basin (Chopra and Holgate, 2008) and have been modified for the purpose of the numerical model by a classical trial and error method during the calibration of the model. For most of the geological formations, the modelled value is close to the calculated value. However, modelled and measured heat conductivity values were found to differ for some geological formations. It is believed that it is due to lithological variations within those formations and variation of the physical properties with depth.

Table 1: Heat conductivity values (W/m°C) of geological formations in the Perth Basin

Geological Formation	Modelled	Measured at 30°C
TQ	1.5	1.42
Tk	2.20	No data
Kco	2.30 to 2.50	No data
Kwl	1.70 to 2.50	2.56
Kws	1.50	1.71 to 1.72
Kwg	2.55 to 2.60	1.71 to 2.20
Jy	3.05 to 3.20	2.30 to 4.31

Method and boundary conditions

The thickness of each geological formation at given coordinates have been extracted and used together with heat conductivity properties for these layers, to calculate thermal resistances. Assuming a constant surface temperature of 19.5°C at the upper boundary (taken as real mean air value measured at the Perth airport plus 1 °C to account for thermal insulation of rocks) and using the thermal resistance values calculated above and the assumed constant heat flow of 74 mW/m^2, it was possible to predict the temperature distribution within the Yarragadee aquifer.

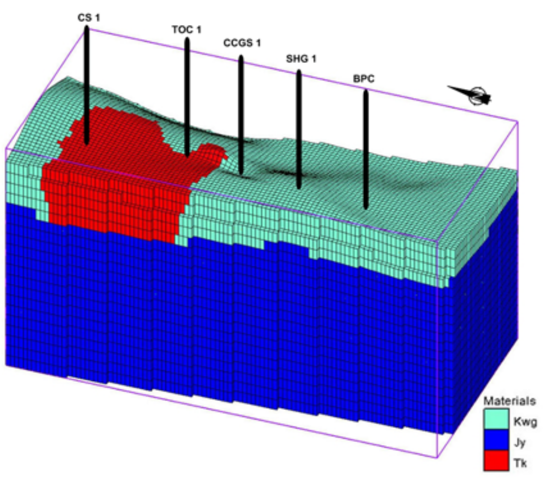

Fig. 1: simplified 3D structural model of the modelled area with geological formations considered in this study and approximate locations of geothermal production bores

CS: Challenge Stadium; TOC:Town Of Claremont;
CCGS: ChristChurch Grammar School;
SHG: St Hilda Geothermal, BPC: Bicton Polo Club.

HSA modelling: Initial temperature distribution in the aquifer (uncoupled Conductive and Convective model)

3D structural model of a selected area of the Perth basin

The same data as before are used but the structural model is limited to the Yarragadee aquifer (Fig. 1).

All layers overlying the Gage Formation are not modelled, apart from the portion of Kings Park Formation that has eroded the Gage and Yarragadee Formations and which is likely to influence groundwater flow and heat transport.

Heat transport modelling using the “equivalent solute” approach and the numerical code SEAWAT

SEAWAT is a standard finite-difference solute code included in the state-of-the-art modelling software Visual Modflow Pro.

Due to the similarities between heat and solute transport, standard solute codes such as SEAWAT can be used to represent heat transport and variables for SEAWAT solute transport simulator can be reinterpreted for heat transport. This has been demonstrated in several studies including Langevin et al (2008). More detailed information on using solute transport simulation for heat transport modelling can be found in Hecht-Mendez et al (2009). Additional information specific to the use of the SEAWAT code for heat transport is available in Ma and Zheng (2010).

In addition, for this study, SEAWAT has been evaluated against analytical results developed for geothermal and injection bores (doublet) and the results were comparable. The analytical solution has been developed by Gringarten and Sauty (1976) to predict the temperature evolution at HSA geothermal production bores used for geothermal urban heating in the Paris basin.

Conceptual model

As groundwater flow needs to be considered when undertaking conductive and convective geothermal modelling, a numerical code had to be used. For the present work, SEAWAT is used. The previously created 3D structural model is imported into SEAWAT and extrapolated to a finite difference 3D grid where the flow and heat transport equations are solved.

Horizontal cell size varies from 140 m to 5 m near the bores and is about 25 m in vertical. Attention has been given to keep aspect ratio (ratio between cell size along x and z and y and z respectively) less than 6.

The calibrated thermal conductivity for Kings Park, Gage and Yarragadee Formations are assigned to the corresponding cells and set constant for each formation.

Hydrogeological parameters are available for the formations of the Perth basin (Davidson and Yu (2005) and proprietary data from Rockwater Pty Ltd) and have been modified for the purpose of the numerical model by a classical trial and error method during the calibration of the model.

Table 2: Modelled hydrogeological parameters of geological formations in the Perth Basin

Geological Fm.	Kh (m/day)	Kh/Kv (-)	S (-)
Tk	$<1x10^{-4}$	1	$2.5x10^{-4}$
Kwg	6.5	10	$2.5x10^{-5}$
Jy	3.5	10	$5x10^{-5}$

Method and boundary conditions

The conductive and convective model is used to give the present-day temperature distribution of the modelled area of the Perth basin.

In addition to the physical and thermal parameters, aquifer boundaries had to be defined. For the simulation presented here, the temperatures of the upper and lower boundaries are taken from the conductive model and are set constant for all simulations (Dirichlet boundary condition). Monitoring bore heads in the vicinity of the modelled area are gridded (kriging method) and assigned as constant head boundaries. The temperatures of groundwater inflow are taken from results of the conductive model.

Barrier (impermeable) boundaries are set at the top and bottom of the model and are consistent with the hydrogeology of the area. The low permeability South Perth Shale overlies the Yarragadee Formation throughout the modelled area.

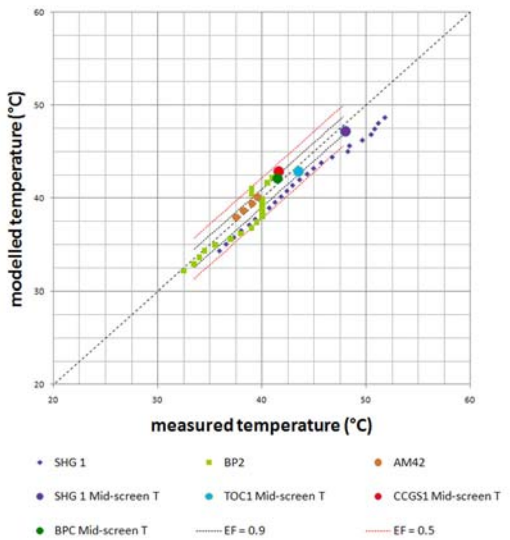

Fig. 2: Calibration plot showing calculated temperatures against measured temperatures

Results

Modelled temperatures were found to agree with measured temperatures and reliable temperature logs from existing geothermal bores (Fig. 2). The evaluation of the model is based on residual errors and follows the method of efficiencies (EF) described by Loague and Green (1991). Overall efficiency values range from 0.91 to 0.95, showing good to very good agreement between measured and modelled temperatures.

Moreover, results from the conductive and convective model were found to be similar, suggesting that regional groundwater flow has little impact on temperature distribution in the Yarragade aquifer. This may not be true locally in areas where the groundwater flow is more important.

Predictive model (year 2000 to 2050)

Conceptual model

Calculated temperatures from the previous model are taken as initial temperatures (January 2000) and potential heads are considered constant and equal to the potential heads measured in January 2010. Sensitivity analyses have shown that the observed decline of potential heads had little impact on the results. The geothermal installations operating schedule is given in Table 3. For bores screened in several different sections of the aquifer (TOC1, CCGS3), a portion of the total flow-rate (function of the length of the slotted section over the total screened length) is assigned to the corresponding cell of the model (run 1). As geothermal bores operate mostly during winter (April to October) when ambient temperatures are lower than the required temperature (temperature of the pool), modelled flow-rates are reduced to average rates in a second simulation (run 2).

Table 3: Geothermal installations operating schedule

Bore	Operating since	Temperature at the borehead (°C)	Q (L/s)
SHG1	2010	48.0	-25
SHG2	2010	36.0*	25
TOC1	2005	43.5	-14
TOC2	2005	29.0*	14*
CCGS1	2002	41.6*	-17
CCGS3	2002	27.0*	17*
CS1	2003/2004	42.0	-40
CS2	2003/2004	36.0*	20*
CS3	2003/2004	36.0*	20*
*: injection bore			

Calibration

CCGS1 temperature and hydraulic head data have been used for calibrating the model as it is the oldest geothermal installation in the area. Little to no increase of the temperature at the borehead has been recorded since the bore was commissioned. Considering the above assumptions, run 2 (Fig. 3) shows an acceptable agreement with pumped temperature increasing by 0.1°C after 10 years.

Note that a more accurate evolution of temperature at the bore could be obtained using a local model with a higher spatial resolution and an explicit numerical solution for advection.

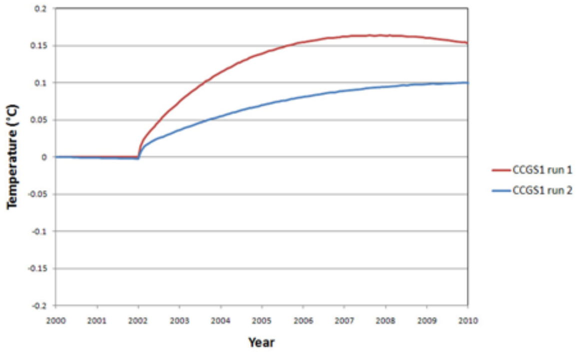

Fig. 3: CCGS1 modelled pumped temperatures

In addition, steady state modelled drawdown is 10.3 m and agrees with the aquifer losses of 8 m measured at the end of the 48 hours constant-rate pumping test.

Results: environmental impact of the injection

Following the calibration, the model was run from January 2000 to January 2050 to predict the evolution of temperatures within the basin.

The model aims are (i) to determine the general evolution of temperature of the Yarragadee aquifer, (ii) to give a first estimation of the lifetime of existing geothermal installations and (iii) to identify areas where there is an impact of injected water on aquifer temperatures.

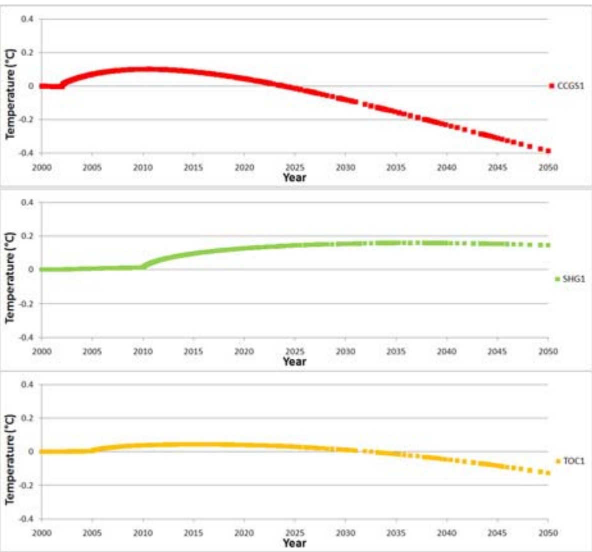

Fig. 4: Predicted evolution of temperature at CCGS1, TOC1 and SHG1

The initial observation is that there is little temperature decline at the production bores after almost 50 years of continuous operation as shown in Fig. 4.

The modelled temperature decline at CCGS1 in January 2050 is 0.39°C after 48 years, and 0.12°C at TOC 1 after 45 years whereas the temperature at SHG1 has increased by 0.14°C after 40 years. This is likely to have little impact on the geothermal installation efficiencies and subsequently the lifetime of all three geothermal installations; estimated to be more than 40 years.

Discussion

For all three bores, the temperature evolution can be described as follows:

- Stage 1: Increased temperature of the pumped water (increase is higher when flow-rate is higher) provoked by the inflow of deeper and warmer groundwater in the bores. This is further facilitated by the presence of upward heads.
- Stage 2: As the cooled groundwater is injected and travels through the aquifer in the direction of the production bore, the rate of temperature increase diminishes and eventually stabilises (this happens earlier when the vertical distance between injection and production screened section is small).
- Stage 3: Pumped temperatures start declining and eventually decline at a linear rate. It is calculated that bores CCGS1 and TOC1 will reach Stage 3 in year 2050 because of the smaller vertical separation between production and injection screened sections, whereas SHG1 is likely to still be in Stage 2.

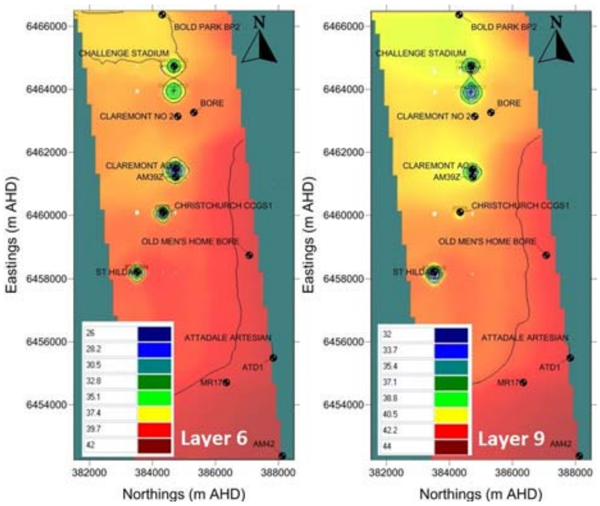

Fig. 5: Calculated temperature distribution (°C) in selected layers: layer 6 from -520 to -676 m AHD and layer 9 from -651 to -767m AHD

The modelled results show that the cooler injected water has a limited impact on the pumped groundwater temperature because of the moderately low vertical hydraulic conductivities, upward heads in the deeper geothermal bores, and the vertical distances between production and injection bore screens.

The cooled groundwater plume is calculated to extend 850 m in a circular pattern from TOC1 (Claremont AC) by 2050 (Fig. 5) indicating that natural groundwater flow has little influence on the shape of the groundwater plume. Conversely, the groundwater plume generated by CS1 (Challenge Stadium) has a very distinctive tear-drop pattern (Fig. 5, layer 9) indicating that a portion of the injected water is recirculated and that thermal contamination is occurring.

Conclusion: HSA direct-use sustainability and future research objectives

Although the presented simulation is decoupled (water density is independent of temperature) and may not be accurate where density effects dominate, the results show that pumped groundwater temperatures are unlikely to change significantly over the next 40 years. This supports the notion that HSA direct-use is a cost-effective solution (payback is about 5 years) for heating buildings or swimming pools for example.

However, temperature depletion seems to extend horizontally and although no visible interference between bores has been recorded, it is advisable to avoid pumping from the same depth as water is injected. Therefore, it is recommended that future production bores should be sited at least 500 m from one another and at different depths (i.e. 100 to 150 m deeper than the nearest injection screens).

To increase the accuracy of the model and to be able to guarantee the sustainability of HSA direct-use projects, additional work could be performed:

- Create local, high resolution models for each geothermal installation.
- Perform temperature logging periodically.
- Model heterogeneity patterns of the Yarragadee aquifer.
- Refine the structural model by considering geological members within the Osborne and Leederville formations.
- Refine the calibration of the model using a transient constant-rate pumping test.
- Perform hydraulic head versus depth measurements.
- Correlate the stratigraphy (siltstone and sandstone beds) between production and injection bores to increase vertical accuracy.
- Monitor geothermal installations periodically to obtain monthly data of injection temperatures, pumped water temperatures, flow-rates and injection pressures.
- Evaluate the impact of density forces (forces driving the formation of convection cells) on initial temperature distribution.
- Consider heat flow variations over the modelled domain.
- Refine the calibration using recent temperature logs of artesian monitoring bores.

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