Numerical modelling for flow, solute transport, and heat transfer in a high-permeability sandstone

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SUMMARY

Demand for water in the Perth Metropolitan Area, Western Australia, is increasing and new water supply options need to be considered. Aquifer replenishment by injection through wells is seen as a part of the solution however before any large scale implementation of an injection well field is considered several trials are being completed. Time lapse induction and temperature logging have been completed as part of two aquifer replenishment trials in the Perth Metropolitan area. The intention of the time lapse logging is to detail the movement of water away from the injector well into the Leederville formation. A hydrothermal computer model constrained by time lapse wireline logging induction and temperature results has been created to understand the movement of water and heat during injection into the Wanneroo sandstone formation. As with most practical numerical modelling, a level of non-uniqueness in the model parameters selected will exist. It is demonstrated that the calibration to time lapse logging results provides an important constraint on the range of flow, solute transport and heat parameters that can be used to build a reasonable hydrothermal computer model. First, the flow and solute transport model is constrained with time lapse electrical conductivity distributions at the monitoring wells. Next, the model is expanded to include heat transport. Results of our modelling provide the first field scale estimates of heat parameters in the Leederville Aquifer in Perth.

Key words: Mirrabooka, aquifer, FEFLOW, temperature, TDS, transient modelling, geothermal.

INTRODUCTION

Demand for water in the Perth Metropolitan Area, Western Australia, is increasing due to a growing population and insufficient rainfall over recent years. Strict control on water usage has been implemented while new water supply options need to be considered. One of the proposed solutions is to inject treated water into an aquifer and store for future abstraction. A Premier's Water Foundation grant, administered by the Department of Water, was awarded to a joint research project including Water Corporation, Curtin University, and CSIRO. The subject of the research project was aquifer storage and recharge (ASR). The trial site is at the M345 ASR site at Mirrabooka, Western Australia. One aspect of the research was the development of time lapse logging technologies for ASR. This required generation of hydrothermal numerical models based on measurements from two cycles of water injection and extraction at the M345 site.

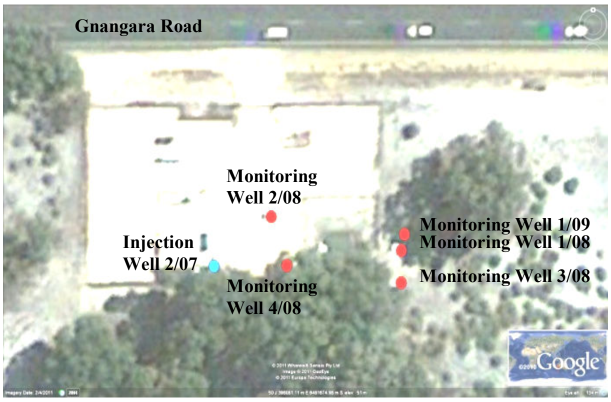

Figure 1 – Well locations at Mirrabooka ASR M345 site. Site coordinates are 31°47'45.52"S 115°23.86"E and horizontal distance in this map is 123 m.

The objectives of the time lapse logging experiment were:

1. To investigate time lapse induction and temperature logging methods for deriving flow, solute transport, and heat parameters with the aid of numerical modelling.
2. To recover heat parameters in the Leederville formation over the injection interval at the Mirrabooka ASR M345 site.
3. To build a first pass hydrothermal model that is calibrated with time lapse temperature, induction logging and mass concentration of total dissolved solids (TDS).

METHODS

Project Background

The trial site consists of an injection well (M345_2/07) and 5 monitoring wells (M345_1/08, M345_2/08, M345_3/08, M345_4/08, and M345_1/09). The distance from the injection well to M345_2/08 and M345_4/08 is approximately 15m. The distance from the injection well to M345_1/09, M345_1/08 and M345_3/08 is approximately 40 m. Well construction details are shown in Table 1, and hydrogeologic conditions at the site are shown in Table 2. The sedimentary layers beneath the site are relatively flat and this project is focused within the injection intervals zone ranging from 290 m to 430 m below ground level. The injection interval is within the Wanneroo member of the Leederville formation.

The injection water temperature and TDS are different than the pre-injection temperature and TDS. This allows indirect detection of the flow distribution via time lapse measurements of these parameters (i.e. temperature and electrical conductivity).

Table 1 - Summary of injection and monitoring wells construction details (Rockwater 2011, p. 5).

Well	Drilled depth (m bgl)	Cased depth (m bgl)	Screen section (m bgl)
M345_1/08	348.5	338.7	332.7 – 338.7
M345_2/08	357.0	338.0	332.0 – 338.0
M345_3/08	360.5	352.7	343.7 – 352.7
M345_4/08	370.0	363.5	352.5 – 363.5
M345_1/09	432.5	417.9	407.0 – 410.0
M345_2/07 (injection)	434.0	427.1	320.1 – 368.1 394.1 – 427.1

Development of a 3-D Numerical Model

A hydrothermal model of the Leederville aquifer is generated using FEFLOW. FEFLOW is a groundwater modelling software produced by DHI-WASY. A simple 10 km by 10 km 3-dimensional model is constructed with one injection/production well and five monitoring wells. The model consists of 38 flat layers located within the depth range from 290m to 430m below ground level. Vertical layering is selected based on both lithologic divisions interpreted from gamma logs and hydraulic conductivity distribution based on flow logs. The resulting model consists of 390234 mesh elements and 205200 mesh nodes. The model is setup as a thermohaline transient model to include flow, solute concentration, and heat parameters.

Temporal Control

The ASR trial was performed in two cycles consisting of an initial water injection of approximately 122 days, a residential waiting period of approximately 45 days, and then extraction of the injected water for 148 days. These two rounds of experiments are known as Cycle 1 and Cycle 2. The simulation was therefore performed over smaller sections for each phase (injection, resident, and abstraction). The results are then merged together to produce a complete time history from Cycle 1 and Cycle 2.

Initial Conditions

Potentiometric head for the Leederville was measured in the Monitoring wells at approximately 40m below ground level and this reference is used to set the model's hydraulic head initial condition for all nodes (Rockwater 2010, p. 4). The mass concentration of total dissolved salts used for this initial condition is derived from the hydraulic conductivity measurements taken from the injection well based on the following formula:

$$TDS = \frac{1}{2}(1000)(EC),$$ where TDS: mg/l
EC: ms/cm

The initial condition for temperature is based on high precision temperature logs taken in the deepest monitoring well (M345_1/09) prior to the ASR trial 9th of August 2009 (baseline temperature logs).

Table 2 - Summary of background baseline measurements of the Leederville formation (Rockwater 2011, p. 5)

Temperature	23 °C – 27 °C
TDS	550 mg/l – 1350 mg/l
Transmissivity	619 m^2/d – 712 m^2/d

Boundary Conditions

There are two screened intervals (i.e. 320 m – 368 m and 394 m – 427 m) in the injection well. These are included in the well boundary condition for numerical modelling (i.e. as multi-well condition). Temperature and mass concentration boundary conditions are setup within the two screened intervals of the injection well. These conditions are based on the field results obtained from the injection well which are then translated into temporally varying forcing functions (i.e. referred to as power function in FEFLOW). Temperature and mass concentration boundary conditions are only active during the injection period. The concentration and temperature well boundary conditions are based on measurement made on injection water immediately before injection via the well screens (Rockwater 2010). The hydraulic head boundary condition is set to 40m below ground level at all boundaries. This study was based on short term flow transport and thermal properties proximal to the well so fix head model boundary was considered sufficient. More complex model boundary could be considered for future modelling.

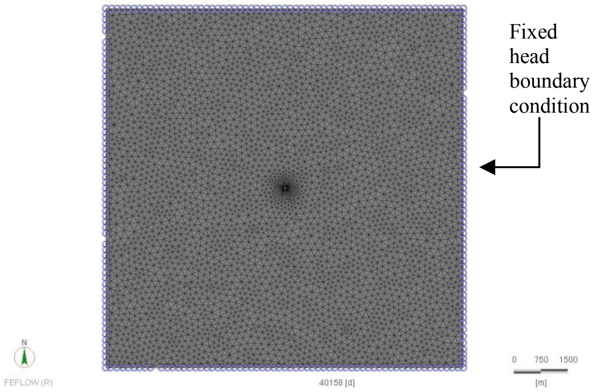

Figure 2 - The head is fixed at 40 m below ground level at the boundaries and temperature and mass concentration are unconstrained.

Material Parameters

Material properties for flow, solute and heat transport must all be estimated for the hydrothermal model. Three components of the hydraulic conductivity tensor are entered into FEFLOW (i.e. K_{xx}, K_{yy} and K_{zz}). A general rule of thumb is defined for these hydraulic conductivity parameters:

$$K_{xx} = K_{yy}, \qquad K_{zz} = \frac{K_{xx} \cdot K_{yy}}{C}$$

Here C is typically of the order 10 for lower permeability layers. Horizontal hydraulic conductivity is derived from hydraulic conductivity estimated from flow logging in the injection well M345_2/07. Hydraulic testing (i.e. constant rate tests) suggests that transmissivity for the aquifer is of the order 620 m^2/day (Rockwater 2009, p. 8). For this first pass modelling the longitudinal and latitudinal dispersivities are set to 1 m. Heat capacity was assigned based on density

(Weatherford, 2009; Waples & Waples, 2004), while thermal conductivity estimates were based on a small number of measurement completed by WAGCOE (i.e. the Western Australian Geothermal Centre of Excellence).

RESULTS

The model predicts hydraulic pressure, TDS concentration, and temperature throughout the three-dimensional domain. Results vary over time from the initial injection of Cycle 1 to the final withdrawal of Cycle 2. Results at individual monitoring wells are extracted over time for calibration purposes. Figure 3 shows one isosurface for hydraulic head distribution within the injection interval. The higher permeability (i.e. fast layers) are clear from the image.

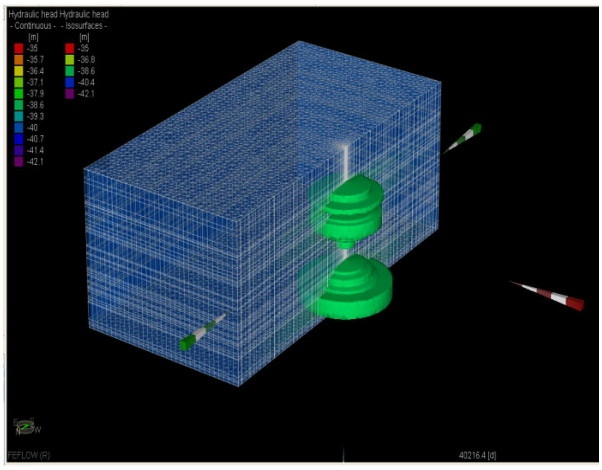

Figure 3 - Isosurface visualisation of the injectant water during Cycle 1 injection phase at injection well 2/07.

Calibration to Well Data

Our model TDS results matched reasonably with the field results although we believe there is still considerable room to refine all material parameters such that model and field data match. Field measurements show that the TDS movement is faster than the final model predictions. This can be calibrated by adjusting the dispersivity or hydraulic conductivity distribution (Harris 2001).

Heat flow occurs by both conduction and by advection. The modelling outcomes are matching reasonably well with the field measurements. A sudden blip in the field measurements indicates the presence of high-permeability layers in that injection zone. To calibrate this phenomenon, the zone needs to be discretised into smaller layers with higher hydraulic conductivities. The thermal spreading during the resting periods between injection and extraction can be calibrated by changing the rock's specific heat.

Figures 4 and 5 show fence diagrams for the start and end of Cycle 1 injection for TDS and temperature respectively. Figure 6 shows are first attempt to match model data to field temperature logs. The general shape of the synthetic temperature logs (i.e. derived from modelling) matches that for the field temperature logs. However more modelling iterations will be required to precisely match model and field data.

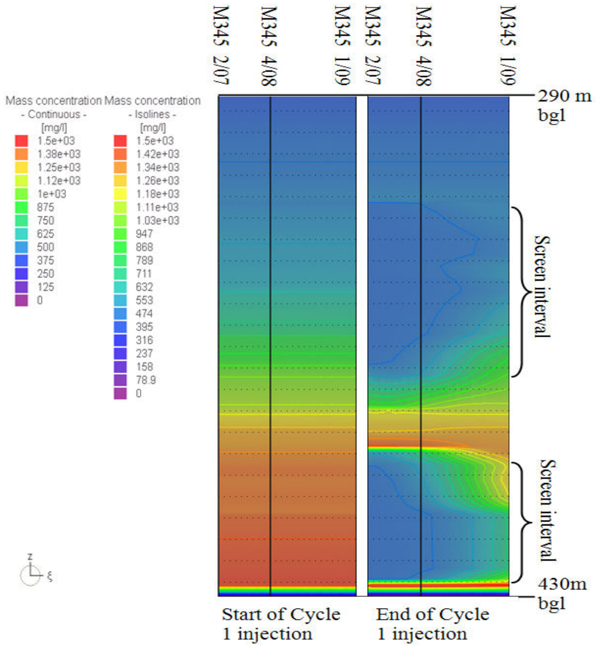

Figure 4 - Time lapse TDS fence diagram for start of Cycle 1 injection and end of Cycle 1 injection.

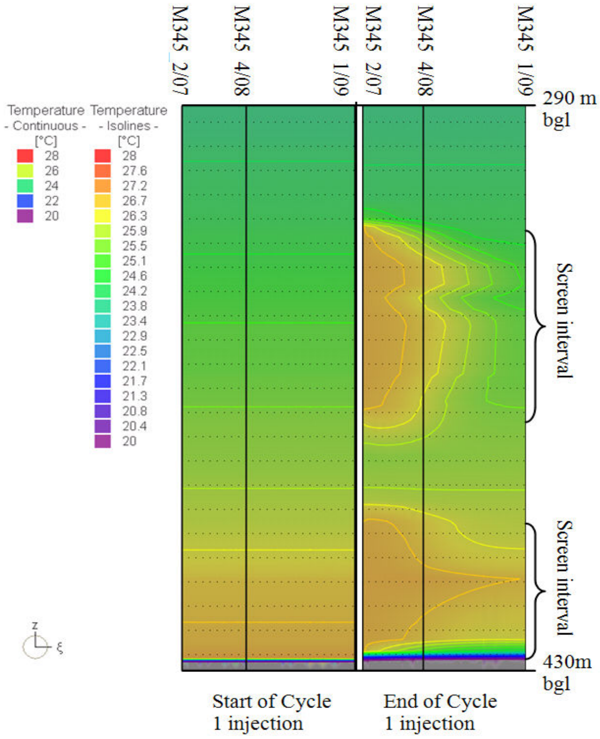

Figure 5 - Time lapse temperature fence diagram for start of Cycle 1 injection and end of Cycle 1 injection.

CONCLUSIONS

We have shown our first steps in calibrating a hydrothermal numerical model to time lapse field induction and temperature wireline logs obtained during injection at the M345 aquifer storage and recovery site. Early results are very encouraging however considerably more work on calibration and model development is required.

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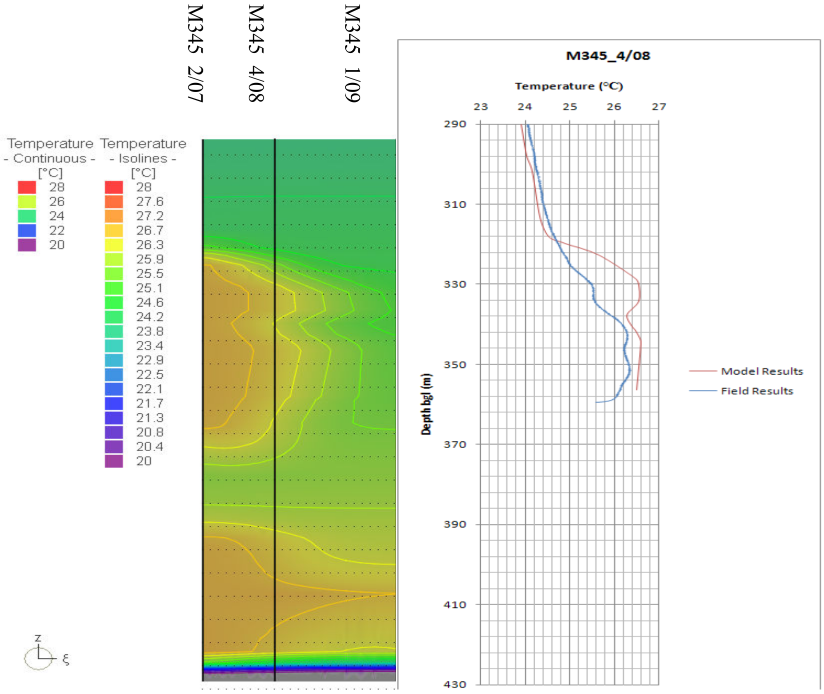

Figure 6 - M345_1/09 time lapse temperature log comparison between model and field results taken on 19/02/2010 during Cycle 1 resident period.