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Experimental observations of saltwater up-coning

Adrian D. Werner *, Danica Jakovovic, Craig T. Simmons

School of Chemistry, Physics and Earth Sciences, Flinders University, GPO Box 2100, Adelaide, SA 5001, Australia

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SUMMARY

The proper management of coastal aquifers commonly requires an understanding of the behaviour of saltwater plumes underlying production wells. The current understanding of saltwater up-coning (i.e. the pumping-induced rise in the freshwater–saltwater interface) is based predominantly on theoretical constructs of salinity and flow responses to groundwater pumping, plus a limited number of field-scale and laboratory investigations. There is a need to produce direct observations of saltwater up-coning, given the considerable and inherent uncertainties associated with the prediction of density-dependent flow and dispersive solute transport behaviour. In this study, time-series observations of saltwater up-coning were made using controlled sand-tank experiments of a two-dimensional aquifer cross-section. A range of mixed convection ratios was tested by invoking different groundwater abstraction rates and saltwater densities. The temporal development of up-coning was characterised in terms of the height of the interface apex, the width of the salt plume, and the salinity of the pumping well. Experimental results were compared to an existing sharp-interface analytical solution and close agreement was obtained for two of the cases. Higher freshwater–saltwater density differences and lower pumping appeared to induce the largest deviations from theoretical up-coning. Dispersive transport processes dominated during phases of near-well up-coning, causing gradual increases in pumped water salinity, although plumes became non-dispersive after the interface made contact with the bore. An interesting departure from the classical up-coning shape was obtained for the situation of highest saltwater density and lowest pumping, in which up-coning occurred as an almost horizontal interface for the majority of the experiment, eventually producing a double-apex shape as the interface neared the well. The experimental results could form a useful basis for the testing of density-dependent groundwater flow and transport models, since they offer controlled laboratory analogues of saltwater up-coning.

Introduction

Overexploitation of groundwater has become a common issue in coastal areas around the world. As a result, many coastal aquifers have experienced saltwater intrusion, i.e. the landward movement of saltwater and subsequent contamination of fresh groundwater resources (FAO, 1997). Typically, water density differences between saltwater and freshwater produce a sloping freshwater–saltwater interface, whereby deeper saltwater is overlain by freshwater (Barlow, 2003). Where fresh groundwater is extracted under these conditions, careful management is required to avoid the vertical rise of saline water into production wells, a process commonly referred to as 'saltwater up-coning'. The rate and extent of saltwater up-coning is controlled by a number of factors, including the aquifer hydraulic properties, the rate and duration of groundwater extraction, the penetration of pumping wells relative to the saltwater–freshwater interface, fluid density differences and other factors such as salt dispersion effects, groundwater recharge and the well and aquifer geometries (Wirojanagud and Charbeneau, 1985; Reilly and Goodman, 1987; Saeed et al., 2002).

The current understanding of the flow and transport processes associated with saltwater up-coning are based predominantly on mathematical analyses (e.g. Bear and Dagan, 1964; Haubold, 1975; Bower et al., 1999). Mathematical analyses of saltwater up-coning commonly adopt one of two approaches to the representation of the freshwater–saltwater interface. The first approach assumes that the saltwater and freshwater are immiscible fluids and a sharp interface exists between the two fluids (e.g. Haubold, 1975). In the second approach, saltwater and freshwater are treated as miscible fluids separated by a transition zone that is controlled by hydrodynamic dispersion (e.g. Bower et al., 1999). Bear (1979) suggests that the sharp interface approximation is appropriate if the transition zone thickness is thin relative to the depth of aquifer. Sharp interface models are simpler to apply, but they often over-estimate the critical rate of groundwater extraction (i.e. the maximum rate of pumping in which the freshwater–saltwater interface does not encounter the well) (Zhou et al., 2005). A major limitation of the dispersive interface approach is that solute dispersion effects are not well understood, are challenging to

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* Corresponding author. Tel.: +61 8 8201 2710; fax: +61 8 8201 2905.
E-mail address: adrian.werner@flinders.edu.au (A.D. Werner).

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parameterise in the absence of observation data and are usually difficult to simulate for small values of transverse dispersivity, α_T (Paster and Dagan, 2008).

Surprisingly, while there are many examples of both analytical and numerical solutions to saltwater up-coning, images of saltwater up-coning under controlled laboratory conditions have not been published previously. Laboratory experiments and the associated experimentation imagery have been used previously to explore the complexities and intricacies of other density-dependent transport phenomena. For example, Goswami and Clement (2007) used sand tank experiments to develop modelling benchmarking results for the situations of steady-state, intruding and receding interface conditions, for the lateral saltwater intrusion case. The sand tank experiments of density-dependent flow by Simmons et al. (2002) focused on the vertical downward movement of unstable salt plumes, using both saturated and unsaturated porous media settings.

There are only a few cases in which saltwater up-coning has been induced and observed under controlled laboratory or field conditions. Reilly and Goodman (1987) simulated a field situation of saltwater up-coning using numerical methods and were able to deduce that the transverse dispersivity was low (in the order of discretisation error), but the match between predicted and observed bore salinity was somewhat weak. The only example of laboratory experimentation of saltwater up-coning appears to be the work of Dagan and Bear (1968). The primary focus of their research was the application of the method of small perturbations to develop analytical solutions for non-steady interface up-coning, including the case of a drain in a laterally infinite two-dimensional aquifer. Dagan and Bear (1968) obtained a non-steady mathematical solution that was valid for interface rise approximately up to one-third the distance between the bottom of the well and the initial interface position. They compare their mathematical solutions to laboratory up-coning experiments by considering the rise of the up-coning plume apex. Experimental conditions were varied by changing the rate of pumping. Only a summarised account of the laboratory results was given (i.e. the shapes of salt plumes were not given and experimental photography was not published), and therefore the salt plume behaviour leading to bore salinisation was not observed directly. Direct observations of saltwater up-coning are required to complement previous modelling analyses and to extend the laboratory experimentation of Dagan and Bear (1968).

The primary objective of this study is to re-produce up-coning under controlled laboratory conditions and to capture (using photography) and quantify the pathways and behaviour of a dense saline plume near a production well. A two-dimensional case is assessed, similar to that analysed by Dagan and Bear (1968), and therefore the production well represents a line sink (i.e. similar to a drain). Experiments are designed to evaluate saline groundwater movements subject to different pumping rates and under different freshwater–saltwater density contrasts. Experimental results are compared to the analytical solution of Dagan and Bear (1968) to assess the agreement between experimental observations and sharp-interface mathematical predictions of up-coning behaviour. The Dagan and Bear (1968) analytical solution is adopted here because it is one of a limited number of two-dimensional solutions (i.e. similar to the present experimental setting) and continues to be adopted in contemporary studies as the equation of choice for up-coning analysis using the sharp-interface approximation (e.g. Van Meir and Lebbe, 2005). Obviously, a numerical modelling analysis of the sand tank would provide additional insight into the observed flow and transport processes; however the primary value of the current work is on the observations of physical experiments and as such, only a limited theoretical analysis is presented.

Experimental methods and materials

Sand tank experiments form the basis of this study. The primary infrastructure is essentially the same as that used by Simmons et al. (2002) in their investigation of density-driven instabilities, except the set-up is modified for the situation of saltwater up-coning. A schematic of the apparatus is given in Fig. 1. The sand tank was constructed using 1.5 cm float plate glass for the front and back, supported by a stainless steel frame at the sides and bottom. The internal dimensions of the sand tank are 117.8 cm length, 120.0 cm height and 5.3 cm width. Plastic inflow–outflow taps have been installed at 10 cm intervals on the sides and bottom of the tank. Sand clogging of the taps was prevented by inserting fine metal mesh into the side taps, and the bottom of the tank was lined with a layer of fine nylon mesh.

Fluid was supplied from constant head reservoirs (five 20 L Mariotte bottles – four freshwater bottles and one saltwater bottle) placed on adjustable shelves and connected to the inflow–outflow taps using 10 mm internal diameter silastic tubing. Mariotte bottles were inter-connected via both water and gas components to eliminate any small differences in the constant heads between individual bottles, in a somewhat similar fashion to that described by Klute and Dirksen (1986). With this arrangement, the Mariotte

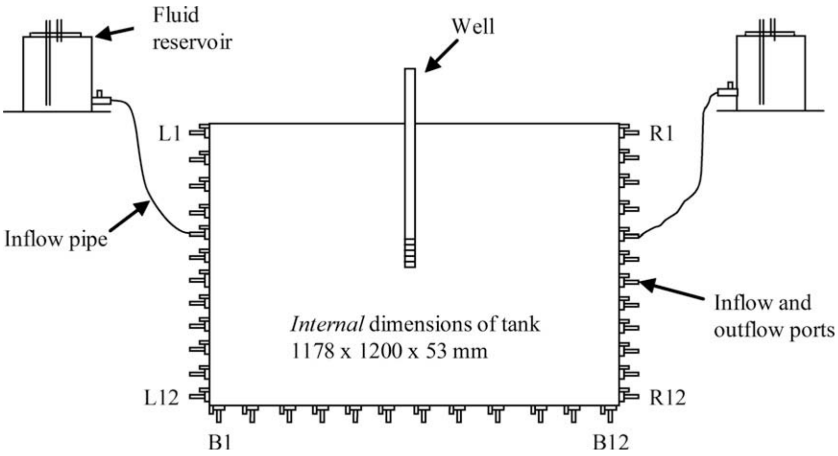

Fig. 1. Schematic diagram of the experimental apparatus (modified from Simmons et al., 2002). Taps are numbered L1–L12 (left side), R1–R12 (right side) and B1–B12 (bottom).