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Recovery of injected freshwater to differentiate fracture flow in a low-permeability brackish aquifer

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SUMMARY

A low-permeability weathered siltstone–sandstone aquifer containing brackish water was investigated to measure recoverability of injected freshwater with the aim of determining the significance of secondary porosity in contributing to groundwater flow and transport. Examination of the core, borehole geophysics, Radon-222, electromagnetic flowmeter (EMF) profiles and step-drawdown pumping tests did not identify whether fractures contribute to groundwater flow. A number of injection and recovery tests lasting from 3 days to 3 months using potable water showed a large degree of mixing with native groundwater. Withdrawal greater than 12–17% of the injected volume resulted in recovered water containing more native groundwater than injected water. A finite element solute transport model was set up to reproduce the observed salinity in recovered water. Without the inclusion of discrete fractures in the model it was not possible to get a fit between the observed and modelled salinity of recovered water within a realistic range of dispersivity values. The model was subsequently verified by using data from long-term injection and recovery trials. This evaluation of mixing conclusively demonstrated that the aquifer behaved as a fractured rock aquifer and not as an aquifer with primary porosity alone. Therefore, aquifer storage and recovery can be a very useful hydrogeological method to identify the occurrence of fracture flow in aquifers where there is a measurable concentration difference between the injected water and ambient groundwater.

1. Introduction

Many tasks of modern hydrogeology include estimation of groundwater age, prediction of contaminant transport or evaluation of groundwater recharge. When dealing with fractured porous media these tasks require determination of the extent to which secondary porosity contributes to groundwater flow and transport of solutes in an aquifer. In some fractured aquifers, matrix permeability is considered to be negligible (Becker and Shapiro, 2000), although in other examples it might greatly contribute to water transfer (Motyka, 1998). In both cases, however, diffusion to the matrix may affect transport and fate of tracers and contaminants (Neretnieks, 1980; Tang et al., 1981; Małoszewski and Zuber, 1993; Cook et al., 2005). In some fractured media formations, contaminant transport is interpreted as being solely affected by diffusion into the matrix (Neretnieks, 1980; Małoszewski and Zuber, 1993), whereas in others solute transport is attributed to dispersive mixing due to heterogeneity of fractured media (Long et al., 1982; Neretnieks, 1983; Dykhuizen, 1992; Becker and Shapiro, 2000).

Several borehole geophysical methods have been used to evaluate vertical heterogeneity that can potentially contribute to groundwater flow (Williams and Lane, 1998; Paillet and Pedler, 1996; Muldoon and Bradbury, 2005; Le Borgne et al., 2007). Sometimes these techniques are able to determine the exact location of fractured zones, their thicknesses and spatial orientation, and even whether the fractures are filled with coatings of secondary material. Since data obtained using a single geophysical borehole logging method can be ambiguous, it is generally recommended to use several techniques in order to determine whether fracture flow is significant (Paillet and Pedler, 1996). A downhole electromagnetic flow metre is useful in evaluation of the heterogeneity of an aquifer in the vertical direction and gives a quantitative description of flow variability in a well as well as the estimation of hydraulic conductivity over discrete intervals (Molz et al., 1989; Paillet and Pedler, 1996; Le Borgne et al., 2007). Muldoon and Bradbury (2005) demonstrated that borehole geophysical logging could be used successfully in the determination of fractured zones in a dolostone aquifer, although the pumping test observed in a large

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set of observation wells showed that the aquifer behaved as a porous medium. Le Borgne et al. (2007) showed that the results from the flow metre analysis coincided well with the packer tests and borehole geophysical data in identifying preferential flow zones in a moderately transmissive (~85 m^2/d) fractured granite/schist aquifer.

Despite these sophisticated geophysical techniques, due to hydrogeological complexity of fractured media characterisation of flow and solute transport remains a challenge. Even following identification of potential fractures, there still remain the question of how spatial variability in bulk hydraulic conductivity and properties of fractures influence groundwater flow. In particular, the potential for fluid and chemical exchange between highly conductive geological features and aquifer matrix is unknown and generally requires implementation of a tracer followed by a detailed analysis of its behaviour. In deep confined aquifers tracer tests are normally performed in a two-well dipole configuration (Huyakorn et al., 1986; Becker and Shapiro, 2000), radial converging flow (Kreft et al., 1974; Becker and Shapiro, 2000), radial diverging flow (Valocchi et al., 1981), or single-well injection–withdrawal tests (Novakowski et al., 1998; Pavelic et al., 2006). A significant difference between injection–withdrawal experiments and other tracer tests is the partial reversal of solute spreading during the tracer recovery phase (e.g. Gelhar et al., 1992).

Aquifer storage and recovery (ASR) is based on the same principle as the single-well injection–withdrawal tracer test. ASR tests are used in managed aquifer recharge to determine the potential of a site for underground water storage. Freshwater is often injected to an aquifer containing brackish or saline groundwater. Apart from dispersive and diffusive spreading of the freshwater plume in an aquifer, regional groundwater drift and density (buoyancy) effects can be responsible for poor recoverability of injected fluid in ASR systems (Bear and Jacob, 1965; Ward et al., 2009).

This paper aims to demonstrate that ASR trials may be helpful in discrimination of fractured flow in an aquifer even at a site where the advanced borehole techniques and pumping tests did not unequivocally explain the nature of groundwater flow.

2. Site description

In the city of Melbourne, Australia, a series of investigations was performed to evaluate the suitability of a confined aquifer for storing of urban stormwater for use in golf course irrigation (Fig. 1; Dillon et al., 2010). The target aquifer consists of Siluro-Devonian interbedded siltstone, mudstone and sandstone located within the Melbourne Trough (Garrat, 1983). Vandenberg and Schleiger (1972) describe this sequence as "flysch" due to the occurrence of geological features typical of Alpides (Dżułyński and Walton, 1965). The target aquifer is not used for urban water supply in the area due to the relatively high salinity of the ambient groundwater (electrical conductivity (EC) 2400–2700 μS/cm) and low borehole yield. Poor hydraulic conductivity (0.03 m/d) along with a low regional hydraulic gradient (0.0001) results in a low natural groundwater velocity (Lennon et al., 2006). The aquifer is overlaid by a thick sequence of clastic sediments and basalts of Cainozoic age (Fig. 1).

The ASR feasibility study included drilling of the four wells depicted in Fig. 1. BH1 and BH2 were completed within the overlying sediments, whereas BH3 and BH4 were installed within the

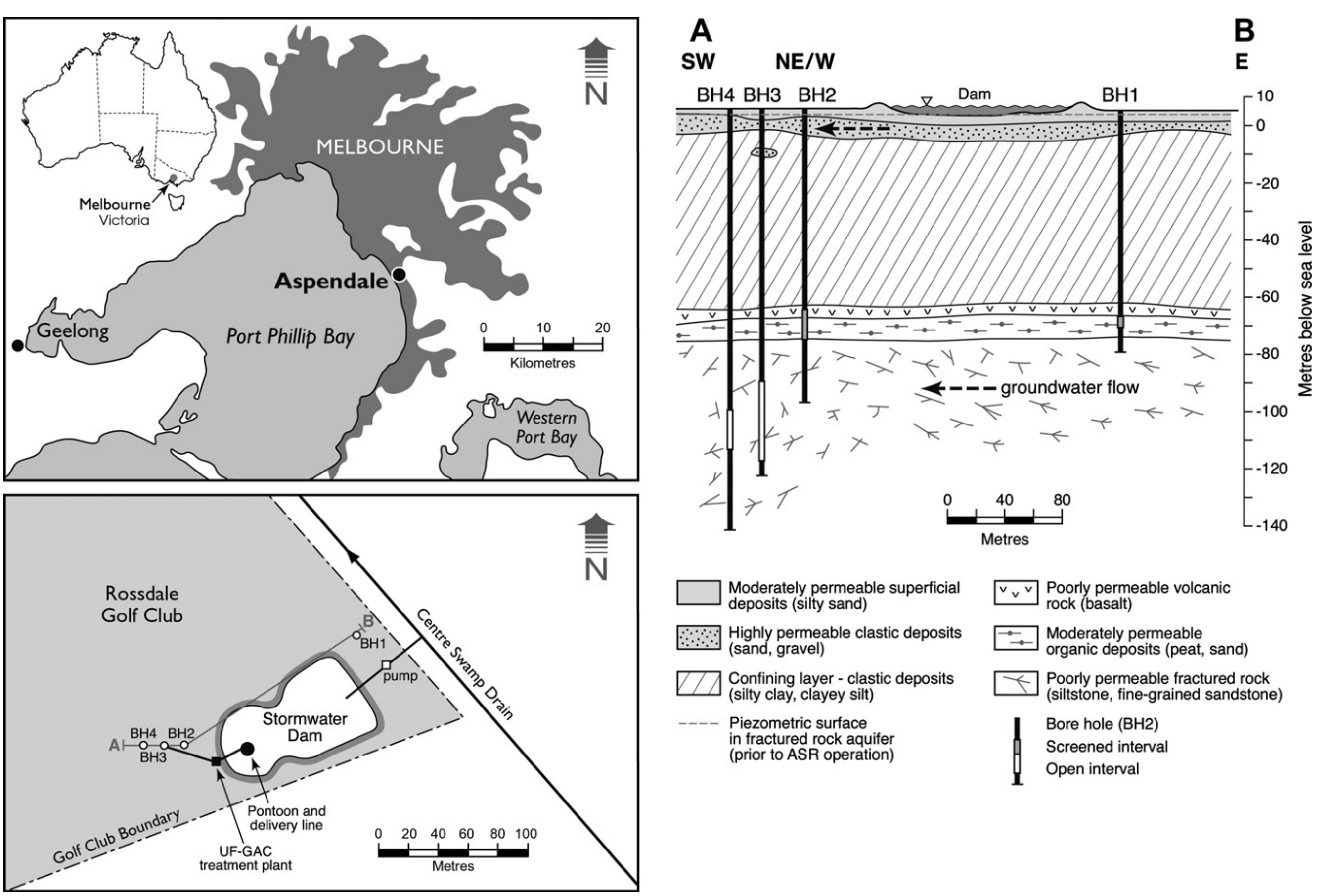

Fig. 1. Map showing location of Rossdale Golf Course in Aspendale, Victoria (left top) and layout of the ASR site in south eastern corner of the golf course (left bottom). Hydrogeological cross-section at the site (right). BH3 is used as an ASR well.