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title: **A coupled groundwater flow, solute and heat transport model to facilitate operation of an aquifer storage transfer and recovery system in a brackish aquifer**

author(s): **Konrad Z. Miotliński**
CSIRO Land and Water, Australia, Konrad.Miotlinski@csiro.au

Peter J. Dillon
CSIRO Land and Water, Australia, Peter.Dillon@csiro.au

Sarah Kremer
BRGM, France, S.Kremer@brgm.fr

Paul Pavelic
IWMI, India, p.pavelic@cgiar.org

Stephanie Rinck-Pfeiffer
United Water, Australia, stephanie.rinck-pfeiffer@uwi.com.au

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INTRODUCTION

Groundwater recharge, retention and reuse are recognised as adaptive strategies to increase security of water supply (van Steenbergen, Tuinhof, 2009). An example using reedbed-treated urban stormwater in an Aquifer Storage Transfer and Recovery (ASTR) system has been tested in the city of Salisbury, South Australia (Dillon, 2005; Rinck-Pfeiffer et al., 2005). Similar to Aquifer Storage and Recovery (ASR) systems that operate throughout the world, ASTR is a method of utilising subsurface storage to provide a reliable buffer against seasonal variation in water demands and supplies while also providing natural treatment to take place within the aquifer. While ASR uses the same well for both injection and extraction, the ASTR system uses separate injection and extraction wells to provide a longer and more uniform residence time in the aquifer (Dillon, 2005). This residence time ensures that the degradation of potential contaminants is more efficient but can also increase the potential for mixing between the injectant and the ambient groundwater. In Salisbury, the brackish aquifer had to be efficiently flushed to recover freshwater suitable for urban reuse.

Eventually, the aquifer is intended to be a reliable source of potable quality water.

A finite element groundwater code FEFLOW (Diersch, 2009) was used to simulate injection and extraction operations in well fields of various designs (Pavelic et al., 2005), and following site construction and initial operation, the model was subsequently calibrated with data from pumping tests, hydraulic head variations and solute breakthrough to wells (Kremer et al., 2010) and subsequently also using water temperature.

The objective of the research is to combine the use of solute and heat transport to reduce uncertainty in groundwater modelling of the ASTR system.

STUDY SITE

The bore field consists of 6 wells positioned within a rhombic domain (4 outer wells and 2 central wells), with a uniform 50 m separation between the wells. The captured stormwater is injected to the confined T2 carbonate aquifer between depths of 160–220 m (Fig. 1).

Regional groundwater flow gradient is 0.0015. The transmissivity of the aquifer is 120 m^2/d. The ASTR wells are however screened only in the upper part of the profile (T2a, T2b) where permeability of the aquifer is lower (T = 50 m^2/d). The reason for this was to avoid short residence times of injected water before recovery.

In the initial phase of the site operation (i.e. flushing period) the stormwater was injected using the two wells located in the central part of the bore field. Once the salinity had declined in the four outer wells, these were used as the injection wells for ongoing operation, and water was extracted from the two inner wells. As a result, 377 × 10^3 m^3 of stormwater was injected from September 2006 to June 2008 (Table 1).

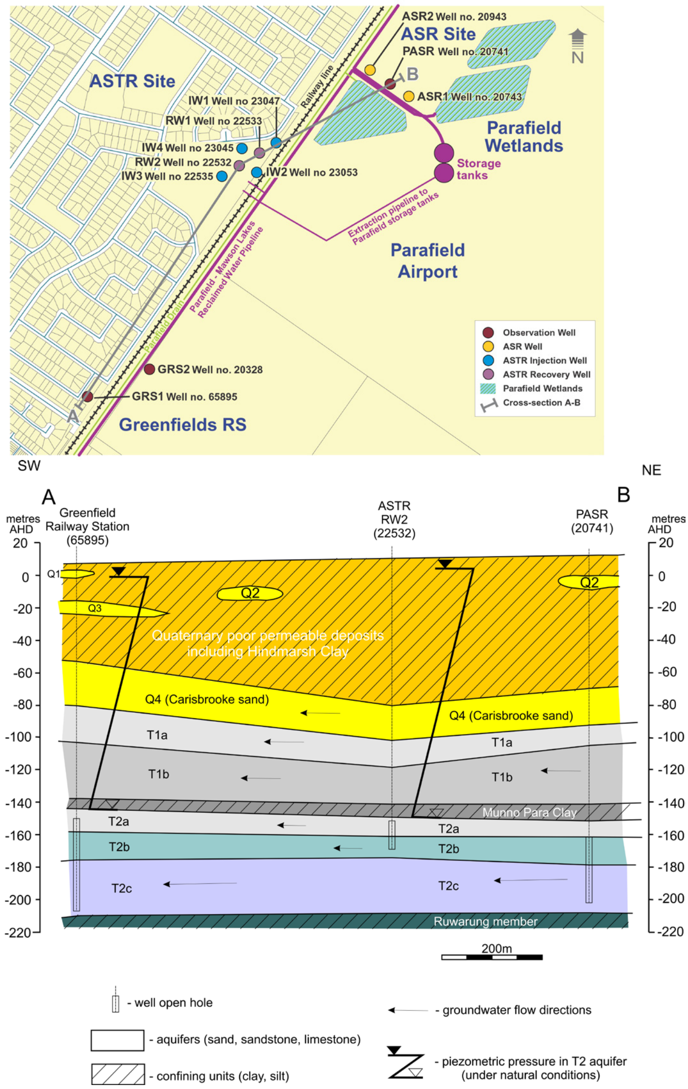

Figure 1. Map of the site and hydrogeological cross-section through Cenozoic deposits.

Table 1. Quantities of water (in 103 m³) injected (+) and extracted (-) at ASTR system from September 2006 to March 2009.

	IW1	IW2	IW3	IW4	RW1	RW2	TOTAL injected	TOTAL extracted
Sept 2006 June 2008	0.0	0.0	0.0	0.0	+197.3	+179.8	+377.1	0.0
Sept 2008 Jan 2009	+9.1	+9.0	+3.0	+8.8	+0.1 –0.3	0.0 –0.7	+30.0	–1.0
Feb 2009 Mar 2009	0.0	0.0	0.0	0.0	–44.8	–44.8	0.0	–89.6

METHODS

Salinity (Electrical Conductivity, EC) and temperature of water was monitored using periodic profiling. Electrical conductivity is considered to be a conservative tracer here, although dissolution of calcite due to injection of stormwater is feasible. Thermal properties of limestone are known from the literature (Clauser, Huenges, 1995). The FEFLOW (Diersch, 2009) finite element code was applied to simulate groundwater flow as well as transport of solute and heat in the aquifer. The three-dimensional solute and heat transport model was calibrated using a trial-and-error method on the basis of breakthrough curves for the outer wells during the initial flushing phase.

RESULTS AND DISCUSSION

The ambient groundwater was brackish (3650 µS/cm on average) with a temperature of 27°C, whereas the injected stormwater was fresh (250 µS/cm on average) and exhibited temperature variations in the range of 8-15°C in winter, when most water was injected.

Injection of stormwater over 857 days of aquifer flushing resulted in the decrease in EC of groundwater from 3650 µS/cm to 700 µS/cm at the outer wells and a decline in temperature from 27 to 20.5°C at the outer wells (shown for IW3, Fig. 2). The temperature breakthrough curve is retarded (R≈2) compared with EC (Fig. 2), which is consistent with the theory of heat transport in aquifers (Anderson, 2005). The modelled values fit the observed data well during the flushing period.

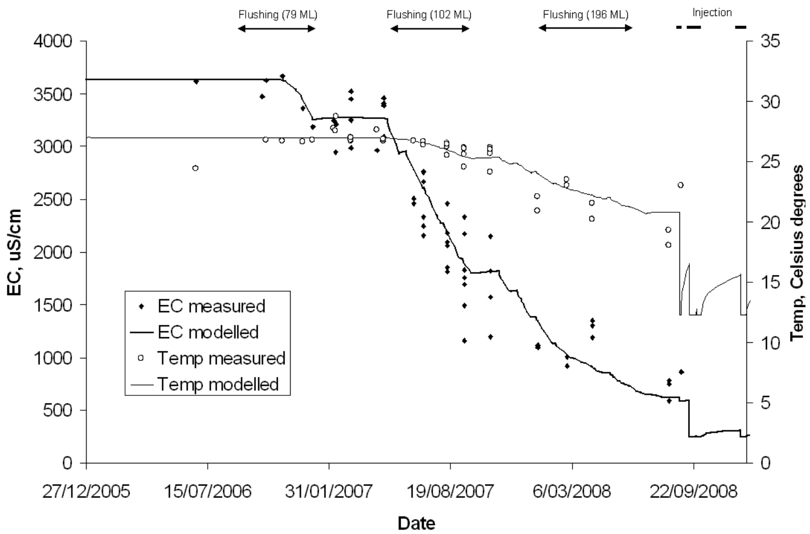

Figure 2. Observed and modelled breakthrough values of EC and temperature of water in the outer well IW3 (This well was first used as an injection well in Sept 2008, which caused step changes in EC and temperature).

Given the variable nature of rainfall and subsequently the volume of stormwater available for recharge, the numerical model was used to simulate a range of operating scenarios in dry, typical and wet sequences of rainfall years. This enabled an operating rule to be defined to allow operators to predict the volume of water recoverable at suitable quality for the following summer based on the volume of winter recharge, while also ensuring the storage zone remains fresh and sustains ongoing operation as a drinking water supply. The results suggest that at this site ASTR can be an effective means of improving quality of recharged water while meeting salinity constraints (Kremer et al., 2010).

The coupled model of groundwater flow, solute and heat transport is a powerful tool to analyse the interactions among the wells in the ASTR system. We showed that groundwater flow and solute transport model can be constrained by using temperature data which can be measured easily and rapidly during a typical groundwater survey. FEFLOW has the capability of simulating both solute and heat transport concurrently, which is a big advantage of this code. Nevertheless, further evaluation of the presented model against data taken from a prolonged storage and extraction periods is required. Other environmental tracers (SF_6) will be helpful in the examination of the heterogeneity of the aquifer and in the improvement of the model.

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